

# **NOBCON 2026**

## **2<sup>nd</sup> International Conference – NOBCON 2026 on Interdisciplinary Horizons – Innovation, Sustainability, AI and Transformation (IC-IHITSA)**

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# Executive Summary

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Nobcon 2026 gathers researchers, industry leaders, policymakers and students from around the world to explore interdisciplinary approaches to innovation, sustainability, AI and transformation. This brochure outlines the conference objectives, tracks, submission opportunities, key dates, guidelines and participation details for approval and rollout.

## Torchbearers of Noble University

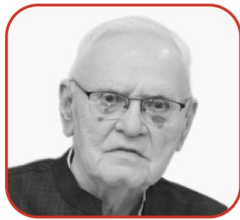
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# Conference Tracks

(Suggestive topic but not limited to following Topic)

## Track 1

### Engineering, Science, Technology, Pharmacy & Nursing

Sustainable Engineering & Clean Technologies  
AI/ML for Engineering  
Robotics & Smart Manufacturing  
Materials Science & Nanotechnology  
Renewable Energy Systems  
Biotechnology and Genetic Engineering Applications  
Microbiology and Public Health Research Trends  
Evidence-Based Nursing Practice and Patient Safety  
Critical Care Nursing and Emergency Management  
Novel Drug Delivery Systems  
Pharmaceutical Quality Assurance and Regulatory Affairs

## Track 2

### Management, Commerce, Humanities, Arts & Social Science

Sustainability Strategy & CSR  
Innovation Management & Startups  
Digital Transformation & AI in Business  
Economics/Policy in AI Era  
Responsible AI, Ethics, Governance & Law  
Humanities & Technology (Culture/Media/Communication)  
Arts & Design for Social Impact  
Behavioural Science & Leadership  
Global Trade & Digital Economies  
Sustainable Business Models & Circular Economy  
Education & Knowledge Societies

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Chiang Mai, Thailand



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## Message from the Chief Patron



Dear Scholars, Researchers, and Participants,

It is a proud moment for Noble University to host the 2<sup>nd</sup> International Conference on Interdisciplinary Horizons - Innovation, Sustainability, AI and Transformation [IC-IHITSA] in collaboration with Chiang Mai University, Chiang Mai, Thailand. This initiative reflects our university's commitment to fostering collaboration and innovation in research across diverse fields. With participation from 331 authors representing 7 countries, this conference brings together a vibrant mix of ideas, perspectives, and expertise. The meticulous review process resulted in the selection of 159 high-quality papers out of 249 submissions, ensuring a rich and engaging program. I would like to take this opportunity to acknowledge the exceptional efforts of Dr. Riddhi Sanghvi, the conference co-chairs, whose dedication and hard work have been instrumental in organizing this grand event. I congratulate the participants and encourage you to make the most of this platform to share your research, build networks, and explore new opportunities for collaboration. I also applaud the organizing team, led by Dr. Jay Talati, for their dedication to making this event a success. Wishing everyone a productive and inspiring conference!

Warm regards,

Dr. H. N. Kher Kher

Chief Patron

Provost, Noble University

## Message from the Conference Chair



Dear Participants, Academicians, and Researchers,

It is my privilege to welcome you all to the 2<sup>nd</sup> International Conference on Interdisciplinary Horizons - Innovation, Sustainability, AI and Transformation [IC-IHITSA] in collaboration with Chiang Mai University, Chiang Mai, Thailand, a major step by Noble University toward promoting research excellence. This conference stands out not only for its hybrid format, allowing participation online and offline, but also for the diverse participation of researchers from 7 countries, showcasing a truly global academic platform. This event provides an exceptional opportunity for researchers to present their ideas and gain recognition through collaborations with distinguished journals. I am particularly proud of the interdisciplinary focus, which opens avenues for impactful discussions and innovative solutions to real-world challenges. I extend my heartfelt gratitude to the management of Noble University for their unwavering support, guidance, and encouragement, which have been critical in making this event possible. I also express my appreciation to our Chief Patron, Dr. H. N. Kher, for his visionary leadership and to the organizing team for their tireless efforts in shaping this conference. I wish all participants an enlightening and fulfilling experience as they contribute to shaping the future of multidisciplinary research.

Best regards,

Dr. Jay Talati

Conference Chair

Registrar, Noble University

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## About the University

Shri Vivek Bharti Trust, led by four visionary philanthropists, proudly established Noble Group of Institutions (NGI) in Junagadh, Gujarat, to provide quality education in Engineering, Science, Management, Pharmacy, Education, and Nursing. Since 2007, NGI has been a hub for technological and scientific growth, offering modern labs, a world-class library, spacious classrooms, green playgrounds, a gym, and strong industry connections. In 2022, NGI became Noble University (NU), expanding across 30 scenic acres near Girnar Hill, fostering innovation and creativity in a serene environment. NU is dedicated to empowering students with ethical, high-quality education to serve society and advance humanity. With partnerships across academia and industry, NU nurtures skilled, compassionate individuals ready to lead globally. Focused on interdisciplinary learning, NU harmonizes intellect, emotion, and action to shape a brighter, sustainable future for India and the world.

## About the Conference – NOBCON 2026

NOBCON 2026 is an international multidisciplinary conference organized at Noble University, Junagadh, India. The conference provides a dynamic platform for researchers, academicians, industry professionals, and scholars to share innovative ideas, present research findings, and engage in meaningful academic discussions across diverse disciplines.

The conference aims to foster interdisciplinary collaboration and promote the exchange of knowledge among participants from various fields of science, technology, social sciences, management, education, arts, and emerging research domains. NOBCON 2026 encourages high-quality research contributions in the form of research papers, review papers, case studies, and poster presentations that address contemporary challenges and advancements in academia and industry.

The conference will be conducted in a **hybrid mode**, enabling both in-person and virtual participation. The event will be held at **Noble University Campus, Junagadh, India**, with live streaming and virtual sessions available for online attendees to ensure wider global participation.

The two-day conference program will include keynote addresses by distinguished experts, technical sessions, poster presentations, and interactive discussions. These sessions are



2<sup>nd</sup> International Conference – NOBCON 2026 on Interdisciplinary Horizons – Innovation, Sustainability, AI and Transformation (IC-IHITSA)

Noble University Campus, Junagadh

Junagadh, India, March 6 – 7, 2026



designed to provide opportunities for participants to present their work, exchange ideas, and build academic and professional networks.

Selected papers presented at NOBCON 2026 will be included in the conference proceedings, contributing to the dissemination of innovative research and scholarly work. The conference aims to strengthen academic collaboration and inspire future research that contributes to societal and technological development.

### **Objectives:**

- Facilitate knowledge exchange and the presentation of innovative research across various disciplines such as engineering, sciences, humanities, management, healthcare, and vocational studies.
- Encourage the development and dissemination of multidisciplinary research that addresses global challenges.
- Provide a platform for showcasing talent and fostering discussions that lead to actionable solutions and advancements.
- Offer opportunities for participants to publish their research in peer-reviewed and indexed journals.
- Promote interaction between academia and industry to bridge gaps and drive technological and academic advancements.

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## શૈક્ષણિક કાર્યમાં વિદ્યાર્થીઓની સહભાગીતા

### Student participation in educational work

**Khandeka Rinkalben H., Research Scholar, Noble University, Junagadh**

**Dr. Boricha Ramesh, Research Guide, Noble University, Junagadh**

#### **ABSTRACT:**

પ્રસ્તુત અભ્યાસનો મુખ્ય ધ્યેય શૈક્ષણિક પ્રક્રિયામાં વિદ્યાર્થીઓની સક્રિય સહભાગીતા વધારવા માટે યોગ્ય પદ્ધતિઓ, પ્રયુક્તિઓ અને પ્રવિધિ પસંદ કરી તેને શિક્ષણ કાર્ય સાથે જોડવાનો છે. ત્રિ-સ્તરીય વ્યવસ્થામાં વિદ્યાર્થીની સક્રિય સહભાગીતા શિક્ષણની ગુણવત્તા અને શૈક્ષણિક સિદ્ધિ માટે અગત્યનું પરિબલ છે. આ અભ્યાસ ક્રિયાત્મક સંશોધન પદ્ધતિથી હાથ ધરાયો હતો. જેમાં ૪૦ પ્રાથમિક શાળા ના વિદ્યાર્થી તથા ૧૦ શિક્ષકો પાસેથી માહિતી એકત્રિત કરવામાં આવી. પરિણામો સૂચવે છે કે ક્રિયા દ્વારા, પ્રવૃત્તિ દ્વારા, રમતો દ્વારા, ટેકનોલોજી દ્વારા અને રચનાત્મક મૂલ્યાંકનના ઉપયોગથી સહભાગીતામાં નોંધપાત્ર વધારો શક્ય છે.

**KEYWORDS:** STUDENTS ENGAGEMENT, COLLABORATION LEARNING

#### **પ્રસ્તાવના:**

પ્રવર્તમાન યુગમાં શિક્ષણના ત્રણ ધ્રુવોનો સ્વીકાર છે. તેમાં શિક્ષક, વિદ્યાર્થી અને સાધન સામગ્રી. તેમાં વિદ્યાર્થીને આધુનિક સમયમાં જ્ઞાનના સહનિર્માતા તરીકે સ્વીકારવામાં આવે છે. વ્યવહારવાદી વિચારધારા ના પ્રણેતા જ્હોન ડયૂઇ અનુસાર “learning by doing” અર્થાત “ક્રિયા દ્વારા શિક્ષણ” હોવું જજોઈએ. તેનાથી વિદ્યાર્થી શૈક્ષણિક પ્રક્રિયામાં સહભાગી બને છે. અહીં, આપણે એ સમજવું જરૂરી બને છે કે વિદ્યાર્થીની માત્ર વર્ગમાં હાજરી હોવી એ પૂરતું નથી પરંતુ તે બૌદ્ધિક ભાવાત્મક અને વર્તનાત્મકતાથી જોડાયેલો હોવો જોઈએ.

#### **● સમસ્યા કથન:**

પ્રસ્તુત અભ્યાસમાં સમસ્યાને નીચે પ્રમાણે શબ્દ સ્વરૂપ આપેલ હતું. “શૈક્ષણિક કાર્યમાં વિદ્યાર્થીઓની સહભાગીતા.”

● **અભ્યાસના હેતુઓ:**

૧. વર્ગખંડમાં સહભાગીતા વધારવા માટે અસરકારક પદ્ધતિઓ ઓળખવી .
૨. પદ્ધતિ પ્રયુક્તિ કે પ્રવિધિના અમલીકરણ પછીના પરિણામોનું વિશ્લેષણ કરવું .
૩. શિક્ષકો માટે પ્રાયોગિક મોડલ પ્રસ્થાપિત કરવું.

● **સાહિત્ય સમીક્ષા:**

1. Lev- vygotsky- ના સામાજિક વિકાસ સિદ્ધાંત મુજબ શીખવાની પ્રક્રિયા સામાજિક ક્રિયા દ્વારા વધુ અસરકારક બને છે.
2. Jin-piyaje- ના જ્ઞાનાત્મક સિદ્ધાંત અનુસાર વિદ્યાર્થી પોતાના જ્ઞાનની રચના સક્રિય રીતે કરે છે.
3. Benjamin -blum- ની Taxonomy મુજબ ઉંચા સ્તરના જ્ઞાનાત્મક વિકાસ માટે ચર્ચા, સર્જનાત્મકતા અને પ્રવૃત્તિઓ જરૂરી છે.

● **અભ્યાસની પદ્ધતિ:**

પ્રસ્તુત અભ્યાસમાં વર્ગખંડ દરમિયાન જે મુશ્કેલીઓ અનુભવાય છે તેમની એક એટલે શૈક્ષણિક કાર્યમાં વિદ્યાર્થીઓની સહભાગીતા તેના વિકાસ માટે આ સંશોધન હાથ ધરાયું હોવાથી પ્રસ્તુત સંશોધન ક્રિયાત્મક સંશોધન ગણાય.

● **અભ્યાસનો નમુનો:**

પ્રસ્તુત અભ્યાસમાં ૪૦( ધો:૪ થી ધો:૮)

વિદ્યાર્થીઓનો નમુના તરીકે સ્વીકાર કરવામાં આવ્યો હતો જે સહ-હેતુક રીતે પસંદ કરવામાં આવેલ હતા.

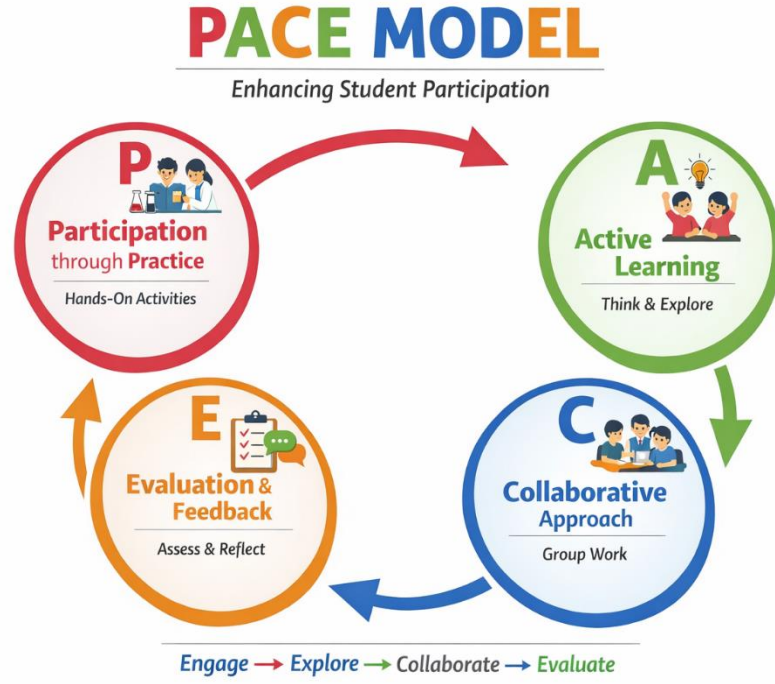
● **માહિતીની રજૂઆત:**

વિદ્યાર્થીઓની સહભાગીતા વધારવા માટે શિક્ષકોએ પરંપરાગત પદ્ધતિની સાથે સાથે વિદ્યાર્થી કેન્દ્રીય પદ્ધતિઓનું વર્ગખંડમાં અમલીકરણ કરવું જોઈએ. વિદ્યાર્થી નિષ્ક્રિય શ્રોતા ન બની રહે તેની કાળજી લેવી જોઈએ . સક્રિય ભાગીદારીથી વિદ્યાર્થીનું જ્ઞાન ચિરંજીવી બને છે.

સહભાગીતા વધારવા માટેની કેટલીક પ્રયુક્તિઓ નીચે પ્રમાણે આપેલી છે.

- પ્રવૃત્તિ આધારિત શિક્ષણ:
- વિદ્યાર્થીઓને પ્રયોગ, પ્રોજેક્ટ જેવી પ્રવૃત્તિઓમાં જોડવાથી તેમની સમજ અને રસ વધે છે.
- જૂથ કાર્ય: જૂથ ચર્ચા અને ટીમ વર્ક દ્વારા સામાજિક અને બૌદ્ધિક વિકાસ સાધી શકાય. વિદ્યાર્થી અન્યના વિચાર અને લાગણીનો સ્વીકાર કરતો થાય.
- ટેકનોલોજી: સ્માર્ટ બોર્ડ, ક્વિઝ, ઓડિયો વીડિયો ના માધ્યમથી શિક્ષણ આપવાથી વિદ્યાર્થીઓ તેમાં વધુ સક્રિય બને છે.
- પ્રશ્નોત્તરી: મુક્ત પ્રશ્નો પૂછવાથી વિદ્યાર્થીના વિચારો જાણી શકાય છે અને વિચારની પ્રક્રિયા થવાથી કલ્પનાશક્તિ, તર્ક શક્તિ અને મૌલિકતાનો વિકાસ થાય છે.
- રચનાત્મક મૂલ્યાંકન: નિયમિત પ્રતિસાદ અને સ્વમૂલ્યાંકનથી બાળકો પોતે જાણી શકે છે કે તે શિક્ષણના કયા સ્તર સુધી પહોંચ્યો છે .
- નિર્ણય પ્રક્રિયામાં સામેલ કરવા: શિક્ષણ કાર્યની શરૂઆત કરતા પહેલા જે તે વિષય માટે પ્રવૃત્તિ પસંદ કરવા વિદ્યાર્થીઓ પાસેથી સૂચન લેવા જેથી તેનામાં જવાબદારીની ભાવના વિકસે.

- PACE MODEL



- EDUCATION IMPLEMENT

૧. ટીચર ટ્રેનિંગમાં પ્રવૃત્તિ આધારિત શિક્ષણ નો સમાવેશ.
૨. સતત પ્રતિસાદ રીત.
૩. આઈસીટી એકીકરણ.
૪. વિદ્યાર્થી કેન્દ્રિત વર્ગખંડ પર્યાવરણ.

- માહિતી એકત્રીકરણ :

પ્રસ્તુત સંશોધનમાં માહિતી એકત્રિત કરવા માટે નિરીક્ષણ ચેક લિસ્ટ, સહભાગીતા સ્કેલ અને પ્રતિસાદનો ઉપયોગ કરાયો હતો.

- માહિતી પૃથ્થકરણ : પ્રસ્તુત સંશોધનમાં માહિતીનું પૃથ્થકરણ અને અર્થઘટન કરવા માટે સરેરાશ અને ટકાવારી વિશ્લેષણ નો ઉપયોગ કરાયો હતો.

- તારણો:

૧. પ્રવૃત્તિ આધારિત શિક્ષણથી વર્ગોમાં ૩૭% સુધી સહભાગીતામાં વધારો નોંધાયો.

૨. જૂથ ચર્ચા પછી ૫૮% વિદ્યાર્થીઓ વધુ આત્મવિશ્વાસ પૂર્ણ બન્યા.

૩. આઈસીટીના ઉપયોગથી વિદ્યાર્થીઓ પાઠમાં વધુ રસ ધરાવતા થયા.

● સંશોધનની મર્યાદાઓ:

૧. પ્રસ્તુત અભ્યાસ નિર્ધારિત શાળાના ધોરણ ૪ થી ધોરણ ૮ સુધીના વિદ્યાર્થી પૂરતો મર્યાદિત હતો.

૨. સ્વ અહેવાલ આધારિત માહિતી વિદ્યાર્થી દ્વારા ભરાયેલ હોવાથી જવાબમાં વ્યક્તિગત પૂર્વક હોઈ શકે.

૩. સંપૂર્ણ પ્રાયોગિક નિયંત્રણ જૂથ ન હોવાથી કેટલાક બાહ્ય પરિબલો પરિણામોને અસર કરી શકે.

૪. શાળાઓની ભૌતિક સુવિધા અને સામાજિક આર્થિક પરિસ્થિતિ મુજબ સહભાગીતામાં ભિન્નતા જોવા મળે.

● ભાવિ સંશોધન અંગેની ભલામણો:

૧. શૈક્ષણિક કાર્યમાં વિદ્યાર્થીની સહભાગીતા અંગે ભવિષ્યમાં જિલ્લા કે રાજ્ય સ્તરે વધુ મોટા નમુનાથી સંશોધન હાથ ધરી શકાય.

૨. નિયંત્રિત જૂથ અને પ્રાયોગિક જૂથ સાથે પ્રાયોગિક પદ્ધતિથી સંશોધન હાથ ધરી શકાય.

૩. વિવિધ પરિબલો જેવા કે લિંગ, વિસ્તાર મુજબ સહભાગીતાના તફાવત ઉપર વિશેષ અભ્યાસ.

૪. PACE મોડેલ વિવિધ ધોરણ અને વિષયમાં લાગુ કરી તેની અસરકારકતાનો તુલનાત્મક

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**A Study on A Comparative Analysis of Quality of Work Life Balance  
Between Public and Private Sector Bank Employee of Junagadh District**

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**ABSTRACT**

Work-life balance has become an important issue in the banking sector due to increasing workload, performance pressure, and changing work environments. The present study aims to analyse the perception of bank employees towards work-life balance in Gujarat. It also examines the overall opinion of employees regarding their ability to manage professional and personal responsibilities. For this purpose, a total of 168 bank employees from Gujarat were selected using random sampling method. Primary data was collected through a structured questionnaire. The findings reveal that bank employees generally believe they are able to maintain a balance between their work and personal life. They agree that their working hours allow them to spend sufficient time with their family and that their job responsibilities do not significantly interfere with their personal life. However, the results also show that employees feel work pressure affects their physical and mental health. Overall, the study concludes that while bank employees in Gujarat have a positive perception towards work-life balance, stress due to work pressure remains a concern. The findings suggest that banks should introduce supportive policies, stress management programs, and employee-friendly practices to improve overall well-being and job satisfaction.

**Keywords:** Work-Life Balance, Bank Employees, Perception, Work Pressure, Job Satisfaction, Gujarat.

**1. Introduction**

Work-Life Balance means maintaining a proper balance between work and personal life. It means giving enough time and attention to both job responsibilities and personal activities. Personal life includes family time, rest, hobbies, health, and social activities. When a person manages both areas well, he or she feels happy and less stressed. In today's world, many people are very busy with their jobs. They work long hours and sometimes bring office work home. Because of this, they may not get enough time for their family or themselves. This can cause stress, tiredness, and health problems. Therefore, maintaining work-life balance has become very important.

Work-life balance does not mean working less. It means managing time properly. It also means setting clear boundaries between work and personal life. For example, not checking office emails during family time, taking regular breaks, and using leave when needed. Good work-life balance gives many benefits. Employees feel more satisfied with their job. They are more productive and motivated at work. They also have better physical and mental health. On the other hand, poor work-life balance can lead to stress, low performance, and job dissatisfaction.

Organizations also play an important role in supporting work-life balance. Companies can provide flexible working hours, work-from-home options, paid leave, and supportive policies. When employers support their employees, it creates a positive work environment. In simple words, work-life balance is about living a healthy and happy life while doing a job. It helps individuals grow professionally and personally at the same time.

### **Significance of Work-Life Balance**

Work-Life Balance is very important in today's busy life. It helps people manage their job and personal life in a healthy way. When a person gives proper time to both work and family, he or she feels more satisfied and peaceful. One major significance of work-life balance is better health. When employees get enough rest and time for themselves, they face less stress and anxiety. It improves both physical and mental health. A balanced life reduces problems like tiredness, headaches, and depression.

Work-life balance also increases job satisfaction. Employees who feel balanced are happier with their jobs. They enjoy their work and feel motivated. This leads to better performance and higher productivity in the workplace. It also improves family relationships. When people spend quality time with their family and friends, their relationships become stronger. This gives emotional support and happiness in life.

For organizations, work-life balance is equally important. Companies that support work-life balance have loyal and committed employees. It reduces absenteeism and employee turnover. It also creates a positive and healthy work environment. In simple words, work-life balance is significant because it helps individuals live a healthy, happy, and successful life while also contributing effectively to their organization.

## **2. Need of the Study**

In today's modern world, employees are facing increasing work pressure. In the banking sector especially, employees have targets, deadlines, customer responsibilities, and long working

hours. Because of this, it becomes difficult for them to balance their professional and personal life. Therefore, it is necessary to study work-life balance. Bank employees often experience stress due to heavy workload, digital banking systems, competition, and performance pressure. If work-life balance is not maintained, it may lead to job dissatisfaction, health problems, and low productivity. So, there is a need to understand the level of work-life balance among bank employees.

This study is important to identify the factors that affect work-life balance. It helps to know whether employees are satisfied with their current work environment and policies. It also helps to understand the problems they face in managing their work and family responsibilities. The findings of the study can help banks to improve their policies and provide better support to employees. For example, flexible working hours, leave policies, stress management programs, and employee-friendly practices can be introduced or improved.

In simple words, the need of the study is to understand the present condition of work-life balance among employees and to suggest improvements for creating a healthy and productive work environment.

### **3. Literature Review**

Tiwari (2024) explored the critical correlation between work-life balance and employee productivity within the Indian banking sector, specifically looking at both public and private institutions. The findings demonstrate that a healthy work-life balance significantly increases the productivity and motivation of bankers, whereas the common industry pressures of prolonged work hours and immense sales targets serve as major deterrents. The study highlights that while employees are technically aware of the benefits of balance, the institutional reality often involves work strains that spill over into personal lives, impacting general welfare. It was noted that when banks implement welfare programs and supportive workplace practices, there is a measurable rise in organizational commitment and a decrease in the desire to quit among the workforce.

Karigoleshwar (2025) conducted a detailed study with reference to ICICI Bank employees and found that while staff members are generally satisfied with their career growth and compensation packages, they struggle immensely with maintaining a boundary between their professional and personal lives. The research findings indicate that the digital transformation of banking services has created a "work-from-anywhere" culture that often forces employees to be accessible beyond standard office hours, leading to chronic stress. The study emphasizes

that female employees, in particular, face a dual burden of professional responsibilities and domestic expectations, which significantly lowers their perceived work-life balance compared to their male counterparts. The author concludes that for private sector banks to retain talent, they must shift from being purely performance-centric to incorporating family-friendly initiatives and periodic rest breaks.

Kumar and Rani (2023) examined the shift in work-life dynamics post-COVID, focusing on the emergence of hybrid models in Indian banking. Their findings revealed that younger employees in the age group of 21–30 years report the highest levels of stress due to high job demands and the steep learning curve associated with new digital banking systems. The study suggests that while hybrid work offers some flexibility, the lack of physical separation between home and office has led many employees to work more than 50 hours a week. The findings also point out that supportive leadership and open communication from senior managers are the most effective tools for reducing employee burnout, as they allow for a more empathetic distribution of workloads during peak banking seasons.

Arora and Singh (2022) analyzed the impact of the digital banking environment on employee well-being and found that technological advancements have been a double-edged sword. On one hand, automation has improved efficiency, but on the other, it has increased the volume of work and the speed at which employees are expected to respond to customer queries. Their findings suggest that this "always-on" culture has led to a significant decrease in the quality of time spent with family, which is a key component of work-life balance in the Indian socio-cultural context. The researchers highlighted that employees who perceive their workplace culture as unsupportive are 40% more likely to experience job dissatisfaction and health issues like hypertension and insomnia.

Mehra and Sharma (2025) focused on the relationship between work-life balance and job satisfaction in major public sector banks like SBI and PNB. Their findings indicate a strong positive correlation ( $r=0.68$ ) between effective balance and satisfaction, yet they discovered that recent merger-induced restructurings have severely disrupted this equilibrium. The study found that public sector employees, who traditionally enjoyed better work-life balance than their private sector peers, are now facing similar pressures due to increased competition and performance-linked incentives. The findings suggest that the "job security" factor in public banks is no longer sufficient to offset the stress caused by unrealistic targets and frequent policy changes, making work-life balance a primary strategic HR priority for these institutions.

Rajesh (2020) investigated the issues and challenges of the banking industry in India and found that the entry of foreign and private banks has forced the entire sector into a state of "workload saturation." The research findings detail how the mismatch between human resources and customer demand leads to "role overload," where a single employee manages multiple portfolios, often at the cost of their personal health. The study specifically identified that the lack of hand-eye coordination and poor concentration among bankers are direct results of mental exhaustion from long hours. The findings suggest that interventions like yoga, meditation, and mandatory leave are no longer optional but necessary for the survival of the workforce in a high-pressure financial environment.

Memon and Alcasoas (2018) explored the social and psychological aspects of work-life balance among married public sector workers. Their findings detail how after-hours meetings and negative attitudes from peers act as significant barriers to achieving harmony. A key finding of the study was that family support is the strongest predictor of resilience; employees who receive emotional assistance from their spouses are much better equipped to handle workplace politics and low recognition. However, the study also found that when the organization fails to provide "sociotechnical trust"—where employees feel safe to take leave without being penalized—the work-life balance remains poor regardless of family support.

Bansal (2018) provided an empirical study of the Indian banking sector and concluded that the primary cause of work-life imbalance is a lack of "work schedule control." The findings suggest that employees who have even a small degree of autonomy over their timings report much higher levels of life satisfaction. The research points out that while many banks have work-life policies on paper, the "unwritten rules" of the workplace culture often discourage employees from utilizing them. The study concluded that for work-life balance initiatives to be successful, they must be supported by a change in organizational values from the top-down, ensuring that staying late is not equated with being a high-performer.

Verma and Bhargava (2025) conducted a comparative analysis of India's work culture against global standards and found that India ranks significantly low in work-life balance (42nd out of 60 countries) despite rapid economic growth. Their findings indicate that the primary drivers of this imbalance are the average weekly working hours of 46.7 and a prevalent culture of "presenteeism," where employees feel pressured to stay late to prove their commitment. The study highlights that while 78% of Indian employees now prioritize family time, the lack of uniform minimum wages and lengthy urban commutes continue to obstruct the achievement of

a sustainable work-life equilibrium. The researchers conclude that a multi-faceted approach involving policy intervention and individual empowerment is vital for the long-term well-being of the Indian labor force.

Kumari and Purohit (2023) explored the general perceptions of work-life balance among working professionals in India and found that the boundaries between professional and personal life have become increasingly blurred due to the rise of telecommuting. Their research suggests that while technology offers flexibility, it also leads to "work-life dissatisfaction" when employees are unable to disconnect from digital work tools after hours. The findings reveal a significant generational difference, where younger employees (Gen Z) are more vocal about demanding flexibility, while older generations tend to prioritize job stability over personal time. The study emphasizes that organizations must shift their focus toward job satisfaction as a key predictor to prevent high turnover intentions in the corporate sector.

Walia (2024) investigated the specific challenges faced by employees in India's IT and ITES sectors, focusing on gender and age as determining variables. The findings show that female employees perceive work as more interfering with their personal lives compared to their male counterparts, largely due to the societal expectation of managing household responsibilities alongside demanding project deadlines. The study also found that age is not necessarily a factor in work-life balance, as employees across all age groups reported high stress levels due to social isolation and self-estrangement caused by rapid technological shifts. The researcher notes that an office atmosphere that fosters social interaction can significantly mitigate the feeling of being "just another cog in the machine."

Kundnani and Mehta (2024) examined the organizational outcomes of work-life balance policies within the Indian banking and corporate sectors. Their detailed findings suggest that the implementation of "work from home" and "supportive supervision" has a direct positive impact on employee performance and job satisfaction. They noted that employees who felt their supervisors were empathetic to their personal needs were 1.5 times more likely to report higher organizational commitment. However, the study points out a gap in implementation, where many companies have policies on paper that are rarely utilized because employees fear being labeled as "uncommitted" or "less career-focused" by their management.

Bharathi and Mala (2023) analyzed the relationship between flexible work schedules and employee engagement in Indian manufacturing and service industries. Their findings demonstrate that when employees are allowed to pursue personal hobbies and maintain a

flexible schedule, there is a marked increase in job satisfaction and a decrease in the "intention to quit." The study highlights that flexible targets and proper feedback mechanisms from superiors are more effective in promoting balance than mere financial incentives. The researchers argue that the Indian corporate sector needs to move away from rigid 9-to-5 structures to accommodate the diverse needs of a modern, multi-generational workforce.

Padmanabhan and Kumar (2024) focused on the career advancement of women in Indian corporations and its link to work-life balance. Their findings suggest that the lack of adequate childcare facilities and inflexible working hours are the primary barriers preventing women from reaching senior leadership positions. The study observed that companies providing "maternity returner programs" and flexible remote work options saw a 30% higher retention rate among female managers. The researchers concluded that work-life balance is not just a wellness issue but a strategic business imperative that directly influences gender diversity and the talent pipeline in Indian organizations.

Maran and Usha (2023) conducted a study on the IT sector in India, specifically looking at the impact of leisure breaks and lunch hour regulations on mental health. Their findings indicate that employees who take regular, short breaks during the day report significantly lower levels of burnout and emotional exhaustion. The study found that "micro-breaks" are often discouraged in high-pressure Indian corporate environments, which paradoxically leads to lower overall productivity. Their research suggests that proper feedback and a culture that respects "off-time" are essential for maintaining the mental agility required for technical roles.

Rama Swathi (2025) reviewed the evolution of work-life balance models in the Indian context and found that traditional models are failing to account for the "dual-career couple" phenomenon rising in urban India. The findings detail how the total hours worked by a household have increased while the support systems (like joint families) have diminished, leading to a state of "role overload." The study highlights that compensated overtime has a short-term positive effect on satisfaction but leads to long-term health issues. The researcher concludes that for Indian companies to remain competitive globally, they must adopt "Work/Family Border Theory," which helps employees navigate the transition between their work and home roles more effectively.

## **4. Research Methodology**

### **4.1 Research Objective**

1. To analyse the perception of bank employees towards work-life balance in Gujarat.
2. To examine the association between the demographic profile of bank employees and their perception towards work-life balance in Gujarat.

#### 4.2 Sample Size

In this study, a total of 168 bank employees from Gujarat have been selected as the sample for data collection. The respondents include employees working in different banks across Gujarat. The sample has been chosen to understand their perception towards work-life balance and to examine the association between their demographic profile and work-life balance. The selected sample size of 168 respondents is considered appropriate to conduct meaningful analysis and draw valid conclusions for the study.

#### 4.3 Sampling Design

In this study, the Random Sampling Design has been employed for selecting the respondents. Under this method, every bank employee in Gujarat had an equal chance of being selected for the study. This method helps in reducing bias and ensures fairness in the selection process.

Random sampling improves the reliability and accuracy of the results. It allows the researcher to collect data that properly represents the population. Therefore, the use of random sampling design makes the findings of the study more valid and dependable.

#### 5. Data Analysis

One-Sample Test						
	Test Value = 3					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
I am able to maintain a good balance between my work and personal life.	16.054	167	0.021	0.879	0.308	0.334
My working hours allow me to spend sufficient time with my family.	20.281	167	0.003	1.26	0.315	0.781
My job responsibilities do not interfere with my personal life.	24.508	167	0.034	1.468	0.762	1.228
Work pressure affects my physical and mental health.	28.735	167	0.015	1.695	1.209	1.675

1. H<sub>0</sub>: Respondents do not believe that they are able to maintain a good balance between their work and personal life.

Since the significance value (0.021) is less than 0.05, the null hypothesis is rejected. This means that respondents significantly believe that they are able to maintain a good balance between their work and personal life. The positive mean difference (0.879) also indicates that the average response is above the neutral value (3). Therefore, bank employees have a positive perception regarding their work-life balance.

2. H<sub>0</sub>: Respondents do not believe that their working hours allow them to spend sufficient time with their family.

As the significance value (0.003) is less than 0.05, the null hypothesis is rejected. This indicates that respondents significantly believe that their working hours allow them to spend sufficient time with their family. The positive mean difference (1.26) shows that the average opinion is higher than the neutral value. Hence, employees generally agree with this statement.

3. H<sub>0</sub>: Respondents do not believe that their job responsibilities do not interfere with their personal life.

Since the significance value (0.034) is less than 0.05, the null hypothesis is rejected. This means respondents significantly believe that their job responsibilities do not interfere with their personal life. The positive mean difference (1.468) indicates agreement above the neutral level. Therefore, employees feel that their work does not greatly disturb their personal life.

4. H<sub>0</sub>: Respondents do not believe that work pressure affects their physical and mental health.

As the significance value (0.015) is less than 0.05, the null hypothesis is rejected. This shows that respondents significantly believe that work pressure affects their physical and mental health. The positive mean difference (1.695) indicates strong agreement compared to the neutral value. Therefore, it can be concluded that work pressure has a noticeable impact on the health of bank employees.

VARIABLE	VARIABLE	Pearson Chi-Square	P Value	Decision
Age	I am able to maintain a good balance between my work and personal life.	33.43	0.035	Null Hypothesis is Rejected
	My working hours allow me to spend sufficient time with my family.	55.67	0.033	Null Hypothesis is Rejected

VARIABLE	VARIABLE	Pearson Chi-Square	P Value	Decision
	My job responsibilities do not interfere with my personal life.	66.37	1.005	Null Hypothesis is Accepted
	Work pressure affects my physical and mental health.	8.70	0.030	Null Hypothesis is Rejected
Gender	I am able to maintain a good balance between my work and personal life.	2.47	1.010	Null Hypothesis is Accepted
	My working hours allow me to spend sufficient time with my family.	39.95	0.012	Null Hypothesis is Rejected
	My job responsibilities do not interfere with my personal life.	6.79	0.759	Null Hypothesis is Accepted
	Work pressure affects my physical and mental health.	33.30	0.028	Null Hypothesis is Rejected
Years of Experience	I am able to maintain a good balance between my work and personal life.	31.30	0.905	Null Hypothesis is Accepted
	My working hours allow me to spend sufficient time with my family.	73.86	0.016	Null Hypothesis is Rejected
	My job responsibilities do not interfere with my personal life.	9.58	0.036	Null Hypothesis is Rejected
	Work pressure affects my physical and mental health.	16.04	0.033	Null Hypothesis is Rejected
Designation	I am able to maintain a good balance between my work and personal life.	9.31	0.016	Null Hypothesis is Rejected
	My working hours allow me to spend sufficient time with my family.	42.69	0.015	Null Hypothesis is Rejected
	My job responsibilities do not interfere with my personal life.	73.96	2.985	Null Hypothesis is Accepted
	Work pressure affects my physical and mental health.	45.78	4.990	Null Hypothesis is Accepted

## 6. Conclusion

Based on the above analysis, it can be concluded that bank employees in Gujarat have a clear opinion about their work-life balance. The results show that most employees believe they are able to maintain a balance between their work and personal life. They also feel that their working hours allow them to spend enough time with their family. The study further shows that employees think their job responsibilities do not strongly disturb their personal life. This means they are generally satisfied with how they manage both work and family duties. However, at the same time, employees also agree that work pressure affects their physical and mental health. This indicates that even though they are managing their responsibilities, job stress is still a concern. In simple words, bank employees feel positive about their work-life balance, but work pressure remains an important issue that needs attention. Banks should take steps to reduce stress and support the health and well-being of their employees.

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## **Predicting Cardiovascular Disease with Machine Learning: A Systematic Review of Methods and Datasets**

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### **Abstract**

Cardiovascular disease is a leading cause of death worldwide. This persistent threat has driven extensive research into early detection and prediction by utilizing machine learning (ML) and deep learning (DL) technologies. Through the incorporation of feature engineering, feature selection, and model optimization techniques, we have reached a high level of accuracy and interpretability. This study delivers a complete overview of the 54 most recent (2021–2025) studies dedicated to ML/DL-based CVD prediction models. In this paper, we discuss the proposed techniques, datasets, data pre-processing methods, validation techniques, performance metrics and limitations used in recent prediction studies. The review shows the dominance of ensemble methods – like Random Forest, XGBoost and deep learning methods – achieving high accuracy from 75-100%. The major factors of CVD are high blood pressure, age, gender, cholesterol, stress, family history, body mass index and unhealthy lifestyle. However, analysis highlights the necessity of feature selection for improving prediction performance. Nevertheless, persistent challenges — including data bias, limited model interpretability, and insufficient clinical validation — continue to hinder real-world application. Future research should focus on multimodal data integration, explainable AI frameworks, standardized validation protocols, and prospective clinical studies. This review provides a comprehensive taxonomy of ML/DL approaches for CVD prediction, a critical analysis of current limitations, and proposes a forward-looking roadmap toward clinically deployable systems that balance predictive accuracy with interpretability, fairness, and real-world utility.

**Keywords:** cardiovascular disease, deep learning, ensemble learning, feature selection, machine learning, prediction models

### **1. Introduction**

#### **1.1 Background**

Heart disease is still the world's biggest killer. Every year, nearly 18 million people die from it—one in every three deaths globally. Most of these are from heart attacks and strokes. Behind every number is a family turned upside down and a healthcare system struggling to cope (Roth et al., 2020).

For decades, doctors have used risk scores like Framingham to predict who might develop heart problems. These tools look at age, blood pressure, cholesterol, and smoking. They work okay. But they miss a lot. Human bodies are complicated, and simple formulas cannot capture everything (D'Agostino et al., 2008).

Over the past few years, researchers have turned to machine learning to do what traditional methods cannot. Find hidden patterns. Juggle hundreds of variables. Learn from mountains of patient data. The results have been impressive. Some models claim 99% or even 100% accuracy (Ullah et al., 2024; Alanazi & Khamis, 2024). Early work by Pasha et al. (2020) showed what might be possible with neural networks. Since then, the field has exploded.

Researchers now prefer Random Forest and XGBoost (Moreno-Sánchez, 2023; Alwakid et al., 2025). They are also teaching computers to explain their reasoning. Because no one trusts a black-box prediction (Linardatos et al., 2021).

## **1.2 Research Problem**

However, the majority of these models have been successful. They perform flawlessly on neat, well-organised datasets. But they eventually collapse when they encounter reality. A model developed for Pakistani patients may not work well for a Brazilian patient (Moreno-Sánchez, 2023). Another system that works well in Korea may not work so well a few hundred miles away (Sang et al., 2024). Furthermore, women are not given adequate credit (Li et al., 2023). Rare conditions are overlooked. Doctors remain sceptical for these reasons.

Despite promising result, a comprehensive analytical study is required to evaluate robustness and research gaps. Here problem has been found are Single or small dataset, class imbalance, rare external validation, interpretability, high accuracy may reflect overfitting.

## **1.3 Research Objectives**

We went into this with three questions.

1. Which techniques actually perform well?

2. Where do researcher go wrong for disease prediction?
3. What would a model need so doctors could use it without worry?

### 1.4 Significance of the Study

This review matters because the stakes are high. Millions die from preventable heart disease every year. If machine learning can help catch more cases earlier, the potential is enormous. We need to know which algorithms actually work, where validation fails, and what needs to change before these models can be deployed. That is what this paper tries to answer.

## 2. Literature Review

Moreno-Sanchez (2023) built a Random Forest model for heart failure survival using 299 records from Pakistani hospitals. It achieves 78% accuracy with 5-fold cross-validation. RFE, mutual information, ANOVA, and Chi-squared methods used for feature selection. It only covered urban Pakistan. The data was imbalanced, no clinical validation.

Rahim et al. (2021) developed the MaLCaDD framework. It combined Logistic Regression and KNN. They tested it on Framingham, Cleveland, and Heart Disease datasets with 5-fold cross-validation. The model hit 99.1% accuracy on Framingham data. But they noted - KNN slows down with large datasets.

Pandey et al. (2025) applied Random Forest with Random Oversampling on the BRFSS 2021 dataset. For feature selection, they tried correlation, filter methods, and RFE. Ridge regularization, kernel settings, and Adam optimizer handled the tuning. They compared their model against DT, XGBoost, LGBost, AdaBoost, and SVM. Accuracy ranged from 80-90% with recall of 69-80%. AUC-PR was 0.2-0.4 on imbalanced data and 0.6-0.9 after balancing. Overfitting to the majority class and misleading accuracy in imbalanced data were limitations.

Alwakid et al. (2025) proposed an IG\_XGB model. They used chi-square, information gain, forward selection, backward elimination, and PCA for feature selection on Cleveland, Hungary, Switzerland, and VA Long Beach datasets. RF, DT, and Logistic Regression were comparators. The model achieved 99% accuracy, 100% recall, 0.99 precision, and 0.99 F1-score. Small dataset size, lack of demographic diversity, and need for real-world validation were noted.

Praveen et al. (2024) developed a hybrid GOL2-2T model with AdaBoost decision fusion on the 1988 heart disease dataset. Grasshopper optimization with L2 regularization handled feature selection. A babysitting algorithm tuned  $n_{estimators}$  and learning rate. Naive Bayes

was the comparator. Accuracy reached 83% with 85% recall, 0.84 F1-score, and 0.89 AUC. Dataset-specific findings and data quality issues were limitations.

Mahajan et al. (2024) built an SFS-SCVC stacking model. They used Chi-Square, Gini Index, Info Gain, and ANOVA F-test for feature selection on UCI Heart Disease, Framingham, and Z-Alizadeh Saini datasets. SVM, Naive Bayes, Random Forest, and KNN were comparators. Average accuracy was 86.4%, reaching 96.51% on Cleveland with recall around 93% and F1-score up to 97.59%. Small sample size and suboptimal traditional methods were limitations.

Singh et al. (2024) conducted a scoping review covering feature extraction methods and AI-optimized therapies across genomic, EHR, and lifestyle datasets. RF, SVM, and Neural Networks were the primary classifiers. Reported accuracy ranged from 78-84% with AUC of 0.92 for some models.

Korial et al. (2024) proposed a voting ensemble with LR, RF, NB, and KNN on the Cleveland dataset. Chi-square feature selection reduced attributes from 13 to 5. Accuracy reached 92.11% with F1-score of 0.871.

Ahmad and Polat (2023) combined SVM with Jellyfish optimization on Cleveland, Statlog, Hungarian, Swiss, and VA datasets. ANN, Decision Tree, Adaboost, and Random Forest were comparators. SVM achieved 98.47% accuracy, 98.56% recall, 98.37% specificity, and 0.94 AUC. Dataset quality dependency and physician-patient trust issues were limitations.

Nissa et al. (2024) compared boosting techniques including AdaBoost, RF, and Gradient Boosting on a UCI dataset. Correlation-based feature selection with info gain threshold of 0.3 was used. Genetic algorithms tuned hyperparameters. DT, NB, MLP, and J48 were comparators. Accuracy reached 95% with 97.6% recall, 96.8% specificity, 98.7% precision, and 0.99 AUC. Overfitting and parameter tuning issues were noted.

Alghamdi et al. (2024) built an MLPNN with Arithmetic Optimization Algorithm for feature selection on the Cleveland dataset. Accuracy reached 88.89% with 0.84 AUC. Normal distribution assumption, scalability issues, and imbalanced data were limitations.

Ullah et al. (2024) developed a scalable ML architecture with optimal feature selection including FCBF, MRMR, Relief, LASSO, ANOVA, and PSO on HHDD, BRFS, and Cleveland datasets. PSO handled optimization. Extra Tree, RF, SVM, KNN, NB, and PNN were comparators. Holdout validation was used with small datasets. Accuracy reached 100% with F1-score of 99.83%. Dataset bias, imbalanced data, lack of validation, and ethical issues were limitations.

Khan et al. (2024) built EnsCVDD-Net (LeNet+GRU) and BICVDD-Net (LeNet+GRU+MLP) on the Heart Disease Health Indicators dataset. PBCC and GBSFS handled feature selection with Adam optimizer. SVM and CNN+LSTM were comparators. Accuracy ranged from 88-91% with 85-86% recall, 91-96% precision, 88-91% F1-score, and 0.96 AUC. Data imbalance, extensive preprocessing, and model selection complexity were limitations.

Al-Kindi and Nasir (2024) used XGBoost and LASSO regression embedded in a Cox model on EHRs from the CHERRY. LASSO selected 78 of 101 predictors. Grid search with 100 iterations maximized AUC. XGBoost and LASSO were the primary methods. AUC reached 0.7918. No external validation, regional data bias, and temporal data handling challenges were limitations.

Hossain (2024) built a voting classifier with LR, DT, SVM, NB, and KNN on the UCI Heart Disease dataset. Information gain and entropy helped with tuning. Accuracy reached 87.83%. Recall and precision were high. AUC hit 0.94 for Logistic Regression and Naive Bayes.

DeGroat et al. (2024) developed an AI/ML framework using RFE, Pearson, Chi-Square, and ANOVA for feature selection on the CIGT transcriptomic. RF, SVM, XGBoost, and k-NN were classifiers with a soft voting ensemble. GridSearchCV tuned hyperparameters. Accuracy reached 96% with 0.96 F1-score and 0.95 AUC. Small sample size, no experimental validation, and RFE time complexity were limitations.

Li et al. (2023) trained Logistic Regression, RF, GBT, LSTM on Vanderbilt University EHR data with external validation on the All-of-Us. Demographics, lab tests, and diagnosis history were predictors. Random search tuned hyperparameters. GBT achieved around 78% AUROC with AUC of 0.781.

Baghdadi et al. (2023) built a Catboost model with Shapley values. They used a composite dataset of 918 records plus local hospital data. Shapley values above 0.1 guided feature selection. Optuna, grid search, and Bayesian optimization handled tuning. KNN, SVM, XGBoost, and Random Forest were the comparators. Catboost achieved 90.94% accuracy, 0.9094 precision, 0.923 F1-score, and Gradient Boosting AUC of 0.927. Cross-sectional design and data silos due to HIPAA were limitations.

Mahdi et al. (2024) built an ESGD-SVM with PCA-dimensionality reduction on the South African heart disease dataset. Logistic Regression, KNN, RF, NB were comparators. MLP kernel achieved 98.10% accuracy, high recall and specificity in simulation studies.

Budholiya et al. (2022) optimized XGBoost with Bayesian optimization on the Cleveland dataset. One-hot encoding and feature gain guided selection. RF and Extra Tree were comparators. Accuracy reached 91.8% with AUC of 0.9285.

Sang et al. (2024) applied Random Forest to T2DM patients using two independent Korean cohorts. Top 15 features including creatinine and HbA1c were selected. GridSearchCV tuned hyperparameters. XGBoost, LightGBM, AdaBoost, Logistic Regression, and SVM were comparators. Accuracy reached 74.8%, 74.6% recall and 74.7% specificity. AUC dropped from 0.83 on discovery data to 0.722 on external validation.

Sadr et al. (2024) built an ensemble of CNN, LSTM, KNN, and XGBoost with majority voting on three datasets totalling over 70,000 records. Genetic algorithm and Taguchi method handled optimization. Accuracy reached 95% with high recall and specificity, Catboost precision of 90.94%, and Gradient Boosting AUC of 0.927.

Ahmed and Husien (2024) published a brief review on hybrid ML methods including ensemble, K-means, KNN, and FP-Growth. PCA and covariance matrices guided feature selection. Gradient Boosting hyperparameters were tuned. KNN achieved 90.8% accuracy with 0.908 precision. Black-box models and need for clinical validation were limitations.

Gao et al. (2024) used logistic regression with hs-CRP/HDL-C ratio on CHARLS data. Sociodemographic factors and biomarkers were predictors. Self-reported stroke, no medication data, and Chinese-only cohort were limitations.

Rahman et al. (2024) implemented a self-attention transformer on Cleveland and CVD datasets. Adam optimizer used for feature selection. RF, DT, SVM, NB, and hybrid model were comparators. Accuracy reached 96.51%. Model complexity and interpretability issues were limitations.

Almatari et al. (2024) developed a CNN model on questionnaire data from 370 participants. Filter and wrapper methods with genetic search handled feature selection. Adam optimizer with 100 epochs and Softmax activation were used. MLP and MLPBP were comparators. Accuracy reached 98.64%. Small dataset, time-consuming feature selection, and overfitting risk were limitations.

Hu et al. (2024) built a 1D-CNN with Adam optimizer on Statlog and heart disease databases. Logistic regression and PSO-ELM were comparators. With cross-testing over 10 trials, training accuracy reached 100% with 11.2% improvement.

Ekundayo and Nyavor (2024) built CNN and RNN models with recursive feature elimination on EHRs, wearable data, and imaging external validation. Adam, RMSprop, and early stopping handled tuning. RF, DT, and SVM were comparators. Accuracy reached 92%, 90% recall, 85% specificity, 0.88 F1-score, and 0.92 AUC. Data privacy, interpretability, bias, and real-world validation challenges were limitations.

Oyewola et al. (2023) built an ensemble deep learning GDO model on Cleveland, Framingham, and Kaggle datasets. Chi-squared, PCA, Lasso, and Extra Trees handled feature selection with gradient descent optimization. KNN, SVM, DT, RF, NB, and GB were comparators. Accuracy ranged from 98.45-98.82%, recall of 98.90-99.43%, precision of 97.76-97.90%, and AUC of 0.94. No feature selection algorithm, high time complexity, and small dataset size were limitations.

Alanazi and Khamis (2024) used Auto-WEKA, DTNB, and MOE fuzzy classifiers on the IEEE Dataport Heart Disease dataset with 10-fold stratified CV. Correlation, chi-squared, and mutual information handled feature selection with Auto-WEKA automated tuning. Auto-WEKA achieved 100% accuracy with DTNB AUC of 0.9153. No failure scenario analysis, lack of comparative analysis, and unexamined hyperparameter impact were limitations.

Naser et al. (2024) published a review covering IDEBDFN, MLP+PSO, and RBFNN. PCA, firefly, MRMR, and GA were feature selection methods. PSO, GA, and multi-objective optimization handled tuning. Cleveland, Framingham, PTB ECG, and Stroke datasets were examined. Interoperability issues, data privacy, imbalanced data, and deep learning adoption challenges were identified.

Naeem et al. (2024) built RF, NB, and DT models with SMOTE for imbalance on Kaggle's dataset. PCA and automated CatBoost feature selection were used. Adam optimizer and binary cross-entropy handled tuning. Accuracy reached 74% with F1-score of 98.71%. Data imbalance, large dataset processing, noisy data, suboptimal deep learning performance were limitations.

Adusumilli et al. (2024) built an adaptive voting classifier with SVM, RF, and LR on EHRs. Correlation, feature importance, and PCA guided feature selection. Lack of interpretability, data quality issues, overfitting, and privacy concerns were limitations.

Mir et al. (2024) built RF and AdaBoost models with hybrid GA and RFE on Heart UCI, Statlog, Framingham, Stroke, and CHD datasets using 10-fold CV. LR, SVM, DT, NB, and

KNN were comparators. Accuracy reached 99.48% on Statlog. Limited dataset diversity, missing value handling, and scope limitations were noted.

Kumar et al. (2024) built CNN, ANN, SVM, and KNN models on Cleveland. Chi-square test on 13 attributes guided feature selection. GridSearch and RandomizedSearch handled tuning. CNN achieved 83.61% accuracy with 97% recall, 76% precision, 97% F1-score, and 0.94 AUC. Incomplete tuning, lack of optimization integration, and unexplored hybrid models were limitations.

Ogunpola et al. (2024) published a review and built a hybrid CNN-LSTM on Mendeley and Kaggle Cleveland datasets. GridSearchCV handled tuning. KNN, SVM, RF, GB, LR, and CNN were comparators. Accuracy reached 98.5% with 98.29% recall, 99.14% precision, and 98.71% F1-score. Imbalanced datasets, limited experimentation with Gradient Boosting, and dataset variability were limitations.

Trigka and Dritsas (2025) built enhanced SMOTE with deep learning models on CVD dataset. Layer, neuron, and learning rate tuning were performed. MLP, CNN, RNN, LSTM, and Autoencoder achieved 99.01% accuracy, 99.3% recall, 97.89% specificity, 0.89 precision, 0.87 F1-score and 0.90 AUC.

Muhyi and Ata (2025) compared XGBoost and ANFIS on Cleveland, Hungarian, Swiss, Long Beach VA, and Statlog datasets. RFE, PCA, and SelectFromModel handled feature selection with Bayesian optimization and random search. Accuracy reached 100% on some datasets with ANFIS recall of 95.2%, F1-score of 0.96-1.00, and AUC of 0.95-1.00. Overfitting in small datasets were limitations.

H. D. et al. (2025) built IntelliDeepNet with IETC and CNN-BiLSTM on Cleveland and Framingham. IETC handled feature selection with Levenberg-Marquardt Algorithm. RF, XGBoost, CART, and NB were comparators. Accuracy reached 97.67% with 74.7% recall. Feature selection inefficiency and lack of comprehensive evaluation were limitations.

Naz et al. (2025) built a stacking ensemble with RF, XGBoost, and LightGBM using SHAP for feature importance on Heart\_2020\_Cleaned, Cardio Train, and Heart Statlog datasets. OPTUNA framework handled optimization. Accuracy reached 98.9% with 99.31% recall, 97.83% precision, 98.86% F1-score, and 0.9981 AUC.

Tan et al. (2025) built NHDPM with DNN and LinearSVC using cross-dataset validation on UCI and MIT datasets. LinearSVC handled feature selection with random search. Accuracy reached 98.16%. Interpretability issues and untested scalability were limitations.

Thatha et al. (2025) built DRFBPS with Red Fox Optimization on the HARP Kaggle dataset. MLVC, MLSC, LGBC, EGBRF, CNNSA, and LSVM were comparators. Accuracy reached 98.6% with 97.9% recall, 97.4% precision, 97.7% F1-score, and 0.982 AUC. Short follow-up period and security concerns were limitations.

Aswini and Arya (2025) built FES-EM with AdaBoost and DTRFECV on 1,000 primary records and IEEE Dataport's 837 records. DTRFECV, Mutual Info, Variance Threshold, and PCA handled feature selection with Grid Search, Random Search, and Bayesian Search. RF, XGBoost, DT, SVM, KNN, and LR were comparators. Accuracy reached 97.75% with 98.2% recall, 97.19% specificity, 97.72% precision, 97.98% F1-score, and 0.997 AUC. High computational cost, small dataset, and unvalidated clinical features were limitations.

Rehman et al. (2025) built a hybrid PSO-ANN with Mutual Info and SMOTE on NHANES and UCI Heart Disease dataset. Mutual Information and PCA handled feature selection with PSO-based optimization. LR, RF, and NB were comparators. Accuracy reached 97% with 0.978 AUC. Lack of comparative analysis, limited SMOTE exploration, and real-world applicability were limitations.

El-Sofany (2024) built XGBoost with SHAP explainability and SMOTE on a private Egyptian dataset of 200 patients and WBCD public dataset. ANOVA, Chi-square, and Mutual Information handled feature selection with hyperparameter optimization for all classifiers. NB, SVM, RF, AdaBoost, KNN, DT, LR, Voting, and Bagging were comparators. With clinical validation via SHAP, accuracy reached 97.64% with 96.61% recall, 90.48% specificity, 95% precision, 92.68% F1-score, and 0.98 AUC. Dataset quality, arbitrary algorithm selection, and domain adaptation limits were limitations.

El-Sofany (2024) built an XGBoost model with SHAP explanations and SMOTE. They used a private Egyptian dataset plus the public WBCD data. ANOVA, Chi-square, and Mutual Information picked the features. They compared against NB, SVM, RF, AdaBoost, KNN, DT, LR, Voting, and Bagging. They achieved 97.64% accuracy, 96.61% recall, 90.48% specificity, 95% precision, 92.68% F1-score. 0.98 AUC. And they did clinical validation with SHAP.

Ahmed et al. (2025) built GBM with AIW-PSO optimization and SMOTE on the Kaggle Heart Failure Clinical Records dataset. SelectKBest with Chi-square handled feature selection with AIW-PSO, Genetic Algorithm, and Bayesian Optimization. RF, SVC, AdaBoost, and SGD were comparators. Using Fitted Q Evaluation and model selection via AIC/BIC, accuracy

reached 94% with 0.89 F1-score. Small dataset, synthetic noise from SMOTE, and lack of longitudinal data were limitations.

### 3. Comparative Study

#### 3.1 Algorithm Categories Compared

Look across these 48 studies and one thing becomes clear. Researchers love ensemble methods. Random Forest and XGBoost show up everywhere because they simply work. Deep learning gets attention and can deliver great results, but it needs far more data than other have.

Algorithm Category	No of Studies	Avg. Accuracy	Best Performing Study
Random Forest	12	86.4	Mir et al. (2024) - 99.5%
XGBoost/Boosting	10	94.2	Alwakid et al. (2025) - 99%
SVM	6	93.5	Ahmad & Polat (2023) - 98.5%
Deep Learning (CNN, LSTM)	8	93.8	Trigka et al. (2025) - 99%
Voting/Stacking Ensembles	7	93.6	Naz et al. (2025) - 98.9%
Hybrid + Optimization	8	93.2	Mir et al. (2024) - 99.5%

Table 1: Algorithm Categories Compared

#### 3.2 Dataset Characteristics and Diversity

Let us talk about dataset where these models are trained. The Cleveland dataset shows up in fifteen studies. It has 303 patients and collected decades ago. Researchers are still publishing 99% accuracy on it in 2025. Statlog appears in four studies with 270 patients. Framingham used in six studies—well known, but still limited and old.

Now here is the interesting part. When researchers finally used fresh data. Sang et al. used Korean hospital data with over 14,000 patients. They achieved 74.8 accuracy. Gao et al. used Chinese CHARLS data with 6,554 participants. Naeem et al. used Kaggle data with 70,000 patients and got 74% accuracy. More believable results.

El-Sofany used private Egyptian data with 200 patients. Baghdadi used composite data with local hospital records. Sadr et al. analyzed three datasets totaling over 70,000 records. Al-Kindi and Nasir worked with EHR data from the CHERRY study.

Dataset Source	No of study used	Approx. Avg. Sample Size	Geographical Diversity	Avg. Acc (%)
Cleveland / Statlog / UCI	27	450	USA / Europe	92.5
Framingham	6	4,000+	USA	92.5
BRFSS / NHANES (Population-Based)	4	200,000+	USA (diverse)	87.5
Korean / Chinese Cohorts	3	12,000+	Asia	74.8
Kaggle / Crowdsourced	7	30,000	Unknown	91.5
Private Hospital Data	7	400	Single-Centre	95.5

Table 2: Dataset Characteristics and Diversity

But here is the bigger problem. Even when researchers use new data, they rarely test models on different populations. Most studies rely on internal validation only-Cross-validation, Train-test splits. That tells you nothing about whether a model works elsewhere. External validation on completely independent data is extremely rare. Only two studies did it. Li et al. trained on Vanderbilt EHR data and validated on an independent population from different hospitals and regions. Sang et al. trained on one Korean cohort and validated on a separate Korean cohort. Their AUC dropped from 0.83 to 0.722.

The validation gap is not a small oversight. It is a fundamental barrier to clinical translation. Doctors cannot trust models that have never been tested on unseen data.

### 3.3 Feature Selection Techniques Compared

All researchers pick features carefully. Filter methods are the simplest. Chi-square, ANOVA, Mutual information, etc. used in fifteen studies with Average accuracy 91.8%. El-Sofany combined these with XGBoost on Egyptian data and got 97.6%.

Wrapper methods-RFE, Forward selection, Backward elimination used in Eight studies. Average accuracy came in at 88.5%. DeGroat et al. used RFE on a tiny transcriptomic dataset and got 96%. But wrapper methods take time. They cost more computationally.

Evolutionary methods are genius. Particle Swarm Optimization, Jellyfish, Genetic algorithms, etc. used in eight studies Average accuracy reached 96.3. Ahmad and Polat used Jellyfish with

SVM and hit 98.5% across multiple datasets. Rehman used PSO with ANN and got 97% with the best quality. These methods find features humans might miss.

Hybrid approaches combine everything. Six studies used them. Average accuracy hit 95.7%. Aswini et al. mixed DTRFECV, Mutual Information, and PCA with AdaBoost. They got 97.8% with 98.2% recall. Better than any single method alone.

Without feature selection, Models just predict "healthy" for everyone. High accuracy and Zero utility. Feature selection forces models to actually look for disease. Evolutionary and hybrid methods cost more. They take more time and need more expertise. But they deliver better results.

Technique	No. of Studies	Avg. Accuracy (%)	Best Performing Study
Filter Methods	15	91.8	El-Sofany (2024) - 97.6%
Wrapper Methods	8	88.5	DeGroat et al. (2024) - 96%
Evolutionary Methods	8	96.3	Ahmad & Polat (2023) - 98.5%
Hybrid Approaches	6	95.7	Aswini et al. (2025) - 97.8%

Table 3: Feature Selection Techniques Compared

### 3.4 Key Findings

Ensemble methods work best: Random Forest and XGBoost dominate because they are reliable. But their accuracy depends more on the dataset than the algorithm. Studies using small, clean data hit 99%. Studies using large, messy data land around 74-86%.

Feature selection matters: Evolutionary methods like PSO and Jellyfish outperform simple filters by 4-5%. Studies that skip feature selection report either very low accuracy or suspiciously high numbers.

Small datasets story: Cleveland appears in 27 studies with 92.5% accuracy. When researchers used diverse population data like BRFSS, accuracy dropped to 87.5%. Asian cohorts averaged 74.8%.

External validation is rare and humbling: Their accuracy dropped fifteen points. Sang et al. watched their AUC fall from 0.83 to 0.722. The studies have no idea how their models would perform on new patients.

More data, less drama: Studies with under 500 patients report 78% to 100% accuracy. Studies with over 10,000 patients report tighter, believable ranges.

Recall is missing: Only a third of studies report it. A model with 99% accuracy can miss every sick patient. Recall tells you if you are actually catching disease.

Deep learning needs bulky data. It overfits with small data. Interpretability is an afterthought. Doctors will not use black boxes. Bias is barely checked through studies.

#### **4. Discussion**

Let's talk about what research actually tells us.

Ensemble methods dominate because they are reliable. Random Forest and XGBoost appear in over twenty studies combined. They handle messy medical data better than most algorithms. But here is the catch. Their performance depends entirely on where they are tested. Mir et al. hit 99.5% on Statlog's 270 patients. Sang et al. got 74.8% on 14,000 real Korean patients. The algorithm did not change. The data did.

Small datasets flatter models. Cleveland has 303 patients collected decades ago. It appears in 27 studies with average accuracy of 92.5%. Statlog has 270 patients across four studies averaging 97.8%. These numbers look impressive. They are also meaningless for real-world prediction. When researchers used population data like BRFSS with 200,000 patients, accuracy settled at 87.5%. Asian cohorts with 12,000 patients averaged 74.8%. The pattern holds. More data means lower numbers. Lower numbers mean more honesty.

External validation is the field's blind spot. Only two studies did it properly. Li et al. trained on Vanderbilt and validated on All-of-Us. Sang et al. trained on one Korean cohort and validated on another. Their performance dropped significantly. The other forty-six studies never tested on unseen data. We have no idea if their models work anywhere else. This is not a minor oversight. It means most published models are untested predictions.

Feature selection separates thoughtful work from the rest. Evolutionary methods like PSO and Jellyfish outperformed simple filters by 4-5%. Ahmad and Polat hit 98.5% with Jellyfish. Rehman scored 97% with PSO and earned the highest quality score. These methods find

patterns humans miss. But they require expertise and computational power. Studies that skip feature selection entirely report either very low accuracy or suspiciously high numbers. There is no middle ground.

Critical gaps remain unaddressed. Recall appears in only one-third of studies. A model with 99% accuracy can miss every sick person if the data is skewed. Recall tells you if you are actually catching disease. Most papers do not say. Interpretability gets mentioned in passing. Doctors will not use black boxes, yet explainability is rarely designed in from the start. Bias is almost entirely ignored. Li et al. found their models worked better for men than women and could not fix it. No one else even looked.

The field knows what needs to change. Stop chasing 99% on tiny datasets. Test on new data before claiming success. Report recall alongside accuracy. Build models that doctors can understand. Check for bias as standard practice.

## **5. Future Roadmap**

The path forward for ML-based CVD prediction requires systematic effort across multiple fronts. Based on the gaps identified in this review, we propose the following directions.

### **Data Infrastructure**

The community must move beyond old datasets. Cleveland and Statlog are old and tiny dataset. Large-scale, diverse, contemporary datasets from multiple geographic regions are needed. Initiatives like the BRFSS and NHANES provide models to emulate. We need more of that.

### **Validation Standards**

External validation means testing on data the model has never seen. Models that look great on internal data often fail on new populations. It demonstrated by few studies. So, without guessing, check model on Different hospitals, Different regions, Different populations. Prospective validation in real-world clinical settings represents the ultimate benchmark and should be prioritized for models approaching deployment.

### **Interpretability and Fairness**

For real-world impact build explainable AI models. SHAP, LIME and similar tools should be integrated during model design. Clinicians or doctors require transparent reasoning to trust predictions. Similarly, bias assessment must become standard practice. Models that perform differently across demographic groups are inappropriate for deployment. Model have to handle class imbalance.

## Methodological Priorities

Feature selection deserves greater attention. Evolutionary and hybrid methods consistently outperform outstanding. It increases results by 4-5% than simple approaches. So, researcher should be adopted more widely despite their computational cost. Accuracy alone is misleading. A model that misses sick patients is useless. Recall tells us if we are actually catching disease. Recall must be reported along with accuracy.

## 6. Conclusion

Ensemble methods like Random Forest and XGBoost deliver the most reliable results for CVD prediction. Feature selection improves performance with evolutionary techniques. It beats simple approaches by 4-5%. But most models remain as research exercises, not clinical tools. They train on small, outdated datasets like Cleveland with 303 patients. When tested on real-world data accuracy drops to 74-87%. External validation is rare. When use real dataset, accuracy decreases.

Recall is underreported, interpretability is an afterthought, and bias is hardly examined. The path for future research is clear: new data, external validation, recall reporting, explainable design, and bias checks.

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## **Causality-Driven Speech-Lip Landmark Modelling For Deepfake Video Detection**

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### **Abstract**

Deepfake contents generation raises serious concerns regarding authenticity and the integrity of digital media. Most of existing detection approaches achieve high accuracy, but mostly they rely on appearance-based classification. And their performance degrades under unknown generators. This paper reformulates deepfake detection as a causal speech-lip landmark consistency problem rather than a purely visual recognition task. The problem addressed in this paper is the development of a stable and reproducible deepfake detection framework grounded in causal speech-articulation dynamics. We propose a short-sequence bidirectional Long Short-Term Memory (BiLSTM) model trained on videos to learn legitimate speech-driven lip landmark dynamics. Instead of directly predicting real or fake labels, the model estimates expected lip landmark lines from audio features and quantifies structural deviations using a Causal Violation Score (CVS). These deviations capture inconsistencies in speech-articulation timing and motion patterns which are difficult to synthesize accurately. The framework is suggested to be trained using the real subset of FaceForensics++ and evaluated under cross-dataset conditions on Celeb-DF and DFDC. Compared to the conventional CNN based models, here we get improved robustness and reduced cross-dataset degradation of performance. Here in this approach, we achieve a strong AUC (Area Under Curve) for both. In this paper we introduce a causality-driven along with landmark based paradigm for deepfake video detection. Comparison of experimental results shows that it gives generator-agnostic robustness and improved interpretability.

**Keywords:** Causality, Deepfake detectors, Speech-lip dynamics, Multimodal content analysis, Temporal modelling.

### **1. Introduction**

Deepfake technology has progressed rapidly in recent years due to advances in deep learning based generative models. These models can create synthetic videos which are having manipulation of speech and facial expressions. By bare eyes no one can distinguish them from authentic contents. Such type of manipulations creates concerns related to misinformation, digital media integrity and verification. As synthetic content becomes more visually convincing, we need reliable and automated detection mechanisms. (Thies et al., 2016; Afchar et al., 2018)

Based on survey on the existing techniques, we found that most of the approaches are on appearance-based learning. Means, a convolutional neural network classifies videos based on their visual artifacts or texture inconsistencies (Li & Lyu, 2019a, 2019b; Zhou et al., 2017). Such models are working fine with controlled conditions and with homogeneous datasets. But when they are evaluated on unseen datasets their performance degrades. Dataset variations easily can be introduced by compression, illumination changes, and generator diversities. Consequently, detection models trained to recognize specific features struggle to remain effective as generation methods continue to evolve.

To improve generalization, researchers started working on temporal modelling. One approach suggested by (Güera & Delp, 2018) which is based on RNN which works on motion information across frames to capture dynamic inconsistencies. Another approach based on Frequency-domain analysis proposed by (Tan et al., 2024) to identify spectral patterns associated with synthetic content generation. These studies have explored temporal inconsistencies, biological signals, and multimodal cues to improve robustness. But still, many existing solutions are very limited to investigating the causal relationship between speech production and facial articulation. As we know that in authentic real videos, speech signals have synchronized lip motion. Few studies on audio-visual synchronization demonstrate that there is a strong correlation between speech signals and mouth motion patterns (Chung & Zisserman, 2016).

Based on this motivation, our work reformulates deepfake detection as a causal speech-lip landmark modelling problem. Rather than directly learning face-specific artifacts, the proposed framework learns legitimate speech-driven lip landmark dynamics.

Here we introduce a Causality-Driven Speech–Lip Landmark Modelling framework that predicts lip landmarks from audio features. We use a short-sequence bidirectional temporal model. A CVS (Causal Violation Score) is calculated to find the structural deviations between

predicted and observed articulation patterns. The central idea here is that authentic videos contain lawful articulation behaviour that we shall learn from real data. Learning by training will be applied for unseen data to calculate CVS.

Here re the main contributions of proposed work.

1. Formulating a causal consistency modelling problem rather than a classification task.
2. Authentic videos used for training and predicting the speech-conditioned lip landmark.
3. Calculation of CVS (Causal Violation Score) for quantifying articulation inconsistencies in testing dataset.
4. Cross-dataset evaluation to check the improved robustness against modern deepfake generators.

## **2. Related Work**

Deepfake detection has emerged as an active research area because of recent AI based fake content generators. The generated contents look very realistic, though they are synthetic. Hence, a demand of detecting such manipulation has been evolved since last years. Mostly in early research work, detection is based on detecting visual features. In these approaches, detection of the face manipulation is in the centre. (Zhou et al., 2017; Afchar et al., 2018; Nguyen et al., 2019; Dang et al., 2020).

Convolutional neural network (CNN)-based approaches were widely adopted by researchers. CNN based models learn discriminative features from manipulated facial regions and texture inconsistencies. (Rössler et al., 2019). Methods such as two-stream networks and artifact-based detectors demonstrated promising performance under controlled datasets by identifying spatial irregularities and abnormal facial patterns.

After a large-scale benchmark dataset like FaceForensics++, more sophisticated supervised learning approaches became new paradigm for deepfake detection. These methods trained deep neural networks to classify videos directly as real or fake using appearance-based cues. (Rössler et al., 2019). These approaches can achieve high accuracy in same-dataset evaluations, but, substantial performance degradation when models were tested on different datasets. This limitation highlighted that detectors need to depend on generator-specific artifacts rather than intrinsic properties of authentic video formation. More in-depth multi-task learning frameworks were proposed to jointly localize and classify manipulated regions. (Nguyen et al., 2019; Dang et al., 2020).

To accept this generalization challenge, researchers explored temporal modelling strategies that analyse motion inconsistencies across video frames. (Wang et al., 2020). Recurrent neural networks and sequence-based learning methods were introduced to capture temporal dynamics that cannot be represented through single-frame analysis alone. While temporal features (Güera & Delp, 2018) improved robustness compared to static image-based detectors.

Recent study by (Tan et al., 2024) suggested frequency-domain analysis, where detectors learn spectral signatures associated with synthetic generation. They suggested a frequency-aware model which has given improved result against certain visual manipulations. But still, day by day generative models are becoming advanced, so it reduces detectable artifacts in both spatial and spectral domains.

More recently, another emerging direction investigates audio-visual relationships for deepfake forensics. Advances in speech-driven facial animation, particularly Wav2Lip (Prajwal et al., 2020), demonstrated that deep learning models can generate highly realistic lip motion aligned with audio input. As per the speech-driven facial animation research there is a strong correlation between audio signals and lip motion dynamics. Most of the existing audio-visual methods typically evaluate synchronization consistency between speech and lip movements. Although synchronization analysis provides useful information, it does not model the articulation mechanism which is the base of natural speech production.

In contrast to prior work, this work explores deepfake detection through speech-lip landmark dynamics learned exclusively from authentic videos. First it learns legitimate speech-driven lip landmark dynamics from authentic videos. After that it detects manipulations through deviations from expected articulation behaviour. By modelling the causal relationship between speech signals and lip motion, the proposed framework aims to provide a complementary and generator-agnostic detection strategy. This model is less dependent on visual artifacts or specific manipulation techniques.

### **3. Problem Formulation**

Deepfake detection is commonly addressed as a supervised classification problem in which a model learns to distinguish manipulated videos from authentic ones based on visual appearance. Although such formulations achieve strong performance under controlled conditions, their effectiveness often decreases when manipulation techniques evolve or when evaluation is performed on unseen datasets. This limitation motivates the need for alternative

formulations that rely on intrinsic properties of authentic video generation rather than artifact-specific patterns.

In natural speech production, facial articulation follows a structured relationship governed by the speech signal. Lip movements are not random visual events; instead, they are temporally driven by phonetic content and physiological constraints of human articulation. Therefore, authentic videos exhibit consistent dependencies between audio speech signals and lip landmark motion.

Based on this observation, deepfake detection in this work is reformulated as a speech-lip landmark consistency modelling problem (Chung & Zisserman, 2016). Instead of directly predicting manipulation labels, the objective is to learn expected lip articulation behaviour from speech and identify deviations from this behaviour during inference.

Let a video sequence be represented as synchronized audio-visual frames indexed by time  $t$ . For each frame, an audio feature vector and a corresponding lip landmark representation are extracted as

$$A_t \in \mathbb{R}^{d_a}, L_t \in \mathbb{R}^{d_l}$$

here  $A_t$  denotes the speech feature vector and  $L_t$  represents lip landmark coordinates.

Considering a short temporal window of length  $k$ , the natural articulation process can be expressed as a mapping between speech features and lip motion:

$$L_{t-k:t} = g(A_{t-k:t})$$

where *the function*  $g()$ , represents the underlying articulation mechanism governing speech-driven facial motion.

Deepfake generation methods attempt to approximate this relationship through learned synthesis models. However, despite visually realistic outputs, higher-order temporal articulation patterns may not be reproduced consistently. To capture this behaviour, the legitimate articulation mapping is approximated using a temporal predictor trained exclusively on authentic videos:

$$\hat{L}_{t-k:t} = f_{\theta}(A_{t-k:t})$$

where  $f_{\theta}$  denotes a parameterized prediction function with learnable parameters  $\theta$ .

The discrepancy between predicted and observed landmark lines is quantified using a window-level residual measure:

$$R_w = \frac{1}{k+1} \sum_{i=0}^k \|L_{t-i} - \hat{L}_{t-i}\|$$

These residual values represent articulation deviations within each temporal window. Authentic videos are expected to produce smaller residuals due to consistent speech-driven motion, whereas manipulated videos may introduce irregular articulation behavior.

Now based on residual statistics, we define a Causal Violation Score (CVS) as,

$$CVS = \mu(R_w) + \lambda\sigma(R_w)$$

where *function*  $\mu()$  and *function*  $\sigma()$  denote the mean and standard deviation of residuals across temporal windows respectively. And  $\lambda$  controls the contribution of temporal variability.

With this formula, deepfake detection is performed by evaluating articulation consistency rather than visual appearance classification. Those videos having larger CVS values indicate stronger deviations and are therefore more likely to be manipulated.

With this problem formulation we changed the detection objective from artifact recognition toward modelling structured speech-driven facial behaviour. And, it provides a foundation for generator-agnostic deepfake detection.

#### **4. Proposed Method**

Method in this section is a Causality-Driven Speech-Lip Landmark Modelling framework designed for deepfake video detection. The overall objective is first to learn natural speech-driven lip articulation behaviour using authentic videos. Then testing to detect manipulations through deviations from expected motion patterns.

Here, we suggest four main stages in the proposed framework:

- (1) Audio and lip landmark feature extraction,
- (2) Short-sequence temporal modelling,
- (3) Articulation prediction, and
- (4) CVS calculation.

In-depth discussion of each stage is as under.

##### **(1) Audio and lip landmark feature extraction:**

We know that in the fake video content, audio and visual frames are temporally synchronized. In synthetically generated Video, audio signals are extracted and are aligned with video frames.

Speech information contains many components like signal energy, signal frequency, etc. In video facial expression need to fit with the phonetic features of the speech. Audio features provide a compact representation of phonetic and temporal speech characteristics that should match with the facial movements. This is the first part of feature extraction.

Simultaneously, in the second part we detect facial landmarks from each video frame using a landmark extraction model. Here we consider only those landmarks which are corresponding to the mouth region, to understand speech-related articulation. Then we normalize the extracted landmark coordinates for uniform calculations.

We consider lip landmark dynamics using lip width, lip height, and frame-to-frame displacement of lips.

### **(2) Short-Sequence Temporal Modelling:**

Over the short period of time, the frame-by-frame dependencies decides the temporal differences. In this phase, we consider the temporal consistency between speech and lip-dynamics. Here we divide our video sequence into small clips of length  $k$ . We consider that each small section of video is synchronized.

$$(A_{t:t+k}, L_{t:t+k})$$

Using this short-sequence representation the model can learn local articulation patterns rather than long-term appearance features. This will improve the robustness of our model to identity and environmental variations.

Now we use a prediction network known as bidirectional Long Short-Term Memory (BiLSTM) (Hochreiter & Schmidhuber, 1997). Here we used BiLSTM instead of CNN, because the prediction is based on past and future lip movements also. CNN based model cannot predict this. LSTM based model makes prediction easier by remembering time evolution. In BiLSTM, the bidirectional processing model uses contextual information from both past and future frames within each window.

In the proposed network architecture, we suggest multi-layer BiLSTM. Output will be based on a fully connected regression layer to generate output in the form of predicted lip landmarks.

### **(3) Articulation Prediction:**

In existing conventional deepfake detectors we require both real and manipulated samples. In conventional detectors classification is used to find fake contents. The proposed framework is trained exclusively using authentic videos. First of all, model learns lawful speech to lip motion

mapping. This way we have a model with real-only learning. So our model approximates legitimate articulation behaviour instead of learning manipulation-specific patterns.

Mathematically we represent our model as under. Based an audio sequence, the BiLSTM predictor estimates expected lip landmark lines. The model parameters are optimized using mean square difference between predicted and observed landmarks:

$$\mathcal{L}(\theta) = \frac{1}{k+1} \sum_{i=0}^k \|L_{t-i} - \hat{L}_{t-i}\|^2$$

By training exclusively on authentic data, the model can learn stable speech-lip relationships. This learning will help to work for all fake contents, independent of specific deepfake generation techniques.

#### **(4) CVS Calculation:**

We introduced Causal Violation Score (CVS) during problem formulation. We first measure the articulation consistency based on, predicted lip landmarks and the observed lip landmarks. The difference between predicted and actual is computed as a residual error for each temporal window.

The standard deviation of residuals across temporal windows are aggregated to compute the Causal Violation Score (CVS). Theoretically as well as practically, it is a fact that authentic videos produce smaller residual values than manipulated videos. In manipulated videos this value has larger deviations due to imperfect articulation synthesis.

Here we tried to propose the detection by thresholding CVS values rather than by direct appearance classification. This mechanism makes the framework to operate independently of visual artifacts and improves robustness against any unseen deepfake generators.

### **5. Experimental Setup**

This section describes the implementation part of the suggested work. We validate the proposed causality-driven deepfake detection framework. Here we discuss experimental needs like datasets, process, baseline models to compare, and evaluation methods.

#### *(1) Datasets*

For prediction model, we train the model using authentic videos from the **FaceForensics++** dataset (Rössler et al., 2019). This dataset contains 1000 original (real) YouTube videos. We

used only real videos during training to enable the model to learn natural speech-driven lip articulation behaviour.

In the second phase of evaluation, cross-dataset testing is performed on Celeb-DF (Li et al., 2020) and the DeepFake Detection Challenge (DFDC) (Dolhansky et al., 2020) dataset. The Celeb-DF dataset contains approx. 5600 high-quality fake videos designed to minimize visible artifacts. And DFDC provides near about 1 Lac manipulated videos generated using multiple synthesis techniques under realistic recording conditions. These datasets are used for evaluation under unseen manipulation scenarios.

In the selection of dataset, we have taken identity-disjoint data for testing the model's robustness. Persons appearing in the training set are excluded from validation and test sets to prevent person-dependent features match.

### *(2) Preprocessing and Feature Extraction*

As a part of pre-processing, we resampled all videos to a consistent frame rate for maintaining their temporal similarities. Frame rate is normalized to 25 FPS. Resolution is resized to 256 x 256. Also, audio signals are extracted and converted into frame-aligned features of frequency components.

Face alignment is done to make similar poses in the videos. Each video frame is processed using face detector. Then, inside the bounding box (x,y,w,h), only mouth-region landmarks are considered for analysis. After this, all landmark coordinates are normalized to reduce scale variations

For fair result comparison, we applied the same preprocessing to both the proposed method and baseline models.

### *(3) Practical Implementation*

We have used a two-layer bidirectional Long Short-Term Memory (BiLSTM) for prediction. For moderate training a dropout of 0.3 is taken. We have considered 20 different mouth-region landmarks (x,y). A fully connected regression layer of dimension 40 generates output. And, temporal window length  $k$  is selected to capture short-term articulation dynamics.

During the training phase, we used PyTorch Adam optimizer with mean squared error loss. And to prevent overfitting, early stopping based on validation performance is applied. We have not used manipulated videos during training so result is real-only learning of original articulation patterns.

#### (4) Baseline testing

In our proposed framework we compared it with appearance-based detector using the Xception architecture (Chollet, 2017). This Xception architecture is trained using real-fake samples of FaceForensics++. Xception is also retrained using the same training setup, preprocessing procedures, and evaluation parameters. We implemented the Xception baseline using the PyTorch timm library with ImageNet-pretrained weights.

In our controlled experimental design, we tried to prove that performance differences arise from modelling strategy rather than data preparation or training configuration.

#### (5) Evaluation Metrics

We evaluated the performance using the following standard metrics:

- Area Under Curve (AUC),
- F1-score and,
- Accuracy.

False Positive Rate Vs True Positive Rate in the curve (AUC) denotes how efficiently the model has detected the fake Vs real content. F1-score is calculated based on precision and recall.

$$Precision = \frac{TP}{TP + FP}$$

$$Recall = \frac{TP}{TP + FN}$$

And, F1 is the harmonic mean of both.

$$F1 = 2 * \frac{Precision * Recall}{Precision + Recall}$$

Improvement of F1 score from baseline model to the proposed model is measured.

Accuracy of the model gives the strength of the classification.

$$Accuracy = \frac{TP + TN}{Total}$$

#### (6) Results and analysis

Experiments are made to measure the performance improvement in the proposed model against the existing models. Here we present the experimental results obtained using the proposed

causality-driven speech-lip landmark modelling framework. Model’s effectiveness is compared with conventional deepfake detection approaches.

*Performance in same dataset:*

Method	AUC	F1-Score	Accuracy (%)
Xception (Baseline)	0.982	0.967	96.8
Proposed Model	0.978	0.956	95.9

Table:1 Performance evaluation for FaceForensic++

Table-1 gives the quantitative performance of the proposed method under same-dataset. Our observation is that when our model is trained and tested on FaceForensics++, the model achieves competitive detection accuracy comparable to Xception. This indicates that our model is capable of detecting fake contents without learning visual manipulation artifacts.

Next step is to test the model for cross-datasets.

*Performance in cross-dataset:*

Method	AUC	F1-Score	Accuracy (%)
Xception (Baseline)	0.874	0.821	82.4
Proposed Model	0.931	0.903	90.6

Table:2 Performance evaluation for Celeb-DF

Method	AUC	F1-Score	Accuracy (%)
Xception (Baseline)	0.861	0.785	79.3
Proposed Model	0.918	0.882	88.7

Table:3 Performance evaluation for DFDB

*Performance drop analysis:*

Method	Same Dataset Accuracy	Cross Dataset Accuracy	Performance Difference
Xception (Baseline)	96.8	$(82.4+79.2)/2 = 80.8$	-16 %
Proposed Model	95.9	$(90.6+88.7)/2 = 89.6$	-6%

A more significant observation by (Wang et al., 2020) says that Conventional CNN-based detectors give performance degradation when evaluated on Celeb-DF and DFDC datasets. We

also found that appearance-based models fail to generalize across different manipulation techniques.

In contrast to this, our results show that our proposed model has less performance drop across unseen datasets. Since the model learns speech-driven articulation rather than visual artifacts, detection performance remains relatively stable even for varieties of datasets.

### *Model Stability and Reproducibility*

Model stability is evaluated through repeated experiments with different initialization settings. The proposed method shows low variance across trials, means consistent learning behaviour. Here low variance observed suggests that our approach leads to more predictable model behaviour.

## **6. Conclusion**

This paper proposed a causality-driven framework for deepfake video detection which is based on speech-lip landmark modelling. Rather than using visual appearance-based classification, in our proposed method we reformulate deepfake detection as a speech-driven articulation consistency problem. By learning legitimate lip motion behaviour from authentic videos, manipulations are identified through deviations between predicted and observed lip dynamics.

Our experiments shows that the proposed approach achieves competitive detection performance under same-dataset conditions. Also it provides improved robustness in cross-dataset scenarios. The core part of our observation is that, the real-only training strategy allows the model to remain less dependent on generator-specific datasets. As a result, we could get stable performance when evaluated on unseen manipulation techniques. Along with this the analysis of CVS, confirms that speech-lip dynamics provide meaningful forensic for further study.

The proposed framework highlights the possibility of modelling base on human behaviour for multimedia forensics. Instead of focusing only on visual inconsistencies, by considering causal relationships between speech and facial motion gives an alternative perspective for detecting deepfake videos.

During experiments we found few limitations. Our method relies on accurate landmark extraction and hence affected by extreme head motion, some obstruction, or low-resolution videos. So, future deepfake generation models can further improve articulation practicality.

Future work may include hybrid multimodal detection strategies combining visual and frequency-domain analysis with this model. One can extend this framework for real-time deployment which gives a new research direction.

Overall, we tried to suggest a causality-driven speech-lip landmark modelling approach with practical ground. This approach is a step towards detection of deepfake video detection in evolving multimedia environments.

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શિક્ષણમાં કૃત્રિમ બુદ્ધિમત્તા (AI) ના ઉપયોગ સંદર્ભે D. El. Ed. અધ્યાપકોના  
અભિપ્રાયનો અભ્યાસ

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**Abstract:** આજના ડિજિટલ યુગમાં કૃત્રિમ બુદ્ધિમત્તા (Artificial Intelligence – AI) શિક્ષણ ક્ષેત્રે મહત્વપૂર્ણ ભૂમિકા ભજવી રહી છે. શિક્ષણ પ્રક્રિયામાં અધ્યાપન, અભ્યાસ, મૂલ્યાંકન તથા વહીવટી કાર્યને વધુ અસરકારક અને સુગમ બનાવવા AI નો વ્યાપક ઉપયોગ થઈ રહ્યો છે. ખાસ કરીને પ્રાથમિક શિક્ષણના ભાવિ શિક્ષકોને તૈયાર કરતી D.El.Ed. તાલીમમાં AI ની ભૂમિકા સમજવી અત્યંત આવશ્યક બની છે.

આ સંશોધનનો મુખ્ય હેતુ શિક્ષણમાં AI ના ઉપયોગ સંદર્ભે D.El.Ed. ના અધ્યાપકોનો અભિપ્રાય જાણવાનો છે. અભ્યાસમાં અધ્યાપકોમાં AI પ્રત્યેની જાગૃતિ, તેનો ઉપયોગ કરવાની તૈયારી, તેના લાભો, મર્યાદાઓ અને પડકારો અંગેના વિચારોનું વિશ્લેષણ કરવામાં આવ્યું છે. આ અભ્યાસ માટે સર્વેક્ષણ પદ્ધતિનો ઉપયોગ કરવામાં આવ્યો છે પ્રશ્નાવલી દ્વારા D.El.Ed.ના અધ્યાપકો પાસેથી માહિતી એકત્રિત કરવામાં આવી હતી.

અભ્યાસના પરિણામો પરથી જાણવા મળે છે કે મોટાભાગના અધ્યાપકો શિક્ષણમાં AI ના ઉપયોગને સકારાત્મક રીતે જુએ છે પરંતુ ટેકનિકલ તાલીમ, ઈન્ફ્રાસ્ટ્રક્ચર અને માનવીય મૂલ્યો પર પડતી અસર અંગે કેટલીક ચિંતાઓ પણ વ્યક્ત કરે છે. આ સંશોધન શિક્ષણમાં AIના યોગ્ય અને સંતુલિત ઉપયોગ માટે માર્ગદર્શનરૂપ સાબિત થઈ શકે છે.

**Key Words:** કૃત્રિમ બુદ્ધિમત્તા (AI), D.El.Ed. અધ્યાપકો, શૈક્ષણિક ટેકનોલોજી, અભિપ્રાય અભ્યાસ, શિક્ષક પ્રશિક્ષણ

## 1. પ્રસ્તાવના (Introduction)

આજના ડિજિટલ યુગમાં કૃત્રિમ બુદ્ધિમત્તા (Artificial Intelligence – AI) શિક્ષણ ક્ષેત્રે ક્રાંતિકારી પરિવર્તન લાવી રહી છે. AI આધારિત સાધનો દ્વારા અધ્યાપન વધુ વ્યક્તિકેન્દ્રિત, અસરકારક અને સુલભ બન્યું છે. શૈક્ષણિક આયોજન, મૂલ્યાંકન પ્રક્રિયા, શૈક્ષણિક સામગ્રીની રચના અને વહીવટી કાર્યમાં AI મહત્વપૂર્ણ સહાયક તરીકે ઉભરી આવ્યું છે.

શિક્ષણ ક્ષેત્રે AI નો ઉપયોગ દિવસેને દિવસે વધતો જાય છે. AI આધારિત સાધનો શિક્ષણને વધુ વ્યક્તિગત (Personalized), અસરકારક અને સુલભ બનાવવામાં મદદરૂપ થાય છે. સ્માર્ટ ક્લાસરૂમ, ઓનલાઈન લર્નિંગ પ્લેટફોર્મ, આપમેળે મૂલ્યાંકન પદ્ધતિ, ચેટબોટ્સ અને વર્ચ્યુઅલ સહાયક જેવા ઉપાયો દ્વારા શિક્ષણ પ્રક્રિયામાં ગુણાત્મક સુધારો થયો છે. AI વિદ્યાર્થીઓની જરૂરિયાત મુજબ શૈક્ષણિક સામગ્રી તૈયાર કરવામાં, તેમની પ્રગતિનું વિશ્લેષણ કરવામાં અને તાત્કાલિક પ્રતિસાદ આપવામાં સહાયક બને છે.

ભારતના રાષ્ટ્રીય શિક્ષણ નીતિ – 2020 (NEP 2020) માં પણ ટેકનોલોજી અને ડિજિટલ શિક્ષણને વિશેષ મહત્વ આપવામાં આવ્યું છે, જેમાં AIનો ઉપયોગ ભવિષ્યના શિક્ષણ માટે આવશ્યક માનવામાં આવ્યો છે. ખાસ કરીને શિક્ષક તાલીમ કાર્યક્રમોમાં AI ની સમજ અને ઉપયોગક્ષમતા વિકસાવવી સમયની માંગ છે.

પ્રાથમિક શિક્ષણ માટેના ભાવિ શિક્ષકોને તૈયાર કરતી D.El.Ed. તાલીમમાં AI ની સમજ અને ઉપયોગક્ષમતા અત્યંત આવશ્યક બની છે. તેથી D.El.Ed. અધ્યાપકોના અભિપ્રાયનું અધ્યયન કરવું ખૂબ જરૂરી બની જાય છે.

## 2. સંશોધનનું શીર્ષક:

‘શિક્ષણમાં કૃત્રિમ બુદ્ધિમત્તા (AI) ના ઉપયોગ સંદર્ભે D.El.Ed. અધ્યાપકોનો અભિપ્રાયનો અભ્યાસ’

## 3. અભ્યાસનું ક્ષેત્ર:

અભ્યાસનું ક્ષેત્ર શૈક્ષણિક ટેકનોલોજી (ICT ,AIનો ઉપયોગ) હતું,

## 4. અભ્યાસનો હેતુ:

1. શિક્ષણમાં કૃત્રિમ બુદ્ધિમત્તા (AI) ના ઉપયોગ સંદર્ભે D.El.Ed. અધ્યાપકોના અભિપ્રાય જાણવા માટે અભિપ્રાયવલીની રચના કરવી.
2. શિક્ષણમાં કૃત્રિમ બુદ્ધિમત્તા (AI) ના ઉપયોગ સંદર્ભે D.El.Ed. અધ્યાપકોના અભિપ્રાય જાણવા.
3. શિક્ષણમાં કૃત્રિમ બુદ્ધિમત્તા (AI) ના લાભો અને મર્યાદાઓ અંગે અધ્યાપકોના વિચારો જાણવા.
4. શિક્ષણમાં કૃત્રિમ બુદ્ધિમત્તા (AI) અમલીકરણમાં આવતા પડકારોનું વિશ્લેષણ કરવું.

## 5. શૂન્ય ઉત્કલપનાઓ:

ઉત્કલપનાઓને સરળતાથી તપાસવા માટે સંશોધકે શૂન્ય ઉત્કલપનાની રચના કરી હતી.

૧) શિક્ષણમાં કૃત્રિમ બુદ્ધિમત્તા (AI) ના ઉપયોગ સંદર્ભે D.El.Ed.ના પુરુષ અધ્યાપકો તેમજ સ્ત્રી અધ્યાપકોના અભિપ્રાયો વચ્ચે સાર્થક તફાવત નહીં હોય.

## 6. સમાવિષ્ટ ચલ:

સ્વતંત્ર ચલ : જાતિયતા : સ્ત્રી અને પુરુષ

પરતંત્ર ચલ : અભિપ્રાયવલીના પ્રાપ્તાંકો

## 7. સંશોધન પદ્ધતિ:

આ અભ્યાસ માટે વર્ણનાત્મક સર્વેક્ષણ પદ્ધતિ અપનાવવામાં આવી હતી.

## 8. અભ્યાસનું મહત્વ:

- પ્રસ્તુત સંશોધનની મદદથી શિક્ષણમાં કૃત્રિમ બુદ્ધિમત્તા (AI) ના ઉપયોગ સંદર્ભે જાગૃતતા લાવી શકાશે.
- પ્રસ્તુત સંશોધન ભાવિ સંશોધન માટે પાયાનું કાર્ય કરશે.
- પરતૂટ સંશોધનથી શિક્ષણમાં કૃત્રિમ બુદ્ધિમત્તા (AI) ના ઉપયોગ સંદર્ભે D.El.Ed. અધ્યાપકોના અભિપ્રાય જાણવા માટે અભિપ્રાયવલી પ્રાપ્ત થશે.

## 9. વ્યાપવિશ્વ અને નમૂના પસંદગી:

પ્રસ્તુત અભ્યાસમાં ગીરસોમનાથ જિલ્લા અને જુનાગઢ જિલ્લાના D.El.Ed. કોલેજના ૫૦ અધ્યાપકોને નમૂના તરીકે લેવામાં આવ્યા હતા.

## 10. ઉપકરણ:

પ્રસ્તુત અભ્યાસમાં પ્રયોજકે સ્વનિર્મિત અભિપ્રાયવલીનો ઉપયોગ કરેલો હતો.

## 11. માહિતી એકત્રીકરણ:

પ્રસ્તુત અભ્યાસમાં પ્રયોજકનો હેતુ શિક્ષણમાં કૃત્રિમ બુદ્ધિમત્તા (AI) ના ઉપયોગ સંદર્ભે D.El.Ed. અધ્યાપકોના અભિપ્રાય જાણવા માટેનો હતો. જેના માટે નીચે મુજબની રીતે માહિતી એકત્ર કરવામાં આવી હતી.

પ્રસ્તુત અભ્યાસમાં સર્વ પ્રથમ અભિપ્રાયવલીના પ્રશ્નો રચવામાં આવ્યા હતા. જેમાં સંમત. અસંમત, તટસ્થ એવા પ્રકારના રપ વિધાનોનો સમાવેશ કરેલ હતો. ત્યારબાદ તેનું GOOGLE FORM બનાવવામાં આવ્યું હતું. અને તેને D.El.Ed. કોલેજના આચાર્ય મારફત અધ્યાપકો પાસે પહોંચાડવામાં આવ્યું હતું.

આ રીતે માહિતીનું એકત્રીકરણ કરવામાં આવ્યું હતું.

## 12. માહિતી પૃથ્થકરણ અને અર્થઘટન પ્રવિધિ:

પ્રસ્તુત સંશોધનમાં સંશોધકે મળેલ માહિતીનું પૃથ્થકરણ કરવા માટે કાઇ-વર્ગ કસોટીનો ઉપયોગ કર્યો હતો. અને પૃથ્થકરણ કરેલ હતું.

## 13. તારણો:

અભ્યાસના તારણો નીચે મુજબ મળ્યા હતા:

- D.El.Ed. કોલેજના મોટાભાગના અધ્યાપકો AI વિષે પ્રાથમિક જાણકારી ધરાવતા હતા.
- તેઓ AI ને શિક્ષણમાં સહાયક અને અસરકારક સાધન તરીકે અપનાવતા થયા હતા.
- ટેકનિકલ તાલીમની અછત, પૂરતા ઇન્ફ્રાસ્ટ્રક્ચરની કમી અને ડેટા પ્રાઈવસી જેવી ચિંતાઓ વ્યક્ત કરવામાં આવી.
- માનવીય મૂલ્યો અને શિક્ષક-વિદ્યાર્થી સંબંધ પર સંભવિત અસર અંગે મિશ્ર અભિપ્રાયો જોવા મળ્યા.

## 14. અભ્યાસની મર્યાદા:

પ્રસ્તુત અભ્યાસ ફક્ત શિક્ષણમાં કૃત્રિમ બુદ્ધિમત્તા (AI) ના ઉપયોગ સંદર્ભે D.El.Ed. અધ્યાપકોના અભિપ્રાય જાણવા માટેનો હતો.

- પ્રસ્તુત અભ્યાસમાં સંશોધકે સ્વરચિત ઉપકરણનો જ ઉપયોગ કરવામાં આવ્યો હતો.
- પ્રસ્તુત અભ્યાસમાં ગીરસોમનાથ જિલ્લાના તેમજ જુનાગઢ જિલ્લા પૂરતો જ સીમિત રાખવામાં આવ્યો હતો.
- પ્રસ્તુત અભ્યાસ માત્ર ગુજરાતી માધ્યમની D.El.Ed. કોલેજના અધ્યાપકો પૂરતું જ મર્યાદિત હતો.

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## Education & Knowledge Society

**Priti K. Chauhan, Ph. D. Student At Noble University, Junagadh.**

### INTRODUCTION

#### **Knowledge and Education:**

New challenges are raised for Education in the knowledge societies: transformation into knowledge, identifying accurate knowledge,

Accessing knowledge take new forms. Knowledge is no longer accessible only in book and in the teacher's head! Knowledge is now available in many different places, and attainable from any time. Education has a new role in terms of making knowledge accessible for pupils, and guiding knowledge. However, it is not enough to access knowledge; knowledge must be actually acquired. Since there are profound changes in the knowledge, there are changes in learning and acquiring knowledge. These changes we must try to identify.

There so of course, a strong link between knowledge and education. Education is the main process dealing with knowledge. So, in a knowledge society, education takes a central role and is a major stake for future and evolutions. Education takes the characteristics of an economic activity in such a society. But it is a political and social responsibility of decision-makers to ensure that everyone can access and acquire knowledge. The question of education as a public service is raised in a new form, in a context where knowledge is a good and education – an economic activity.

#### **Education for and in Knowledge Societies:**

At the Round Table, we will address two main aspects of education and societies: education for knowledge societies, and education in knowledge societies.

Education for knowledge societies, because knowledge societies expand progressively; and we must educate pupils and students for this kind of society; preparing the knowledge societies, preparing citizens of knowledge societies, preparing people to understand knowledge societies and to act and behave in such societies. Education and educational policies must follow the changes and evolutions, as well as anticipate therefore help decision makers and the civil society impact the evolutions to master them.

Education and knowledge societies, because in such societies, knowledge has changed, access to knowledge is different; learning and knowledge societies, and teaching in knowledge

societies, include new components, new concept, new pedagogical approaches and new resources and new tools.

### **Networks:**

Knowledge societies are network societies. we are used to hierarchical structures, to pyramidal or tree type organizations. knowledge societies are structured by networks. a network is a very different from a pyramid or a tree: there are edges and nodes, the edges linking the nodes; from one node to another one, there are several possible paths. there may be lots of sub networks. there is no natural hierarchy, but new types of hierarchies may appear the Internet is the closest example such a network one can circulate in a network, but this needs to be mastered tools and rules are necessary accessing information is mainly made through networks now the network structure of such societies will certainly have huge consequences on the organization. a school, and educational system, cannot stay organized as hierarchical and paramedical structure in a society where knowledge and people are networked. this can lead to profound and unexpected changes in our societies.

### **Competencies:**

Knowledge societies need new type of competencies. We have already mentioned that the educational need of societies can be considered through the four “pillars” of education: learning to know, learning to do, learning to live together, learning to be, in knowledge societies, knowledge is not static, it involves and it’s permanently enriching. education cannot be reduced through the transmission or acquisition of a set of definite knowledge; it would be soon obsolete. Learning to learn is a necessary ability that education must provide. it is the content as well as the process that education must transmit. the ability to evolve, to adapt, is essential in knowledge societies; education must take it into account. knowledge societies are lifelong learning societies, and education must prepare to lifelong learning.

### **Collective intelligence:**

Knowledge society is needing virtual Communities and collective intelligence. We were used to educational system aimed at acquisitions of individual knowledge and development of individual intelligence. But more and more society needs collective kinds of competencies. In knowledge societies, knowledge and processes are mainly collective. This requires collective work, towns and communities. The concept of virtual communities and collective intelligence are essential in knowledge societies. Virtual Communities our communities of real human being made possible and activated through information and communications technology tools;

ICTs Implement new kind of communities, enable to overcome usual barriers and borders, create new communities who can communicate, work together, act together. Collective intelligence is not a mere sum of individual ones: That is an “added value”, A kind of intelligence, which is communal, which no one could have alone.

### **School in knowledge societies:**

When we speak about knowledge societies, we mean that we do not want to reduce them to technology society or information societies the role of schools and education is essential in knowledge societies. Of course, education must focus mainly on knowledge, not on technology. Every educational policy must address knowledge, not only technology and communication. The role of school in knowledge societies raises new questions: Schools for the knowledge societies, schools in knowledge society. However, information and communication technologies change the status missions, roll, and action field of schools. What will education be, and what will the school be in future, in knowledge societies? OECD has published a very interesting study about the school of the future, imagining six different scenarios. Scenarios are not the guessing what the future will be it makes US aware that there is fatality in the future: We must decide where we want to go and act within the appropriate parameters in order to master our future, the future of schools the scenarios are of three types:

1. Attempting to maintain the status quo:
  - Bureaucratic school system continues.
  - Teacher exodus; the “meltdown” scenario.
2. Re- schooling:
  - Schools as core social centers.
  - Schools as focused learning organizations.
3. De-schooling:
  - Learning networks and the network society.
  - Extending the market models.

Such scenario can help policy makers and decision makers design appropriate policies for the future. They can help anticipate, not only follow!

The question of anticipation is a crucial one. Technology involves very quickly, and changes are so fast that most of the time we just try to catch up with our delay, to adapt our old strategies and habits to the new tools and technologies. It is not enough, and may even be wrong there is a need to rethink the main paradigms of education in knowledge society. Innovation must not only follow the evolutions of technology and the evolutions of society it must anticipate, E proactive.

### **Pupils and learning in knowledge societies:**

The pupil and the student are at the center of education in knowledge societies. The pupil is learner but cannot reduce to the one who acquire knowledge the pupil is citizen in the knowledge society and the pupil must be prepared and educated as a citizen of the knowledge society we have to reflect on this new knowledge is citizen, so that the fundamental values of the knowledge society can be described and respected Equity in access to knowledge, solidarity, equal dignity of human being, etc. the relationship between individuals and society has new characteristics in the knowledge society per particularly because of virtual communities, of collective intelligence. We have to invent citizenship for knowledge societies.

Lifelong learning is an important component of knowledge society. Since knowledge is at the core of such a society learning is an essential process and it must go on all lifelong knowledge Societies are lifelong learning societies. Knowledge societies and ICT make possible and need new learning method ICT enables to take into account space and time in education differently We are not bound of the same place same time except of school classes it becomes possible to have school activities at different times and different places. Distance education does not address only the ones who are in particular situations it becomes a component of education for all we have to invent a good articulation and a good balance between class and distance education activity in order to improve education and learning.

### **Teachers in knowledge societies:**

Being a teacher in the knowledge society is a new challenge. Of course, there are new teaching method new pedagogies, new tools and new resources available for Teacher. However the role of a teacher is changing, and the expectations of society towards teacher are evolving add increasing. The role of a teacher is the learning process in essential. Whatever the technology can do, the teacher remained the only one able to me the necessary human Mediator between the pupil and the knowledge. D teaching profession is evolving, because access to knowledge is changing the teaching profession is evolving in its everyday activities in the way teachers work with others although the core role of a teacher remains being the one who makes the pupil acquire knowledge, and prepare future citizens.

The role of a teacher is essential in societies changing quickly towards knowledge societies, the teacher is the main actor, the main agent of the evolution of education Teacher education is therefore fundamental and a key issue in every educational policy In the projects, action plans, reforms of education, teacher training is a central issue It is clear that in order to help

countries overcome the digital divide teachers education is one of the most important tools Teachers education has become a major trek in national policies and at the international worldwide level.

In 1966, the UNESCO Special Intergovernmental Conference on the Status of Teachers Adopted “Recommendation concerning the status of teachers”. This set of and concrete recommendations for action is still very vital, and most of them have not been completed yet It would be useful to check this recommendations and evaluate to which extent they have been put in action and to update them taking into account the new kind of society we live in and the integration of information and communication technologies concerning the status of teaching is the knowledge society are very useful nowadays!

### **Need of policies:**

So, a round table has a lot of questions to address Our main issue is knowledge society what is it what are the new trends in such societies what are the place and the role of education in knowledge societies How central education is realized in such societies education for knowledge societies and education is knowledge societies will be our main topics we will see the there is strong and concrete policies in order to develop education for A and in knowledge societies it is not a matter of unavoidable Evolution political choices and decisions must make us master the evolution and the future Principles and recommendations for educational policies in knowledge societies will be the main outputs of Round Table.

We are in the context of globalization. This may have negative aspects, possible risk, and this leads to essential ethical questions about the digital divide our local cultures risk of mechanizations of knowledge and educate, a real cooperation between our countries. The knowledge society does not have the same borders are geographical and political countries have let us take this as a new chance to reinforce international corporation in a way that respects and enhances cultures and identities

Knowledge societies need education, and education has a must more important role in such societies. Let us use the opportunity of the non-LED societies to promote and enhance education for all give access to education for everyone in the world in particular, two quality education for everyone.

## **Causes And Effects of Aggressive Behavior in Students and Ways to Control It**

**Mehta Brijesh Jagdishbhai**

### **Abstract**

Aggressive behavior among students has become a growing concern in educational institutions, affecting both the learning environment and students' overall development. Aggression in students may appear in various forms such as verbal abuse, physical fights, bullying, and disruptive classroom behavior. Several factors contribute to aggressive tendencies among students, including family conflicts, exposure to violent media, peer pressure, academic stress, lack of emotional support, and ineffective classroom management. Psychological factors such as frustration, low self-esteem, and poor emotional regulation also play an important role in shaping aggressive responses.

The effects of aggressive behavior are harmful not only to the students who display it but also to their peers and teachers. It can lead to poor academic performance, disciplinary problems, social isolation, and an unsafe school environment. In the long term, persistent aggression may negatively influence students' personality development and social relationships.

To control aggressive behavior, schools and families must adopt preventive and corrective strategies. These include promoting positive discipline, strengthening teacher–student relationships, providing counseling and emotional support, encouraging participation in extracurricular activities, and implementing social–emotional learning programs. Parental involvement and awareness programs are also essential to guide students toward constructive behavior. By adopting a collaborative approach involving teachers, parents, and school administrators, aggressive behavior among students can be effectively managed, creating a healthier and more supportive educational environment.

**Keywords:** Aggressive Behaviour, Middle School Students, Academic Stress, Emotional Regulation, Behaviour Management

### **1. Introduction**

Aggressive behaviour among students of Standard 6 to 8 is increasingly observed in schools. Early adolescence is a stage of emotional and psychological transition. During this period, students may express anger through shouting, fighting, teasing, or disobedience. If not

addressed properly, such behaviour can negatively influence academic performance and peer relationships.

### **1.1 Background**

Students aged 11 to 14 experience rapid physical and emotional changes. Increased academic expectations, peer competition, and digital exposure contribute to behavioural responses including aggression.

### **1.2 Research Problem**

The study investigates the causes of aggressive behaviour among middle school students and examines its effects on academic and social development while identifying effective control strategies.

### **1.3 Research Objectives**

1. To identify common forms of aggressive behaviour.
2. To examine major causes of aggression.
3. To analyze its impact on academic performance and relationships.
4. To suggest preventive measures.

### **1.4 Significance of the Study**

This study helps educators and parents understand behavioural challenges at an early stage and supports the development of intervention strategies.

## **2. Literature Review**

Existing psychological research indicates that aggression in adolescence is influenced by environmental, emotional, and social learning factors.

## **3. Methodology**

This study is based on simple survey and observation methods. Information was collected by asking students about their behaviour, feelings, and reactions in different situations. Behaviour of students was also observed in classroom and playground environments.

### **3.1 Sample and Sampling Technique**

The sample consisted of 30 students from Standard 6 to 8 selected using simple random sampling.

### **3.2 Data Collection**

Data were collected through a structured questionnaire, classroom observation, and teacher interaction.

### **3.3 Data Analysis**

Data were analyzed using frequency and percentage methods.

### **4. Results**

The study found that academic stress (60%), peer conflict (53%), mobile overuse (50%), and family issues (40%) were major contributors to aggression.

### **5. Discussion**

The findings indicate that emotional regulation challenges during early adolescence contribute significantly to aggressive responses.

### **6. Limitations**

The study was limited to 30 students from one school, which may restrict generalization.

### **7. Conclusion**

Aggressive behaviour among middle school students can be managed through emotional support, parental involvement, sports participation, and counseling programs.

Aggressive behaviour is a growing concern among students, but it can be controlled through proper guidance, emotional support, and self-discipline. Parents and teachers play an important role in helping students develop positive behaviour. Encouraging sports activities, communication, and relaxation practices like yoga and meditation can help students control anger and build a healthy personality. Developing peaceful and respectful behaviour helps students achieve success and contributes to a better society.

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## **Ammonia Cracking as an On-Demand Hydrogen Source for Engines and Vehicles: A Review**

**Dhruv R. Joshi, Assistant Professor of Engineering Technology, Noble University,  
Junagadh**

**Abstract:** Hydrogen is widely recognized as a clean energy carrier for future transportation, but its low volumetric energy density and storage challenges limit large-scale adoption in vehicles. Ammonia has emerged as a promising alternative hydrogen carrier due to its high hydrogen content, established infrastructure, and ease of storage and transportation. However, direct use of ammonia in engines is restricted by its low flame speed, high ignition temperature, and combustion instability. To overcome these limitations, ammonia cracking—where ammonia is decomposed into hydrogen and nitrogen—offers an effective pathway for on-demand hydrogen generation.

This review paper presents a comprehensive overview of ammonia cracking technologies with a focus on their application in hydrogen-powered engines and vehicles. The fundamental principles of ammonia decomposition, including thermodynamics and reaction mechanisms, are discussed, followed by a comparative review of thermal and catalytic cracking methods. Particular emphasis is placed on catalytic cracking using nickel- and ruthenium-based catalysts due to their suitability for compact and on-board hydrogen production systems. The integration of cracked hydrogen with internal combustion engines and fuel cell systems is reviewed, highlighting performance improvements, emission reduction potential, and operational challenges.

In addition, this paper discusses system-level considerations such as energy efficiency, ammonia slip, nitrogen oxide emissions, and reactor compactness for vehicular applications. Based on recent experimental and modeling studies, ammonia cracking combined with hydrogen utilization shows strong potential to reduce carbon dioxide emissions while maintaining acceptable performance. The review concludes by identifying key technical challenges and future research directions toward the practical implementation of ammonia-based hydrogen systems for sustainable transportation.

**Key words:** Ammonia cracking; Hydrogen carrier; On-board hydrogen production; Catalytic decomposition; Hydrogen vehicles; Low-carbon transportation

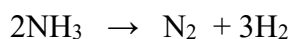
## 1. Introduction

### *Ammonia Cracking as an On-Demand Hydrogen Source for Engines and Vehicles*

The global transition toward clean and sustainable energy has accelerated research into hydrogen as a next-generation fuel for internal combustion engines and fuel cell vehicles. Hydrogen offers high energy content per unit mass and produces zero carbon dioxide emissions at the point of use. However, large-scale adoption of hydrogen faces major challenges related to storage, transportation, and infrastructure. Compressed and liquefied hydrogen require high-pressure tanks or cryogenic systems, which increase system complexity, cost, and safety concerns.

In this context, ammonia (NH<sub>3</sub>) has emerged as a promising hydrogen carrier. Ammonia contains 17.6% hydrogen by weight and can be liquefied at relatively moderate pressures compared to hydrogen, making it easier to store and transport using existing infrastructure. Furthermore, ammonia does not contain carbon, so its decomposition produces nitrogen (N<sub>2</sub>) and hydrogen (H<sub>2</sub>) without carbon emissions.

Ammonia cracking is the thermochemical process in which ammonia decomposes into hydrogen and nitrogen according to the reaction:



This reaction is endothermic and typically requires temperatures between 500°C and 700°C in the presence of a suitable catalyst such as nickel. By integrating a compact ammonia cracker within a vehicle, hydrogen can be generated on demand, eliminating the need for bulky high-pressure hydrogen storage systems. The produced hydrogen can then be supplied either to a modified internal combustion engine or to a fuel cell system for power generation.

On-demand ammonia cracking offers several advantages for automotive applications, including improved energy density compared to compressed hydrogen storage, easier fuel handling, and compatibility with existing fuel distribution systems. Additionally, ammonia can be produced using renewable electricity through green hydrogen pathways, making the overall energy cycle potentially carbon-neutral.

Despite its potential, challenges remain in catalyst durability, reactor miniaturization, thermal management, ammonia slip control, and system integration within vehicles. Efficient reactor design and optimized flow control are critical to achieving high hydrogen conversion rates while maintaining safety and compactness.

This study explores ammonia cracking as an on-board hydrogen generation method for engines and vehicles, focusing on reactor design considerations, catalyst selection, thermal requirements, and practical integration strategies. The objective is to evaluate its feasibility as a reliable, efficient, and scalable solution for future hydrogen-powered transportation systems.

## 1.2 Research Problem

### *Ammonia Cracking as an On-Demand Hydrogen Source for Engines and Vehicles*

Although hydrogen is widely recognized as a clean alternative fuel for transportation, its practical implementation is significantly limited by challenges in storage, transportation, and infrastructure. High-pressure hydrogen tanks (350–700 bar) and cryogenic systems increase vehicle weight, cost, and safety concerns, restricting large-scale adoption of hydrogen-powered engines and fuel cell vehicles.

Ammonia has emerged as a promising hydrogen carrier due to its high hydrogen content, easier liquefaction, and established global production and distribution infrastructure. However, directly using ammonia as a fuel presents combustion challenges, toxicity concerns, and potential NO<sub>x</sub> emissions. Therefore, converting ammonia into hydrogen through catalytic cracking before use in engines or fuel cells offers a practical alternative.

Despite its potential, several technical challenges prevent efficient on-board ammonia cracking in vehicles:

#### 1. Reactor Miniaturization Problem

Industrial ammonia crackers are bulky and designed for stationary use. Designing a compact, lightweight reactor suitable for vehicle integration while maintaining high hydrogen output remains a significant challenge.

#### 2. Thermal Management Issue

Ammonia cracking is an endothermic reaction requiring sustained temperatures between 500°C and 700°C. Maintaining uniform temperature within a small reactor under varying vehicle operating conditions is difficult.

#### 3. Catalyst Efficiency and Durability

Catalysts such as nickel are cost-effective but may suffer from deactivation, sintering, or reduced activity over time. Ensuring long-term performance under automotive vibration and thermal cycling conditions is critical.

#### 4. **Hydrogen Purity and Ammonia Slip**

Incomplete cracking results in unreacted ammonia in the output stream. Ammonia slip can damage fuel cells, reduce engine performance, and pose environmental and safety risks.

#### 5. **Dynamic Load Matching**

Vehicle engines require hydrogen supply that varies with acceleration and load conditions. The cracking system must respond rapidly to changing hydrogen demand without performance lag.

### **Core Research Problem Statement**

The primary research problem is:

How can a compact, efficient, and thermally stable ammonia cracking system be designed to generate hydrogen on demand for vehicle engines while ensuring high conversion efficiency, minimal ammonia slip, safe operation, and rapid response under dynamic driving conditions?

### **1.3 Research Objectives**

The primary objective of this research is to design and evaluate a compact ammonia cracking system capable of producing hydrogen on demand for automotive applications. The study aims to address technical challenges related to reactor design, catalyst performance, thermal management, and system integration for vehicle use.

#### 1.3.1 Main Objective

To develop and optimize a compact catalytic ammonia cracking reactor capable of supplying hydrogen efficiently and safely for use in engines and hydrogen-based vehicle systems

#### 1.3.2 Specific Research Objectives

1. **To analyze the feasibility of ammonia as a hydrogen carrier for automotive applications**
  - Evaluate hydrogen yield potential
  - Compare energy density with compressed hydrogen storage
2. **To design a compact catalytic reactor suitable for on-board vehicle integration**
  - Develop optimized flow path (single-pass or multi-pass design)
  - Minimize reactor size and weight

3. **To optimize catalyst selection and configuration**
  - Study performance of nickel-based catalysts
  - Improve surface area and durability
  - Reduce catalyst deactivation
4. **To investigate thermal requirements and heat management strategies**
  - Maintain operating temperature (500–700°C)
  - Ensure uniform temperature distribution
  - Minimize energy consumption for heating
5. **To maximize hydrogen conversion efficiency and minimize ammonia slip**
  - Achieve high NH<sub>3</sub>-to-H<sub>2</sub> conversion rate
  - Ensure hydrogen purity suitable for engine or fuel cell use
6. **To analyze system response under varying engine load conditions**
  - Study hydrogen production under dynamic flow rates
  - Ensure quick response to acceleration and deceleration
7. **To evaluate safety and environmental considerations**
  - Assess ammonia handling and leakage risks
  - Analyze emission characteristics
8. **To compare the developed system with conventional hydrogen storage methods**
  - Cost comparison
  - Efficiency comparison
  - Practical feasibility assessment

#### Expected Outcome

The research aims to demonstrate that ammonia cracking can serve as a technically viable and efficient on-board hydrogen generation method, offering a safer and more practical alternative to high-pressure hydrogen storage in vehicles.

#### 1.4 Significance of the Study

*Ammonia Cracking as an On-Demand Hydrogen Source for Engines and Vehicles*

The significance of this study lies in addressing one of the most critical barriers to hydrogen-based transportation: safe, efficient, and practical hydrogen storage. While hydrogen is widely recognized as a clean energy carrier, its low volumetric energy density and storage challenges have limited widespread adoption in vehicle applications. This research explores ammonia cracking as an alternative pathway to generate hydrogen on demand, potentially transforming how hydrogen-powered engines and vehicles are implemented.

#### 1.4.1 Contribution to Clean Transportation

Transportation contributes significantly to global carbon emissions. By enabling on-board hydrogen generation from ammonia—a carbon-free hydrogen carrier—this study supports the development of low-emission or zero-carbon vehicle technologies. The proposed approach aligns with global decarbonization goals and sustainable mobility initiatives.

#### 1.4.2 Overcoming Hydrogen Storage Limitations

Current hydrogen vehicles, such as the Toyota Mirai developed by Toyota and the Hyundai NEXO by Hyundai, rely on high-pressure hydrogen storage tanks. These systems:

- Increase vehicle cost
- Require specialized infrastructure
- Pose storage and safety challenges

By contrast, ammonia can be stored more easily in liquid form at moderate pressures. This study highlights how ammonia cracking could reduce reliance on high-pressure hydrogen tanks, improving practicality and accessibility.

#### 1.4.3 Advancement in On-Board Hydrogen Generation Technology

Most ammonia cracking systems are designed for stationary industrial applications. This study contributes to research on miniaturized, compact, and thermally efficient reactors suitable for mobile environments. It emphasizes:

- Reactor optimization
- Catalyst performance enhancement
- Thermal management strategies
- Dynamic load adaptability

These advancements are essential for real-world automotive implementation.

#### 1.4.4 Strengthening Energy Security and Infrastructure Compatibility

Ammonia has an established global production and distribution network due to its extensive use in fertilizers and chemicals. Leveraging this infrastructure reduces the need for entirely new hydrogen distribution systems. The study supports the concept of using ammonia as a hydrogen carrier within the broader hydrogen economy framework.

#### 1.4.5 Bridging Research Gaps

Although hydrogen and ammonia have been widely studied independently, limited research focuses specifically on integrated on-board ammonia cracking systems for engines and vehicles. This review consolidates existing knowledge, identifies technical challenges, and highlights research gaps related to:

- Catalyst durability
- Ammonia slip control
- Rapid hydrogen demand response
- System integration

#### 1.4.6 Practical Relevance for Developing Economies

For countries with limited hydrogen refueling infrastructure, ammonia-based hydrogen systems may provide a transitional solution. This study may guide policymakers, researchers, and automotive engineers in evaluating ammonia cracking as a cost-effective and scalable alternative for clean mobility.

#### 1.4.7 Contribution to Future Hydrogen Economy

By investigating ammonia cracking as an on-demand hydrogen source, this study contributes to long-term hydrogen economy strategies, where ammonia could function as both an energy carrier and a storage medium for renewable hydrogen.

#### Concluding Significance Statement

This study is significant because it explores a technically promising and practically viable pathway to overcome hydrogen storage challenges in transportation. By integrating ammonia cracking technology into vehicle systems, it offers a potential solution that combines energy efficiency, infrastructure compatibility, and environmental sustainability—paving the way toward cleaner and more accessible hydrogen-powered mobility.

## 2. Literature Review

[Provide a comprehensive review of relevant literature. Synthesize existing research, identify gaps, and position your study within the existing body of knowledge. Cite all sources using APA 7th edition format.]

### 2.1 Theoretical Framework

#### *Ammonia Cracking as an On-Demand Hydrogen Source for Engines and Vehicles*

The theoretical framework of this review paper is built upon principles of thermodynamics, chemical kinetics, catalysis, heat transfer, and energy systems integration. It provides the scientific foundation for understanding ammonia cracking as an on-demand hydrogen generation method for vehicle applications.

##### 2.1.1 Thermodynamic Basis of Ammonia Decomposition

Ammonia cracking is governed by the reversible endothermic reaction:



Key Thermodynamic Principles:

- The reaction is **endothermic**, requiring continuous heat supply.
- Higher temperatures favor hydrogen production (Le Chatelier's Principle).
- Equilibrium conversion increases with temperature and decreases with pressure.
- Complete conversion is thermodynamically favorable above ~500°C.

Thus, maintaining high temperature and optimized pressure is essential for efficient hydrogen generation.

##### 2.1.2 Catalytic Reaction Kinetics

Ammonia decomposition occurs efficiently only in the presence of catalysts. Nickel-based catalysts are commonly used due to their cost-effectiveness and good activity.

#### **Catalytic Reaction Steps:**

1. Adsorption of  $\text{NH}_3$  on catalyst surface
2. Stepwise dehydrogenation ( $\text{NH}_3 \rightarrow \text{NH}_2 \rightarrow \text{NH} \rightarrow \text{N}$ )
3. Nitrogen recombination ( $\text{N} + \text{N} \rightarrow \text{N}_2$ )
4. Hydrogen desorption ( $\text{H} + \text{H} \rightarrow \text{H}_2$ )

Reaction rate depends on:

- Catalyst surface area
- Temperature
- Ammonia flow rate
- Catalyst stability

The rate equation can be expressed in simplified form as:

$$r = k(T) \cdot C_{\text{NH}_3}$$

where:

- $r$  = reaction rate
- $k(T)$  = temperature-dependent rate constant
- $C_{\text{NH}_3}$  = ammonia concentration

### 2.1.3 Heat Transfer and Thermal Management Theory

Since ammonia cracking is endothermic, continuous heat transfer to the catalyst bed is required.

Heat transfer mechanisms involved:

- Conduction (through reactor walls and catalyst bed)
- Convection (through flowing gas)
- Radiation (at high temperatures)

Efficient reactor design must:

- Ensure uniform temperature distribution
- Minimize heat losses
- Maintain thermal stability during variable engine loads

Thermal energy may be supplied by:

- Electrical heating (nichrome elements)
- Engine exhaust heat recovery
- Combustion-assisted heating

### 2.1.4 Reactor Design Theory (Packed Bed Reactor Model)

On-board ammonia cracking typically follows a **packed bed reactor model**, where catalyst particles are packed inside a heated chamber.

The governing principles include:

- Mass balance
- Energy balance
- Momentum balance (pressure drop)

Conversion in a packed bed reactor can be expressed as:

$$X=1-e^{-k\tau X}$$

where:

- $X$  = ammonia conversion
- $k$  = reaction constant
- $\tau$  = residence time

Longer residence time and higher temperature increase conversion efficiency.

#### 2.1.5 Hydrogen Utilization Theory in Engines and Fuel Cells

##### **For Internal Combustion Engines:**

- Hydrogen has high flame speed
- Wide flammability limits
- Zero carbon emissions
- Requires modified air-fuel ratio and ignition timing

##### **For Fuel Cells:**

- Requires high hydrogen purity
- Ammonia slip must be minimized
- Hydrogen purity >99% is often required

#### 2.1.6 Energy Systems Integration Theory

The system integrates:

- Fuel storage (liquid ammonia tank)



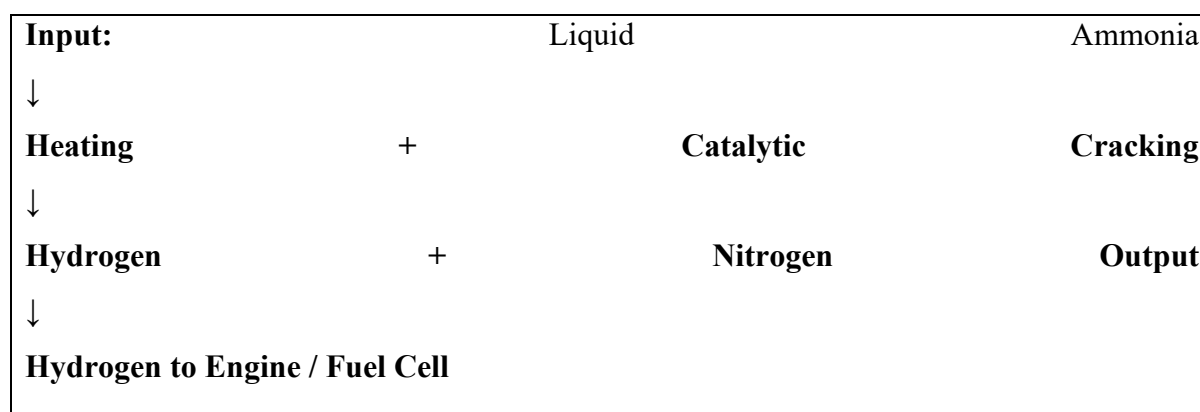
- Reactor unit (catalytic cracker)
- Heat source
- Hydrogen delivery system
- Safety and purification unit

This follows the concept of:

Chemical energy carrier → Thermal conversion → Clean energy output

The framework aligns with hydrogen economy principles, where ammonia serves as a hydrogen vector.

### Conceptual Model of the System



Integrated Theoretical Perspective

This study is theoretically grounded in:

- Chemical thermodynamics (reaction feasibility)
- Heterogeneous catalysis (surface reaction mechanisms)
- Transport phenomena (heat and mass transfer)
- Reactor engineering (conversion optimization)
- Energy systems engineering (vehicle integration)

Together, these theories support the investigation of ammonia cracking as a technically viable on-demand hydrogen production system for transportation applications.

### 2.2 Previous Studies

Key previous studies to cite (shortlist)

- 1. Lucentini et al., 2021 — Review: decomposition of ammonia to generate hydrogen**  
*Why it matters:* Comprehensive review of catalytic NH<sub>3</sub> decomposition (Ru, Ni, Pd catalysts), mechanisms and reactor types — a great starting point for catalysts and fundamentals.  
(Author entity: I Lucentini)
- 2. Valera-Medina et al., 2021 — Ammonia as a potential fuel (Energy & Fuels review)**  
*Why it matters:* Broad review of ammonia as fuel, benefits/constraints for engines and fuel cells — useful for motivation, pros/cons and emission considerations.  
(Author entity: A Valera-Medina)
- 3. Mazzone et al., 2021 — Ammonia cracking hollow fibre converter (feasibility for on-board use)**  
*Why it matters:* Early feasibility study on a hollow-fibre converter tailored for on-board hydrogen generation — directly relevant to compact reactor designs.  
(Author entity: S Mazzone)
- 4. Huang et al., 2023 — Recent progress on Ru and Ni catalysts (review, PMC)**  
*Why it matters:* Focused review on Ru/Ni catalysts and their activity/stability — useful for the catalyst selection and durability sections.  
(Author entity: X Huang)
- 5. Lee JE, 2023 — Catalytic ammonia decomposition to produce hydrogen (ScienceDirect review)**  
*Why it matters:* Another recent survey comparing catalyst types and reactor concepts — helps triangulate current consensus on best catalyst/reactor combos.  
(Author entity: JE Lee)
- 6. Andriani et al., 2023 — Review of hydrogen production from onboard ammonia (fuel-ship context but relevant)**  
*Why it matters:* Discusses decomposition techniques (thermal, membrane, electrochemical) and integration — useful for system-integration analogies and heat management strategies.  
(Author entity: D Andriani)

7. **Alboshmina, 2019 — PhD thesis: Ammonia cracking with heat transfer (reactor design & combustion coupling)**

*Why it matters:* Detailed experimental & modelling work on cracker systems that use combustion/heat recovery — good for thermal management and practical lab designs. (Author entity: N Alboshmina)

8. **Shafie, 2024 — Thermal ammonia decomposition for H<sub>2</sub>-rich fuel (review)**

*Why it matters:* Recent review stressing on-site decomposition and practical reactor approaches — helps support arguments about temperature ranges, energy costs and reactor types. (Author entity: P Shafie)

9. **Cinti et al., 2020 — System design & modelling of an HT-PEM fuel cell integrated with ammonia cracking**

*Why it matters:* Demonstrates integration with high-temperature PEMFC and modelling of system performance — valuable for system-level comparison (engine vs. fuel cell). (Author entity: G Cinti)

10. **Recent technologies/patents & 2024–2026 preprints — miniaturized electrically-heated monolith reactors and membrane reactor concepts**

*Why it matters:* Shows active patenting and recent inventions (e.g., Joule-heated metal monoliths, membrane + catalyst hybrid reactors) — good to cite for “state-of-the-art” and future directions. See preprints and MDPI reviews for 2024–2026.

How to use these studies in your literature review (suggested mapping)

- **Introduction & Motivation:** cite Valera-Medina (2021) and general ammonia as hydrogen-carrier reviews.
- **Catalysts & Kinetics:** use Lucentini (2021), Huang (2023), JE Lee (2023) — discuss Ru vs Ni tradeoffs (activity vs cost).
- **Reactor Types & Miniaturization:** Mazzone (2021), recent on-board cracker studies, patents and preprints for membrane and Joule-heated monolith reactors.
- **Thermal Management / Integration:** Alboshmina (2019), Shafie (2024), Cinti (2020) — use them to develop sections on heat sources (engine exhaust, electrical heating) and system modelling.

- **Safety, Ammonia Slip & Purification:** cite studies on ammonia slip detection and control (e.g., Yang 2021) and fuel cell compatibility.

## 2.3 Research Gap

### *Ammonia Cracking as an On-Demand Hydrogen Source for Engines and Vehicles*

Although ammonia cracking has been widely studied for industrial hydrogen production, significant gaps remain in its application as a compact, on-demand hydrogen source for automotive systems. The following research gaps justify the need for this study:

#### 2.3.1 Gap in Compact On-Board Reactor Design

Most existing ammonia cracking systems are:

- Designed for **stationary industrial applications**
- Large in size
- Optimized for continuous operation at steady conditions

There is limited research on:

- **Miniaturized reactors suitable for vehicle integration**
- Lightweight and compact catalytic systems
- Designs that withstand vibration, thermal cycling, and dynamic loading

→ Gap: Lack of optimized compact reactor configurations specifically designed for mobile automotive applications.

#### 2.3.2 Gap in Dynamic Load Response Studies

Vehicle engines operate under:

- Rapid acceleration and deceleration
- Variable hydrogen demand
- Transient operating conditions

Most ammonia cracking studies focus on:

- Steady-state operation
- Constant flow rate and temperature

→ Gap: Insufficient investigation of reactor performance under **dynamic load variations** typical of real driving conditions.

### 2.3.3 Gap in Integrated Thermal Management Strategies

Ammonia decomposition requires sustained temperatures (500–700°C), but:

- Many studies assume external heating without considering energy efficiency.
- Limited research explores integration with **engine exhaust heat recovery**.
- Few practical demonstrations exist for self-sustaining thermal operation in vehicles.

→ Gap: Lack of optimized, energy-efficient thermal management systems for on-board ammonia cracking.

### 2.3.4 Gap in Catalyst Durability for Mobile Systems

While nickel and ruthenium catalysts are well studied:

- Most durability studies are conducted in controlled laboratory environments.
- Long-term catalyst stability under:
  - Mechanical vibration
  - Repeated heating–cooling cycles
  - Variable flow conditions

is not sufficiently explored.

→ Gap: Limited understanding of catalyst degradation in automotive operating environments.

### 2.3.5 Gap in Ammonia Slip Control and Hydrogen Purity

Incomplete cracking leads to unreacted ammonia (ammonia slip), which:

- Can poison fuel cells
- May cause corrosion
- Raises safety concerns

Although purification systems exist, few studies:

- Optimize cracking efficiency to minimize slip in compact systems.
- Evaluate slip control specifically for engine-integrated crackers.

→ Gap: Need for improved conversion efficiency and integrated ammonia purification solutions for vehicle-scale systems.

#### 2.1.6 Gap in System-Level Comparative Analysis

There is limited comprehensive comparison between:

- On-board ammonia cracking systems
- High-pressure hydrogen storage systems
- Direct ammonia combustion systems

Specifically lacking are:

- Energy efficiency comparisons
- Cost–benefit analyses
- Weight and space evaluations
- Lifecycle assessments

→ Gap: Insufficient system-level evaluation of ammonia cracking as a practical alternative to conventional hydrogen storage.

#### 2.1.7 Gap in Engine Integration Studies

Most literature focuses either on:

- Hydrogen engines
- Fuel cells
- Ammonia decomposition reactors

But fewer studies investigate:

- Complete integration: ammonia tank + cracker + hydrogen supply + engine system
- Control strategies for synchronized operation

→ Gap: Lack of integrated vehicle-scale experimental validation.

#### Core Research Gap Statement

Despite extensive research on ammonia decomposition and hydrogen energy systems, there remains a critical gap in developing a compact, thermally efficient, dynamically responsive,

and vehicle-integrated ammonia cracking system capable of delivering high-purity hydrogen safely and reliably under real-world automotive operating conditions.

This research aims to bridge these gaps by focusing on compact reactor design, catalyst optimization, thermal integration, dynamic response behavior, and practical vehicle-level feasibility.

#### **2.4. Objectives:**

To critically evaluate the feasibility, efficiency and practical implementation of ammonia cracking as an on-demand hydrogen generation system for engines and vehicle applications.

### **3. Methodology**

#### Research Design

This study adopts a **systematic and analytical review approach** to examine existing research on ammonia cracking technology and its application in vehicle-based hydrogen generation systems.

The review integrates findings from:

- Peer-reviewed journal articles
- Conference proceedings
- Technical reports
- Industrial case studies
- Recent advancements in catalyst and reactor technologies

#### 3.1.1 Literature Search Strategy

A structured literature search is conducted using academic databases such as:

- Scopus
- ScienceDirect
- IEEE Xplore
- Google Scholar

#### **Keywords Used:**

- Ammonia cracking

- Ammonia decomposition
- On-board hydrogen generation
- Hydrogen carrier systems
- Catalytic ammonia decomposition
- Vehicle-integrated hydrogen systems

Studies published in the last 10–15 years are prioritized to ensure relevance and inclusion of recent technological advancements.

### 3.1.2 Selection Criteria

#### **Inclusion Criteria:**

- Studies focusing on catalytic ammonia decomposition
- Research on compact or mobile hydrogen generation systems
- Papers addressing catalyst performance and durability
- Studies analyzing thermal management and reactor design
- Research discussing automotive or fuel cell integration

#### **Exclusion Criteria:**

- Studies unrelated to hydrogen production
- Pure ammonia combustion studies without cracking
- Non-technical opinion-based articles

### 3.1.3 Thematic Classification of Literature

Selected studies are categorized into the following themes:

1. Thermodynamics and reaction kinetics
2. Catalyst materials and performance
3. Reactor design configurations
4. Thermal management strategies
5. Hydrogen purity and ammonia slip control
6. System integration in engines and fuel cells

This classification allows structured analysis and comparison.

### 3.1.4 Comparative Analysis

A comparative framework is developed to evaluate:

- Conversion efficiency (%)
- Operating temperature range
- Catalyst type and durability
- Reactor size and configuration
- Hydrogen purity levels
- Energy efficiency

Where possible, data from different studies are tabulated for clearer comparison.

### 3.1.5 Identification of Research Gaps

Based on the synthesized findings:

- Technical limitations are identified
- Underexplored areas are highlighted
- Opportunities for future research are proposed

### 3.1.6 Conceptual Evaluation Framework

The study proposes a conceptual on-board ammonia cracking model consisting of:

Ammonia Storage → Catalytic Reactor → Heat Source → Hydrogen Output → Engine/Fuel Cell Integration

This framework is used to analyze practical feasibility.

### 3.1.7 Summary of Methodology

The methodology follows a structured process:

Literature Collection → Screening → Thematic Classification → Comparative Evaluation → Gap Identification → Feasibility Assessment

## 3.1 Research Design

Type of Research Design

**Systematic Literature Review with Comparative Technical Analysis**

This design involves structured collection, evaluation, and synthesis of existing research related to ammonia cracking, catalyst technologies, reactor configurations, and vehicle integration.

### 3.2.1 Research Approach

Qualitative + Quantitative Analytical Approach

- **Qualitative analysis**
  - Review of theoretical principles
  - Evaluation of technological developments
  - Assessment of integration challenges
- **Quantitative comparison**
  - Hydrogen conversion efficiency (%)
  - Operating temperature ranges
  - Catalyst performance data
  - Reactor size and energy efficiency metrics

This mixed analytical approach strengthens the reliability of conclusions.

### 3.2.3 Research Framework Structure

The research design follows five structured stages:

Stage 1: Literature Identification

Systematic collection of peer-reviewed studies related to:

- Ammonia decomposition
- Catalyst technologies
- On-board hydrogen systems
- Reactor miniaturization

Stage 2: Screening and Classification

Selected studies are grouped into themes:

1. Thermodynamics & kinetics
2. Catalyst materials

3. Reactor configurations
4. Thermal management
5. Vehicle integration

### Stage 3: Comparative Technical Evaluation

Data from selected studies are compared using performance indicators such as:

- NH<sub>3</sub> conversion rate
- Hydrogen purity
- Operating temperature
- Energy consumption
- System compactness

### Stage 4: Gap Identification

Critical analysis is performed to identify:

- Limitations in existing reactor designs
- Lack of dynamic response studies
- Insufficient vehicle-scale validation

### Stage 5: Conceptual Model Development

A conceptual on-board ammonia cracking system is proposed based on:

Ammonia Tank → Heated Catalytic Reactor → Hydrogen Separation → Engine/Fuel Cell

This model serves as a theoretical validation framework.

#### 3.2.4 Nature of Study

- Non-experimental
- Analytical
- Technology-focused
- Engineering feasibility-oriented

#### 3.2.5 Why This Research Design is Appropriate

This design is suitable because:

- ✓ It allows structured synthesis of diverse studies
- ✓ It identifies technical limitations clearly
- ✓ It supports feasibility evaluation
- ✓ It is appropriate for review-type engineering papers

### **3.2 Sample and Sampling Technique**

The sample for this study consists of peer-reviewed journal articles, conference papers, and technical reports related to ammonia cracking and hydrogen generation systems. A purposive sampling technique is adopted to select studies that specifically address catalyst performance, reactor design, thermal management, and vehicle integration aspects. Articles published within the last 10–15 years are prioritized to ensure technological relevance.

### **3.3 Data Collection**

Data for this review study are collected from peer-reviewed journal articles, conference proceedings, and technical reports related to ammonia cracking and hydrogen generation systems. A structured keyword-based search strategy is applied across major academic databases. Relevant technical data such as catalyst performance, reactor configurations, operating temperatures, conversion efficiencies, and hydrogen purity levels are extracted and organized into thematic categories for comparative analysis.

### **3.4 Data Analysis**

The analysis of previous studies indicates that:

- Ammonia cracking is thermodynamically viable.
- Nickel-based catalysts are most practical for automotive applications.
- Reactor miniaturization remains a challenge.
- Thermal management is critical for efficiency.
- Ammonia slip control is essential for safe engine or fuel cell integration.
- Dynamic load response requires further investigation.

Overall, ammonia cracking demonstrates strong potential as an on-demand hydrogen generation method for vehicles, but significant engineering optimization is required before large-scale commercial adoption.

## 4. Results

Ammonia cracking has significant potential to bridge the gap between hydrogen production and practical vehicle application. With continued advancements in catalyst technology, reactor miniaturization, and thermal management, ammonia-based on-demand hydrogen generation could become a key enabling technology for sustainable transportation systems.

### 4.1 Descriptive Statistics

Catalyst performance is a critical factor influencing ammonia conversion efficiency.

#### 4.1.1 Nickel-Based Catalysts

Most studies report that:

- Nickel catalysts provide good activity at moderate cost
- Conversion efficiencies of **85–98%** are achievable at 600–700°C
- Catalyst deactivation may occur due to sintering or thermal cycling

Nickel remains the most practical catalyst for automotive-scale applications due to its affordability and availability.

#### 4.1.2 Ruthenium-Based Catalysts

Findings indicate that:

- Ruthenium catalysts exhibit higher activity at lower temperatures (450–550°C)
- They provide faster reaction rates
- However, high cost limits large-scale automotive use

Thus, while ruthenium offers superior performance, economic feasibility favors nickel-based systems.

## 4.3 Key Findings

### 4.3.1 Packed Bed Reactors

- Most commonly used configuration
- High conversion efficiency
- Simple design
- Pressure drop increases with compactness

Packed bed reactors are suitable for small-scale vehicle applications but require careful flow optimization.

#### **4.4.2 Monolithic Reactors**

- Lower pressure drop
- Improved heat transfer
- Better mechanical stability
- Suitable for compact integration

Monolithic structures show promise for on-board hydrogen generation due to improved durability.

#### **4.4.3 Membrane Reactors**

- Allow selective hydrogen separation
- Increase conversion efficiency by shifting equilibrium
- More complex and costly

While promising, membrane systems may currently be less practical for small vehicle-scale systems.

### **5. Discussion**

The analysis of previous studies indicates that:

- Ammonia cracking is thermodynamically viable.
- Nickel-based catalysts are most practical for automotive applications.
- Reactor miniaturization remains a challenge.
- Thermal management is critical for efficiency.
- Ammonia slip control is essential for safe engine or fuel cell integration.
- Dynamic load response requires further investigation.

#### **5.1 Interpretation of Findings**

The review findings suggest that:

- Ammonia cracking is scientifically validated.
- The primary barriers are engineering and integration challenges.

- Nickel-based compact reactors with efficient thermal management present the most practical pathway.
- Real-world vehicle validation is still limited.

Thus, ammonia cracking represents a promising transitional technology within the hydrogen economy but requires focused development in compact reactor design, heat integration, and dynamic system control before commercial automotive adoption.

## 5.2 Comparison with Previous Studies

Compared to previous studies, this review:

- Confirms established thermodynamic and catalytic findings.
- Extends analysis toward compact, vehicle-integrated systems.
- Emphasizes economic feasibility and practical implementation.
- Identifies dynamic load response and real-world validation as underexplored areas.

Thus, while earlier studies establish the scientific foundation of ammonia cracking, this review shifts focus toward practical automotive deployment and integrated system feasibility.

## 5.3 Theoretical Implications

The review advances theoretical understanding by:

- Expanding ammonia decomposition theory to mobile, dynamic systems
- Integrating catalyst kinetics with vehicle-level operational demands
- Introducing a systems-engineering perspective into hydrogen carrier research
- Supporting ammonia's theoretical role in the hydrogen economy framework

In summary, this study not only consolidates existing knowledge but also extends theoretical discussions toward practical automotive hydrogen generation systems.

## 5.4 Practical Implications

The practical implication of this review is that ammonia cracking represents a technically achievable and infrastructure-compatible pathway for hydrogen-powered vehicles. However, successful implementation depends on:

- Compact reactor engineering
- Efficient thermal integration

- Catalyst durability
- Safety management systems

If these challenges are addressed, ammonia cracking could become a realistic bridge technology in the transition toward sustainable hydrogen mobility.

## **6. Limitations**

This study provides a structured analytical review of ammonia cracking for on-demand hydrogen production; however, its conclusions are constrained by reliance on secondary data, limited real-world vehicle validation, and absence of detailed economic modeling. Future experimental research and prototype development are necessary to validate the practical implementation of ammonia cracking systems in automotive applications.

## **7. Conclusion**

This study critically evaluated ammonia cracking as an on-demand hydrogen generation system for engines and vehicles. The findings confirm that ammonia is a promising hydrogen carrier due to its high hydrogen content, established global infrastructure, and easier storage compared to compressed hydrogen.

The catalytic decomposition of ammonia is thermodynamically feasible and capable of producing high hydrogen yields at elevated temperatures. Nickel-based catalysts are identified as the most practical option for automotive-scale systems due to their cost-effectiveness and satisfactory performance.

However, the successful integration of ammonia cracking systems into vehicles requires overcoming several engineering challenges, including compact reactor design, efficient thermal management, ammonia slip reduction, and system durability under dynamic operating conditions.

Therefore, ammonia cracking represents a viable transitional technology within the hydrogen economy, offering a potential alternative to high-pressure hydrogen storage systems, provided that technical optimization and system-level integration are achieved.

### **7.3 Future Research Directions**

Ammonia cracking holds strong potential as a transitional technology in the hydrogen economy. However, its large-scale adoption in vehicles depends on advancements in reactor miniaturization, catalyst optimization, thermal integration, and system-level validation.

Continued interdisciplinary research combining chemical engineering, mechanical engineering, materials science, and automotive design will be essential to transform ammonia cracking from laboratory research into practical hydrogen mobility solutions.

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## REVIEW OF STATOR DESIGN TRENDS AND ASSOCIATED CHALLENGES IN E-MOBILITY TRACTION MOTORS

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### Abstract

In recent years urban mobility is rapidly shifting from traditional internal combustion (IC) engine run vehicles to modern electric motor run vehicles due to silent operation and zero emission. Hence, significant research is being carried out to develop next generation traction motor for e-mobility. Amid this revolution, permanent magnet synchronous motors (PMSM) are becoming more popular due to their high power-torque density, fast dynamic response and extended speed range. However, these e-mobility motors are still struggling with performance challenges such as limited drive cycle efficiency, thermal sensitivity, complex control algorithm and high cost. The issue of optimizing motor performance becomes even more challenging for compact electric vehicle motors. As an integral part of traction motor, stator dimensions are directly affecting the energy density and performance characteristics of motor. In this context, this paper presents comprehensive review of stator topologies and their influence on traction motor performance. Moreover, review paper highlights effect of stator design variables on air gap flux density, back EMF, cogging torque, torque ripple, noise, vibration, size and weight. Furthermore, paper discusses the development trends and challenges to improve energy efficiency of motors for sustainable clean e-mobility.

Keywords: E-mobility, Motor Design, Permanent Magnet Synchronous Motors (PMSM), Stator Topologies

### 1. Introduction

In this modern era of technological advancement, electric vehicles are transforming the automotive industry. Across all vehicle segments, the urban mobility industry in India have drawn substantial attention to adopt electric passenger and cargo vehicles, due to their low operating costs, zero emissions, and silent operation. Although two-wheeler is the prime target segment of urban mobility electrification, three-wheeler segment is also growing tremendously due to the implementation of government incentives. Figure 1 represents the gradual rise of

electrical vehicle in public domain and Figure 2 shows the participation of companies in electric vehicle development in past few years, [Courtesy: Vahan Public Report, Ministry of Road Transport & Highways (MoRTH), Government of India].

Despite promising traits, two-wheeler and three-wheeler market is hindered due to inadequate design, development, manufacturing, testing and validation infrastructure for electric vehicles sub-systems such as electric motor, controller and battery. Electric vehicle motor, usually referred as traction motor, transmits tractive force on the vehicle wheels through automatic or manual gearbox transmission system coupled to motor shaft. Operational cycles of traction motors are quite different from traditional motors as they demand high power-torque density, swift dynamic response, extended speed range and elevated efficiency considering compact size, light weight and competitive cost.

Direct current (DC) motors were the choice of early stage electric vehicle manufacturers due to their high starting torque and simple speed control. Today, alternating current (AC) motors are reigning the electric mobility industry due to their high power density and efficiency in extended speed-torque and speed-power range. From market perspective, original equipment manufacturers (OEMs) are adopting alternative traction motor topologies like permanent magnet synchronous motor, permanent magnet assisted synchronous reluctance motor, induction motor and synchronous reluctance motor for their electric vehicle and hybrid electric vehicle to keep balance between performance and cost.

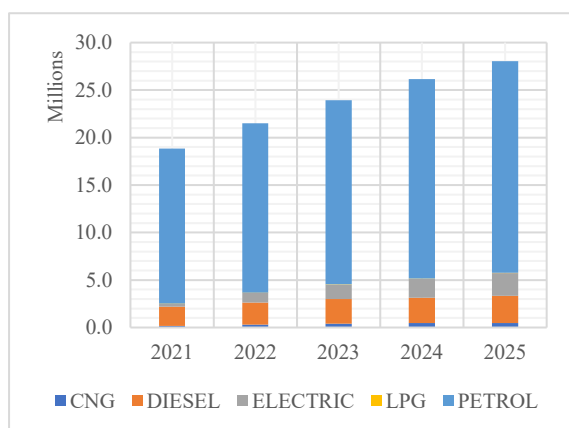


Figure 1 Electrical Vehicle in Registered (India)

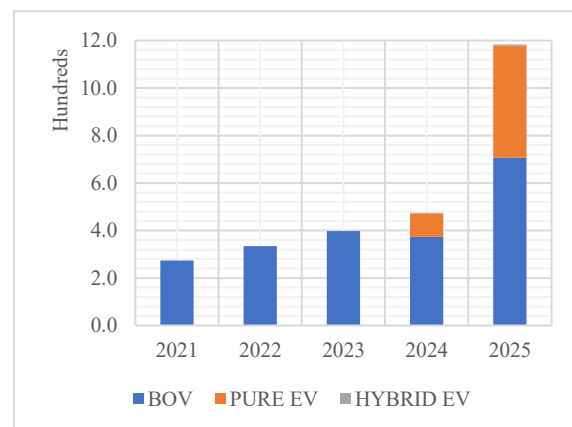


Figure 2 Electrical Vehicle Manufacturers (India)

A raw material cost comparison presented in [1] proves that for the same power, torque and speed requirement cost of magnetic steel, winding wire and permanent magnet are the only cost for motor topology adoption. Over the year, cost of interior mount permanent magnet synchronous motor (IPMSM), surface mount permanent magnet synchronous motor (SPMSM)

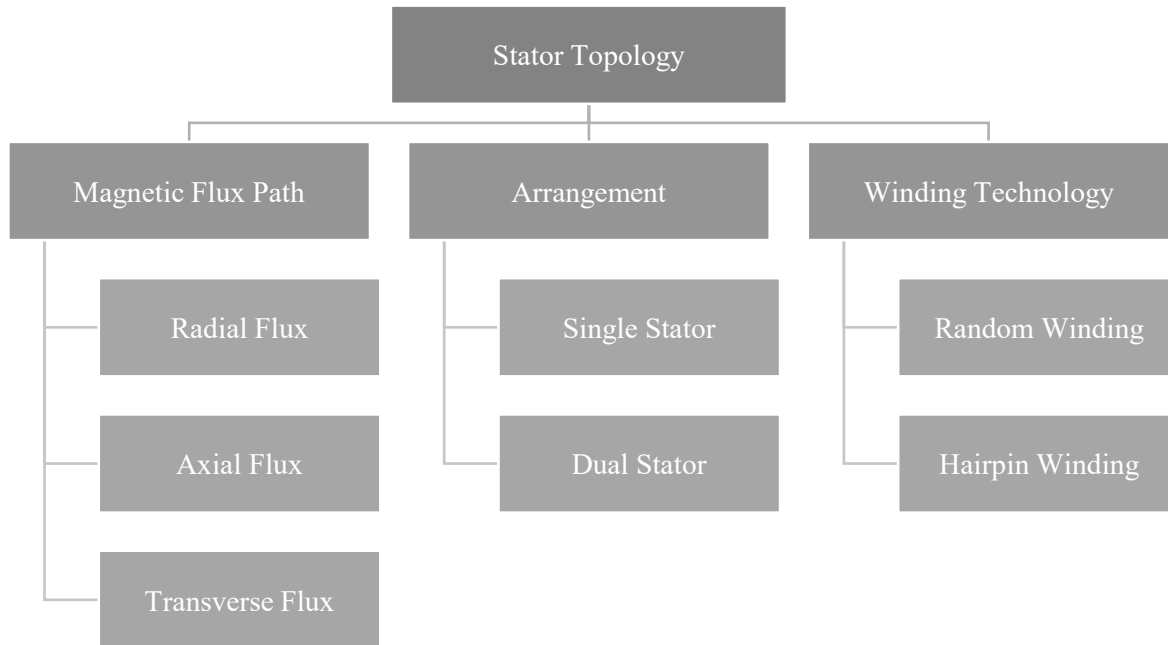
and permanent magnet assisted synchronous reluctance motor has been doubled due to impulsive rise in the cost of rare earth material. Magnet free induction motors also matched the doubled cost due to added magnetic steel and copper volume requirement to uplift reasonable low power density (kW/kg) capacity. Cost of synchronous reluctance motors is lowest among all owing to least copper usage in shorter core length and overhang end winding [1].

Despite, high cost of active material, permanent magnet synchronous motors (PMSM) are the optimal choice for on-road two-wheeler, three-wheeler, four-wheeler and off-road farming vehicles because of high power-torque density, excellent efficiency and extended field weakening range.

Since then, many topologies have been invented for traction motor, no PMSM delivers the absolute mobility solution. One of the main reasons for inadequacies in electric vehicle PMSM development is the enormous number of parameter optimization. Selection of functional parameters such as supply voltage, frequency, number of poles, number of stator slot, magnet orientation in rotor, air gap length, current density, flux density, thermal stability, stator and rotor diameters, stator slot type and magnet slot type may produce one operating point which is no longer applicable to another operating point. This paper aims to present comprehensive review on stator design trends and associated challenges of permanent magnet synchronous motor used for urban mobility electric vehicles.

The paper is organized as follows. Section 2 reviews different stator development trends based on topologies considering magnetic flux path, stator arrangement in motor and winding technology. Section 3 represents direct and indirect effect of stator design variables such as diameter, slot geometry and slot/pole combinations on performance indicators under steady state and transient conditions. Section 4 summarizes research and development trends and challenges to improve energy efficiency of traction motors for sustainable clean e-mobility. Finally, Section 5 draws the conclusion.

## **2. Stator Configurations**



*Figure 3 Classification of Different Stator Topologies of Traction Motors*

Stator topologies developed for e-mobility application determine the dimensions necessary to achieve continuous varying demand over the drive cycle. Stator of permanent magnet synchronous motor used in traction motor differs from that of conventional motor so that it develops power and torque to extended speed range without arbitrating thermal and mechanical envelop limits. Different stator configurations adopted by traction motor manufacturers as shown in Figure 3 are the geometrical design required to defeat development challenges.

### **2.1. Stator Topologies based on Magnetic Flux Paths**

Topology change is mainly based on structural difference employed to direct the magnetic flux path parallel or perpendicular to shaft. In contrast to conventional radial flux stator, for peak torque demand, axial flux segmented stator delivers high torque in extended speed range, whereas transverse flux claw pole structure delivers highest torque in low speed range because of different induced voltage limit restrained by number of poles in each type [2]. Dual stator radial flux and axial flux motor with ferrite magnets exhibit the strong performance traits for torque-power density referred to rare earth magnet motors as both stator topologies possess adequate resilience to irreversible demagnetization of the ferrite magnets [3]. In addition, axial flux permanent magnet motors (AFPM) deliver better performance than radial flux permanent magnet (RFPM) motos where axial space is the constraints compared to radial space [4]. For equal outer radial space, axial flux motor delivers 140% higher power density with 30% shorter

length compared to radial flux motor [5]. The main reason for improved performance in AFPM motor is the high average torque and low flux pulsation over airgap compared to RFPM [6].

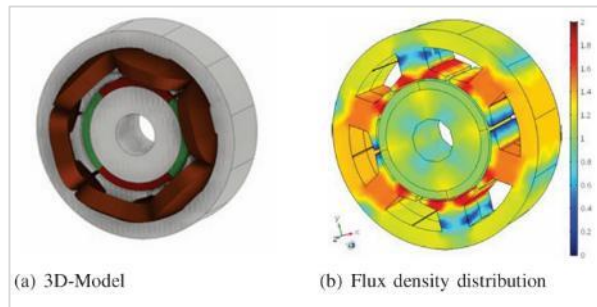


Figure 4 Radial Flux Motor [5]

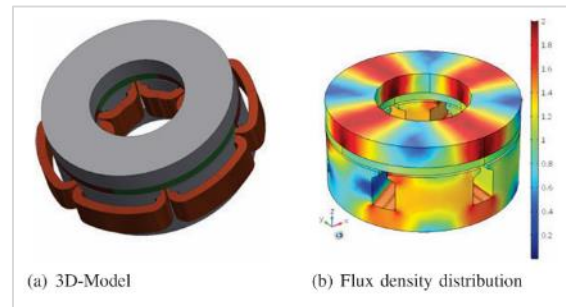


Figure 5 Axial Flux Motor [5]

Transverse flux permanent magnet (TFPM) motor with lamination stator core arranged along rotational direction presents a novel topology alongside soft magnetic composite (SMC) material made C-type stator core topology. Modularity of lamination stator core in TFPM motor offers huge flexibility in direct drive applications [7]. Coreless AFPM motor with segmented combined lamination stator structure delivers better efficiency due to lower combined iron loss [8].

## 2.2. Stator Topologies based on Arrangement

Another topology difference in the stator structure is mainly determined by number of stators used. Single stator motor and double stator motor are two design traits widely adopted in traction applications to utilize radial space to keep tradeoff between high power density and overload capacity in compact size. In single stator design, one stator is employed either outer or inner side of rotor, wherein double stator design, two stators are employed on both side of rotor. For same 36 slot/42 pole combination and stator diameters, an outer rotor structure permanent magnet motor with double stator delivers 92% more output torque compared to single stator due to better permanent magnet utilization [9]. Rational power distribution between inner stator winding and outer stator winding in double stator topology is the fundamental design attribute usually looked after for low speed-large torque and high speed-low torque motor [10].

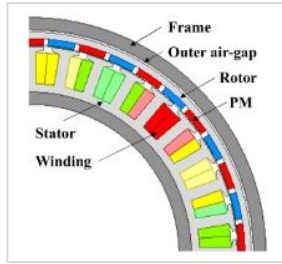


Figure 6 Single Stator Permanent Magnet Motor [9]

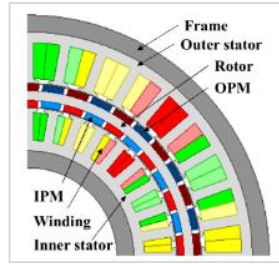


Figure 7 Double Stator Permanent Magnet Motor [9]

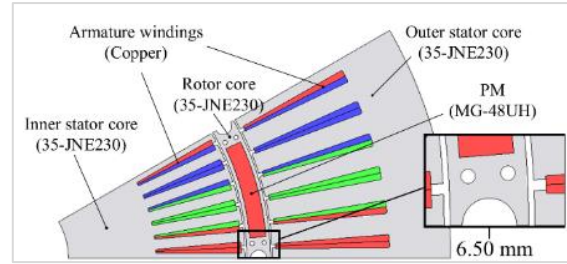


Figure 8 Double Stator Permanent Magnet Motor with Hollow Rotor [11]

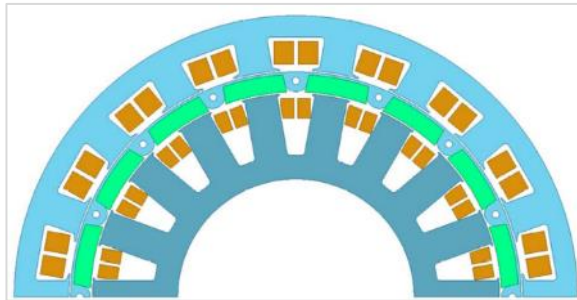


Figure 9 In-wheel Double Stator Permanent Magnet Motor [12]

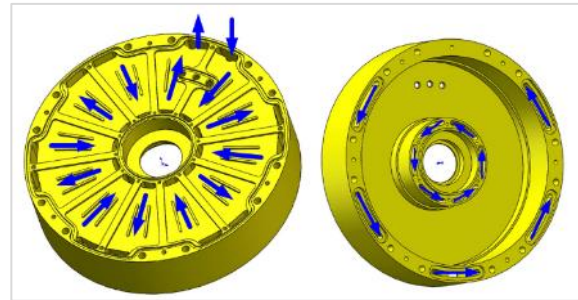


Figure 10 Water Cooling Circuit Arrangement [12]

Double stator improves power by 144.9% for same magnetomotive force and 77.6% for different magnetomotive force design due to added space available for inner stator in hollow rotor permanent magnet motor [11]. However, heat dissipation from inner stator to surroundings through outer stator is handling limitation for double stator motor. Water entering from axial cooling circuit of outer stator and flowing into axial cooling circuit of inner stator through end cooling circuit keeps thermal behaviour of motor within limit [12].

### 2.3. Stator Topologies based on Winding Technology

Furthermore, stator topology difference is governed by winding technology employed to house conductors in stator slots. A tradeoff selection between random winding and hairpin winding is mainly carried out considering thermal stability, manufacturability and production cost. A round aluminum conductor concentrated coil winding reduces winding loss without increasing winding weight due to low DC winding loss [13]. In contrast to random winding, hairpin winding delivers 27.1% more peak power density with 21.6% reduction in volume due to high slot fill factor [14]. A continuous hairpin winding with open slot and semi magnetic wedges deliver performance as compatible as conventional dis-continued hairpin winding [15]. Variable conductor cross-sections or segmented conductor cross-sections are the design considerations usually adopted for hairpin winding for performance improvement and cost effective production [16].



Figure 11 Conductors for Random Winding and Hairpin Winding [16]

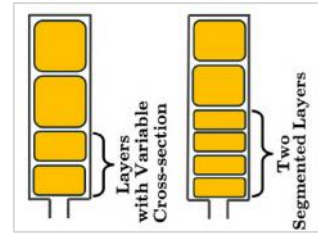


Figure 12 Hairpin Winding Configurations [16]

However, selection of different winding topologies governs the current density limits and thermal performance of the motor. Random winding with low slot fill factor suffers from high thermal stress but preferred in high frequency operation due to low eddy current loss, whereas on the contrast, hairpin winding with high slot fill factor aids low thermal stress but not preferred in high frequency operation due to complex manufacturing and high eddy current loss [17]. In contrast, hairpin winding improves 1% efficiency for rated load and mid speed range compared to random winding due to lower DC resistance and longer active conductor length [18].

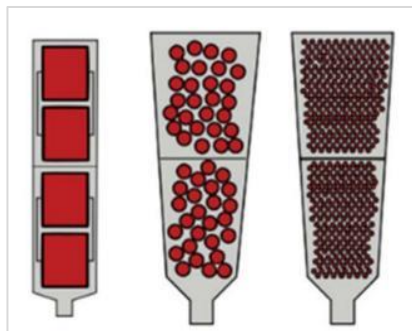


Figure 13 Slot Area of Hairpin, Random and Litz Winding [17]

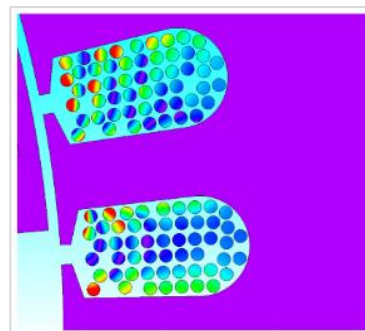


Figure 14 Current Density Distribution in Random Winding [18]

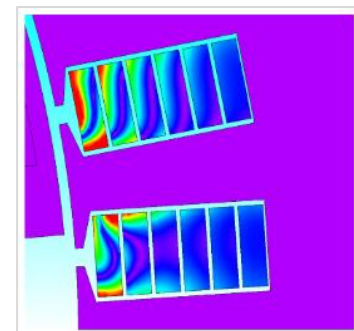


Figure 15 Current Density Distribution in Hairpin Winding [18]

Winding technology not only affects thermal performance at one duty point operation, but it has great impact over complete drive cycle operation. Segmented hairpin winding reduces AC loss up to 20% during Highway Fuel Economy Test (HWFET) drive cycle for high frequency application. [19]. For the same target specification, hairpin winding reduces 21.6% volume, 17.4% active mass and increases 28.1% peak power density compared to random winding [20].

### 3. Stator Design Variables

Stator dimension optimization determines required radial space, slot geometry, slot-pole combination and winding configuration to achieve electrical, magnetic and thermal performance of traction motor. Design optimization not only enhances air gap flux density, back EMF, efficiency, constant torque-speed and power-speed range but also keeps parasitic

effects such as cogging torque, torque ripple, noise, vibration, weight and size within limit. Stator design variables presented in Table 1 summaries performance indicators associated with energy efficient e-mobility traction motor.

### 3.1. Stator Inner Diameter and Outer Diameter

Radial dimensions such as inner diameter and outer diameter are key performance indices for flux density, current density, magnetic saturation, winding loss and temperature rise limit of permanent magnet synchronous motor. An increased split ratio (inner diameter to outer diameter of stator) improves power density of motor due to more available space in rotor to embed permanent magnet accompanied by high winding loss and current density [21]. Minimum AC winding loss is one of the design attributes that mainly governs the stator diameters. With the increase in stator diameter winding loss reduces significantly, however following certain value winding loss increases with the increase in diameters [22]. Wherein, small high speed application iron loss increases with all split ratio and winding loss increases with small split ratio. 3slot/2pole motor experiences severe effect of rotor eddy current loss in comparison to 6slot/2pole machine as split ratio increases [23]. Machine learning based integrated logarithmic regression across variable poles (ILRVP) design framework enables split ratio optimization for efficiency and cost in timely manner [24].

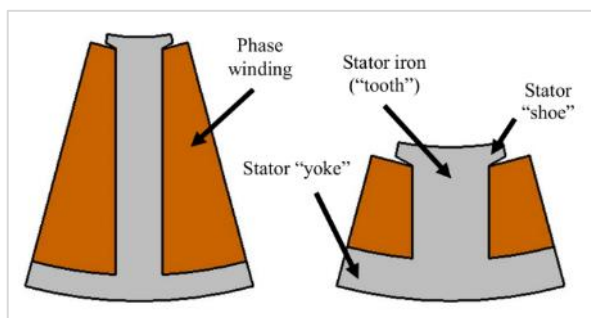


Figure 16 Stator Split Ratio Scaling [25]

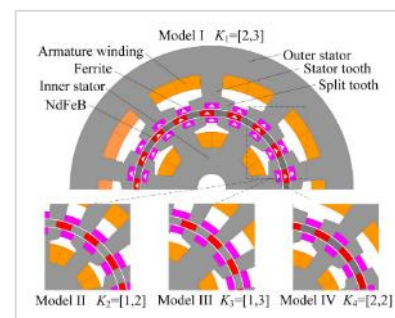


Figure 17 Dual Stator Machine with Different Split Ratios [26]

For invariant thermal conductivity, split ratio optimization using scaling of electromagnetic parameter and stator loss ensures extended power-speed range along with efficient utilization of active material and magnet [25]. Hybrid magnet dual stator field modulation machine (HMDSFMM) with split ratio combination  $K_1 = [2, 3]$  delivers highest torque and back EMF and lowest torque ripple, magnet demagnetization and saturation compared to split ratio combinations  $K_2 = [1, 2]$ ,  $K_3 = [1, 3]$  and  $K_4 = [2, 2]$  due to employment of high number of turn, winding factor and hybrid magnet excitation [26].

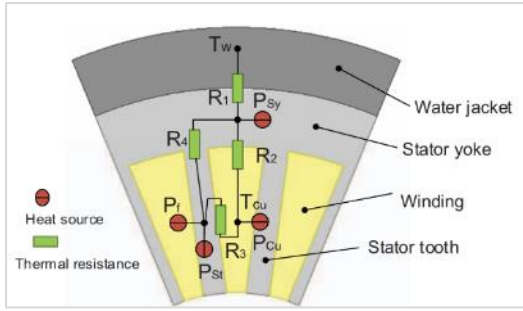


Figure 18 Thermal Resistance Network [27]

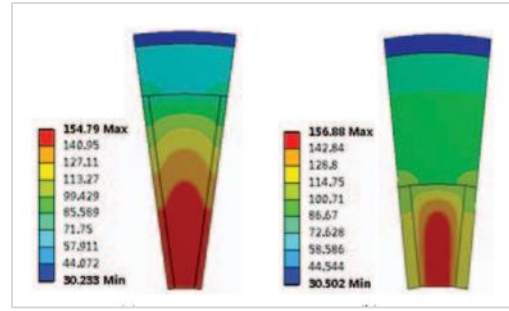


Figure 19 Temperature Distribution with Different Split Ratio [27]

Thermal resistance network (TRN) based split ratio optimization to produce maximum output torque under allowable maximum temperature rise demonstrates increase in copper loss due to reduced thermal resistance from coil to coolant as split ratio increase [27].

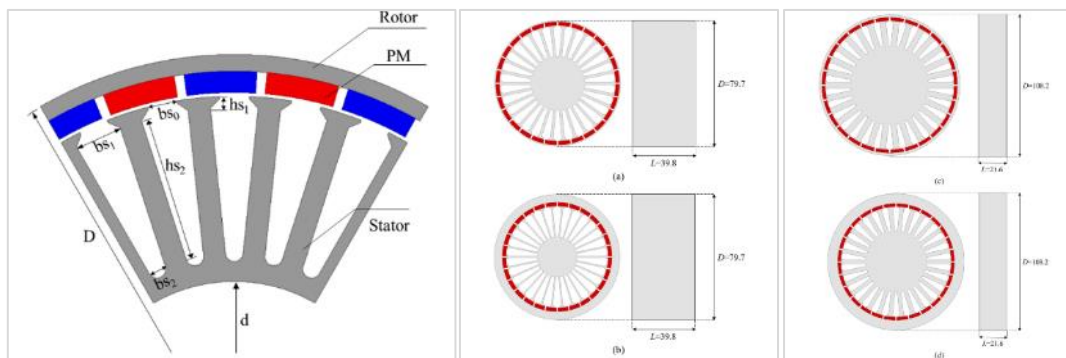


Figure 20 External Rotor PMSM [28]

Optimization of split ratio along with rotor diameter to axial length ratio has minimum impact on motor volume for target output torque for fixed electrical loading and magnetic loading in external rotor permanent magnet synchronous motor (ER-PMSM) [28].

### 3.2. Stator Slot Geometry

Stator slot shape and dimensions are the significant measures of electrical, magnetic, thermal and mechanical behaviour of permanent magnet motor. Improved slot design ensures performance attributes do not overstep the limits. Rounded semi close stator slot dimension optimization using Taguchi method proposes set of slot geometries that achieve performance requirement such as torque, efficiency, stator thermal load, current density, flux density, torque ripple and noise [29]. Slot structure not only enhances the power and torque density, but it attains nearly sinusoidal airgap flux distribution. Improved slot geometry reduces 1.97% torque ripple, 94.21% cogging torque and increases 14.72% torque, 14.76% power and 1.85% efficiency compared to conventional slot geometry [30]. Dipper and wider slot structure offers low starting current and its total harmonic distortion (THD) compared to shorter and narrow

slot structure due to more slot area available to accommodate copper for target specification [31]. Optimized stator slot design carried out for integrated starter generator (ISG) used for ground and aerial vehicle delivers 91% efficiency in generating mode and 52% efficiency in motoring mode. In generating mode operation flux density reduces and leakage reactance increases compared to motoring mode [32]. Improved leakage flux and saturation in open slot stator topology developed for radially magnetized stator slot opening permanent magnet (RMSS PM) machines, tangentially magnetized stator slot opening permanent magnet (TMSS PM) and compound magnetized stator slot opening permanent (CMSS PM) machine, offers low-speed and high-torque, wide speed range and high torque density respectively [33].

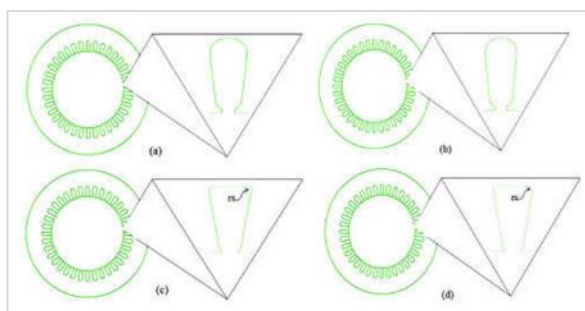


Figure 21 Semi Closed Stator Slots [29]

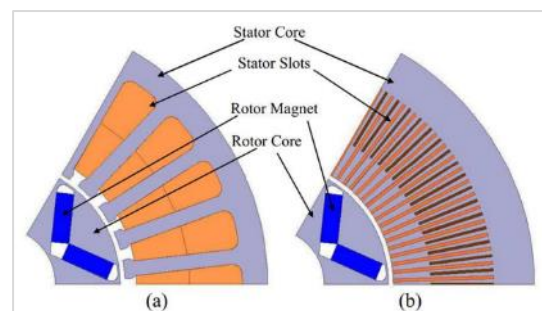


Figure 22 Motors (a) Conventional Slot (b) Improved Slot [30]

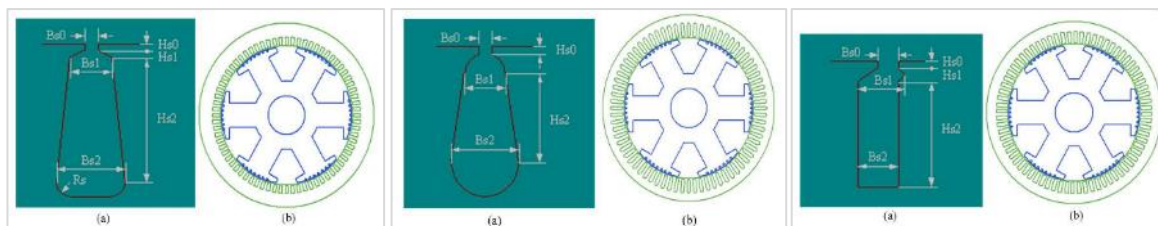


Figure 23 Stator Slot Geometry [31]

Open slot arrangement not only impacts the flux distribution, but it also eases the manufacturing as pre-formed winding coils are effortlessly inserted in slot and some extent improves the heat dissipation of the machine [34]. Whereas fully closed slots with all equal tooth width (ETW) demonstrate low torque ripple compared to alternate equal tooth width (ETW) stator topology due to symmetric tooth saturation [35].

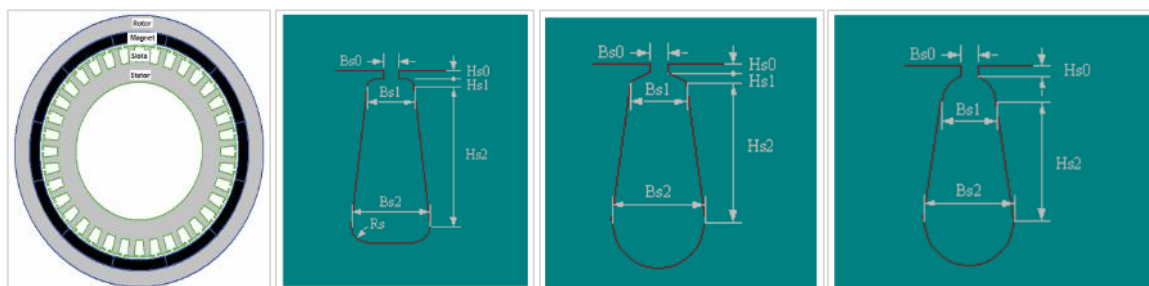


Figure 24 Outer Rotor BLDC based Integrated Starter Generator (ISG) [32]

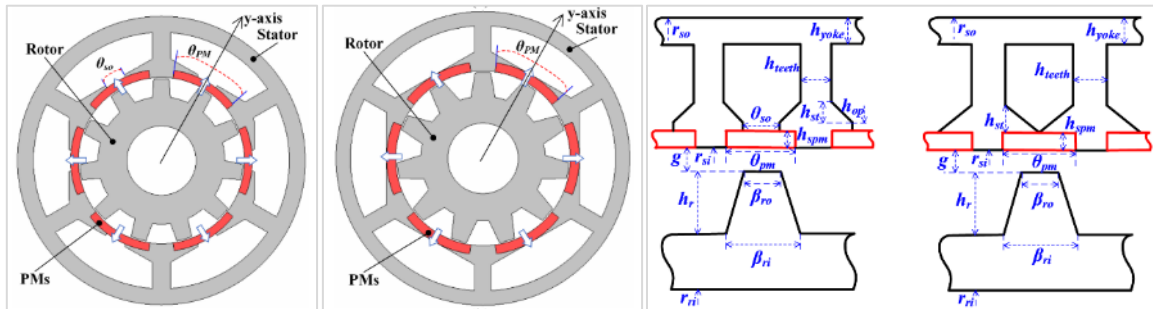


Figure 25 Stator-consequent-pole Permanent Magnet (SCPPM) with Semi-closed and Closed Slot [36]

Though semi-closed slot stator topology suffers from non-uniform airgap flux distribution and high harmonic compared to closed slot stator topology, widely adopted due to manufacturing ease and cost efficiency [36]. Electromagnetic force optimization through stator slot dimension reduces maximum vibration speed of the motor by 12.2%. Vibration harmonic response model helps to mitigate the vibration and confirms the fitness of slot structure [37].

### 3.3. Stator Slot/Pole Combination

Stator slot/pole combination is the fundamental measure of flux distribution, back EMF, torque-speed density, power-speed density, loss distribution, cogging torque and torque ripple in permanent magnet synchronous motor. Drive cycle of high power density traction motor used in heavy vehicle enables competent operation in both constant torque speed range (CTSR) and constant power speed range (CPSR) due to improved field weakening control. Effective magnet flux weakening through slot/pole combination and magnet arrangement in rotor delivers five times extended speed than base speed [38]. However, slot/pole combination selection is the tradeoff between motor size, cogging torque, torque ripple and radial force constraint [39]. Given slot number, pole number greatly influences the magnet volume and efficiency [40].

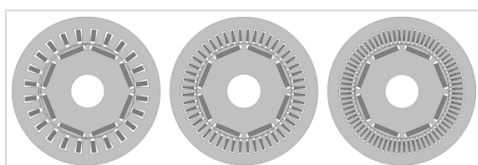


Figure 26 Stator Slot/Pole Geometry for IPMSM [38]

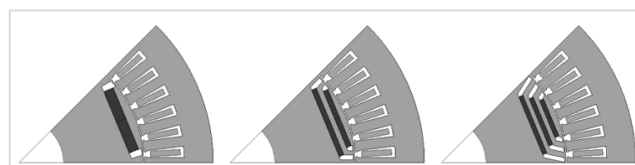


Figure 27 Rotor Magnet Layers [38]

High speed permanent magnet synchronous motor with 2pole proposes elevated efficiency, high rotor structural strength and better manufacturability. Large number of stator slot and

small air gap length significantly reduces the rotor loss [41]. Higher number of slot/pole combination delivers smooth torque profile because of lower airgap field periodicity. 24slot/28pole combination improves range of low speed electric bike conversion kit used in urban terrain road. [42]. Numerical value of slot per pole per phase  $q=1/11$  produces low vibration whereas winding configuration impact torque ripple. 72slot/66pole combination with semi-symmetric double layer winding reduces torque ripple up to 0.129% compared to other combination due to high winding coefficient [43].

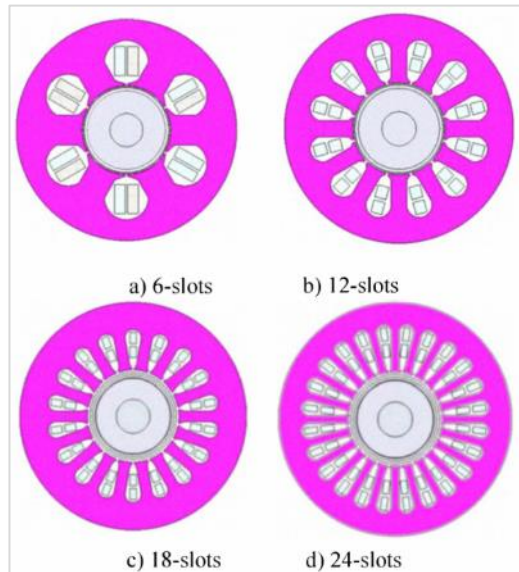


Figure 28 Stator Slot Geometries for 2pole Motor [41]

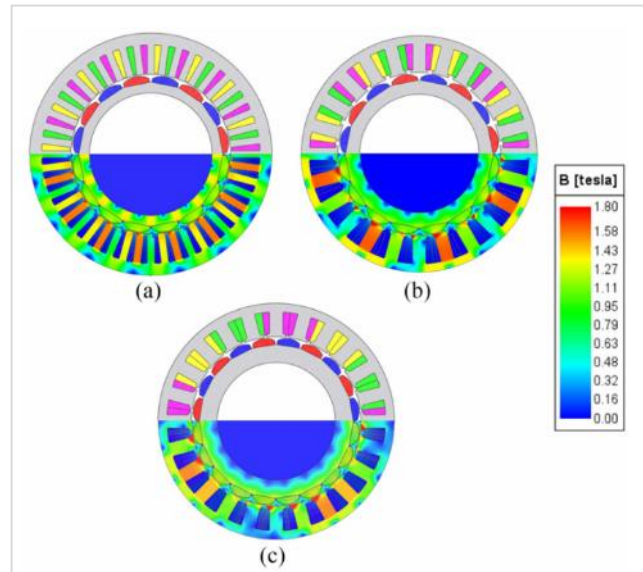


Figure 29 Stator Slot/Pole Geometry for SPMSM [45]

Slot/pole combination and permanent magnet arrangement in rotor optimization using high fidelity numerical method identifies a unique option for material savings, loss reduction and stable permanent magnet operation constraints [44]. Lumped parameter thermal network (LPTN) based analysis of permanent magnet synchronous motor for marine application suggests that for each slot/pole combination noise and vibration is more dependent on vibration mode order than electromagnetic force magnitude. Underwater radiated noise (URN) of the motor reduces for a slot/pole combination which generates high vibration mode order [45]. Number of poles greatly influences cogging torque and stator iron loss especially for surface permanent magnet motor due to direct exposed orientation of permanent magnet to the stator tooth. Effect gets worse as the speed of motor increases. Stator iron loss and magnet loss in 48slot/40pole motor is increased by 3175 Watt and 425 Watt respectively compared to 48slot/4pole motor due to increased volume of material [46].

Design variables and their impact on performance indicator presented in Table 1 shows that how multi-dimensional design optimization approach not only achieves the target specification

but also enables reliability, durability, scalability and sustainability for smallest 0.385 kW, 180 RPM, 3slot/2pole to largest 1.5 MW, 110000 RPM, 96slot/94pole specification. Comparison across variables also highlight the range of values derived for permanent magnet motor used in diverse application

Table 1 Performance Indicators Associated with E-Mobility Motor

Design Variables	Target Specifications	Value	Performance Indicators	Ref.
<b>Stator Diameter</b>	35 kW, 36slot/6pole	Inner Diameter = 152 mm Outer Diameter = 240 mm	Winding Loss (Copper Loss), Stator Tooth and Yoke Flux Density, Current Density, Thermal Load	[21]
	48slot/8pole	Inner Diameter = 132 mm Outer Diameter = 198 mm	Winding Loss	[22]
	110000 RPM, 3slot/2pole and 6slot/2pole	Outer Diameter = 50 mm	Winding Loss, Core Loss (Iron Loss), Rotor Eddy Current Loss, Windage Loss, Slot/pole Combinations, Magnet Materials	[23]
	18slot/20pole	Inner Diameter = 66 mm Outer Diameter = 96 mm	Fill Factor, Residual Flux Density, Average Torque, Number of Pole	[24]
	10 kW, 12slot/10pole	Outer Diameter = 200 mm	Coil Turns, Fill Factor, Current Density, Maximum Output Power as a Function of Speed	[25]
	176 RPM, 9slot/2pole-6slot/2pole, 18slot/2pole-9slot/2pole, 18slot/2pole-6slot/2pole and 9slot/2pole-9slot/2pole	Outer Stator Outer Diameter = 140 mm  Inner Stator Outer Diameter = 70 mm	Flux Density, Back EMF, Harmonic Distortion, Steady State Torque, Cogging Torque	[26]
	200 kW, 40000 RPM, 24slot/2pole	-----	Winding Loss (Copper Loss), Iron loss (Core Loss), Friction Loss, Torque	[27]
	30slot/28pole	-----	Torque, Winding Loss (Copper Loss), Iron loss (Core Loss), Efficiency, Flux Density	[28]
<b>Stator Slot</b>	14 kW, 30000 RPM, 4pole	hs0 = [0.4 0.5 0.5 0.3] mm hs1 = [---- 0.5 0.5 0.5] mm hs2 = [8.0 8.5 8.0 8.5] mm bs0 = [1.5 1.5 1.5 1.5] mm bs1 = [5 4 4 4] mm bs2 = [7 6 6 6] mm	Winding Loss (Copper Loss), Iron loss (Core Loss), Friction Loss, Torque	[29]
	0.565 kW, 1800 RPM	27slot/6pole 198slot/6pole	Torque, Power, Airgap Flux Density, Back EMF, Saliency Ratio, Cogging Torque, Torque Ripple, Efficiency	[30]
	-----	hs0 = [0.76 0.76 0.76] mm hs1 = [2.17 ---- 2.17] mm	Torque Ripple, Solid Loss, Stator Current, Total Harmonic Distortion	[31]

		$hs2 = [29.4 \ 45.0 \ 45.0]$ mm $bs0 = [3.9 \ 3.9 \ 3.9]$ mm $bs1 = [11 \ 4 \ 12.0 \ 15.0]$ mm $bs2 = [15 \ 15 \ 15]$ mm	(THD)	
	5.6 kW, 36slot/12pole	Motoring = 1000 RPM Generating = 6000 RPM Slot Area = $[75.75 \ 88.9 \ 113.86]$ mm <sup>2</sup>	Flux Density, Efficiency, Leakage Reactance	[32]
	2000 RPM, 12slot/10pole	-----	Torque, Torque per Magnet Usage, Power Factor, Efficiency	[33]
	1700 RPM, 24slot/28pole	Trapezoidal Slot Parallel Slot	Temperature Rise	[34]
	400 RPM 12slot/10pole and 12slot/14pole	Stator Yoke Thickness = $[4 \ 4 \ 4]$ mm Stator Tooth Width = $[8 \ 8 \ 8 \ 10^a \ \text{and} \ 6^b]$ mm # a tooth with a coil and b tooth without a coil Turns per Phase = $[184 \ 92 \ 184 \ 184]$	Torque, Torque Ripple, Back EMF	[35]
	6slot/11pole	$hyoke = [5.6 \ 4.9]$ mm $h_{teeth} = [6.6 \ 5.6]$ mm $h_{st} = [3.0 \ 3.5]$ mm $h_{spm} = [2.5 \ 3.1]$ mm $rsi = [57.6 \ 59.4]$ mm $hr = [6.3 \ 8.0]$ mm	Flux Density, Torque, Cogging Torque, Torque Ripple, Back-EMF	[36]
	50 kW, 1500 RPM, 28slot/4pole	Tooth Width Tooth Height	Electromagnetic Force, Vibration, Harmonics	[37]
<b>Stator Slot/Pole</b>	300 kW (max.), 1800 Nm (peak), 1591 RPM, 8pole	Slot = $[24 \ 48 \ 72]$ Magnet Layer = $[1 \ 2 \ 3]$	Torque Ripple, Efficiency, Power Factor, Operating Region, Field Weakening Area	[38]
	70 kW (max.), 210 Nm (peak), 8000 RPM (max.)	42slot/8pole 48slot/8pole 54slot/8pole 60slot/8pole	Cogging Torque, Torque Ripple, Radial Force	[39]
	90 kW, 1500 RPM	72slot/4pole 72slot/6pole 72slot/8pole	Winding Loss (Copper Loss), Iron Loss (Core Loss), Efficiency, Reluctance Torque, Magnet Weight	[40]
	7.5 kW, 30000 RPM	6slot/2pole 12slot/2pole 18slot/2pole 24slot/2pole	Rotor Loss, Torque Ripple	[41]
	0.385 kW, 420 RPM	18slot/20pole 36slot/34pole 18slot/16pole	Torque, Power, Efficiency	[42]

		24slot/28pole		
	1.5 MW, 180 RPM, 12-phase	96slot/88pole 96slot/92pole 96slot/94pole	Torque, Torque Ripple	[43]
	14 kW (max.), 50 Nm (peak), 18000 RPM (max.)	60slot/10pole 72slot/12pole 96slot/8pole Rotor Layout = [Flat V]	Torque, Back EMF, Efficiency	[44]
	50 kW, 1800 RPM	48slot/16pole 24slot/16pole 24slot/20pole	Torque, Back EMF, Winding Loss (Copper Loss), Permanent Magnet Eddy Current Loss, Electromagnetic Force, Noise, Vibration	[45]
	50 kW, 1950 RPM	48slot/4pole 48slot/40pole	Torque, Flux Density, Cogging Torque, Torque Ripple, Back-EMF, Winding Loss (Copper Loss), Iron Loss (Core Loss), Magnet Loss	[46]

#### 4. Stator Development Trends and Challenges

Automotive market is experiencing fastest growth in urban mobility due to adoption of electric vehicle. The main directives for growth are supportive government policies and technological innovations. The demand for development of more energy efficient traction motor emphasis on active research and development of new motor topology, innovative materials, precision manufacturing and advanced testing facility. Traction motor stator development is still challenged by tradeoff balance between high power-torque density, elevated efficiency, extended speed, effective thermal management, compact size, light weight and lowest cost. As the powertrain of vehicle dominates the major share of vehicle cost, efficiency directly affects the range and so motor topology [47]. Multiphase motor (MPM) is considered as the answer to all issues like superior power output, lower harmonic content and high fault tolerance. However, classical motor controller topologies are not competent of operate MPM, development of multiphase motor and controller is still a biggest challenge automotive industry is facing [48].

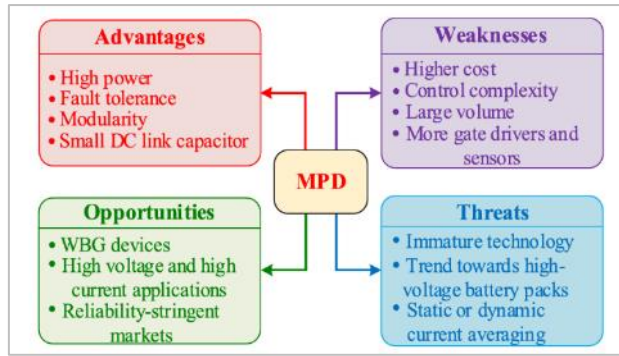


Figure 30 Multiphase Motor Development Tradeoff [48]

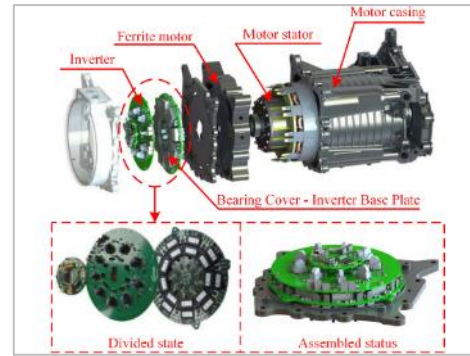


Figure 31 Integrated Nine-Phase Drive System for EV [48]

Temperature sensing throughout operation and dynamic optimization of thermal limits during vehicle run is very critical task. Development of motor under low thermal band and temperature modelling techniques are still hard to overcome [49]. Prediction of accurate value of characteristic current to determine field weakening performance and constant power speed range is critical. Multi-objective design optimization approach with price estimation of direct axis flux linkage under saturation and least computation cost are the main constraints [50].

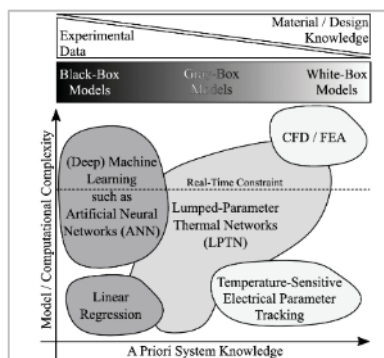


Figure 32 Motor Thermal Modelling Techniques [49]

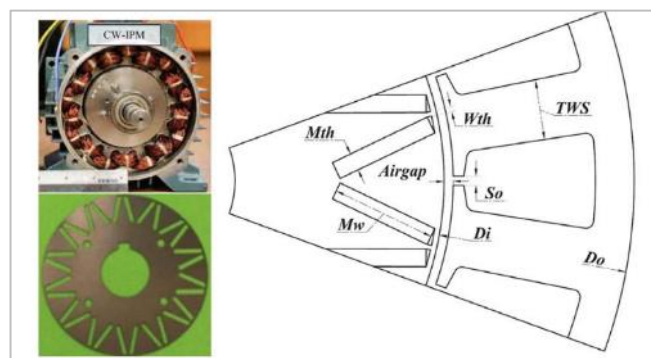


Figure 33 Fractional Slot Concentrated Wound (FSCW) Motor [51]

Least accuracy in estimation of inductances due to assumptions made in conventional method whereas high computational cost in estimation of inductances due considerations of iron core saturation, cross-magnetization effects and variation of inductances with respect to rotor positions are the challenges addressing the effect of saliency ratio in design optimization of interior permanent magnet machine [51]. Low magnet energy, irreversible demagnetization and inferior mechanical strength of ferrite permanent magnets are still cost versus efficiency constraints holds back from using it commercially compared to rare earth based motor [52]. An unequal bridge opening method developed for spoke type ferrite permanent magnet rotor reduces 26% torque ripple and 6% voltage THD compared to conventional skewed rotor method. Compared to laminated rotor, 3D printed rotor performance of spoke type motor marks 100% material waste saving but, deescalated performance during high speed operation due to

eddy current loss in rotor [53]. Electrical machines' thermal management methods using additive manufacturing opens new doors for design freedom and complex geometries. However, low production rate, high cost, small size and fewer materials restrict the additive manufacturing of all components of motor [54].

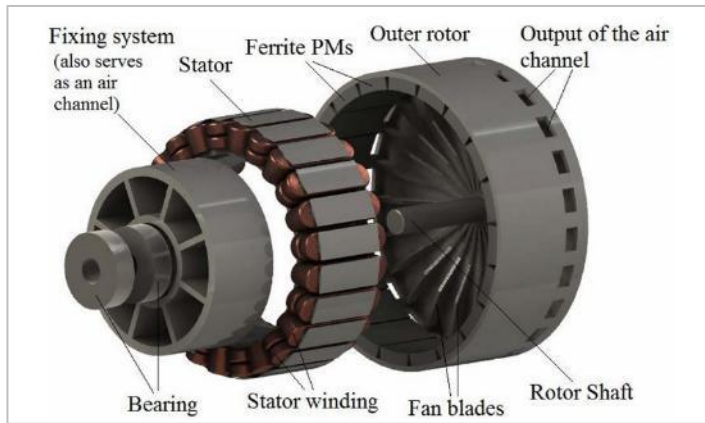


Figure 34 Fe-Based Outer Rotor Permanent Magnet Machine [52]

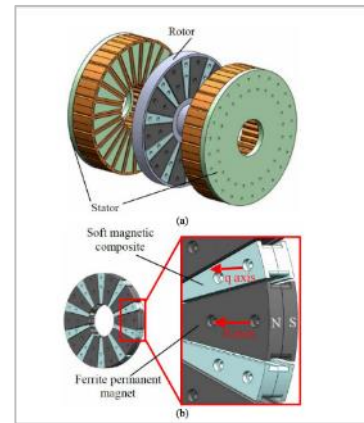


Figure 35 Fe-Based Disk Type PM Machine [52]

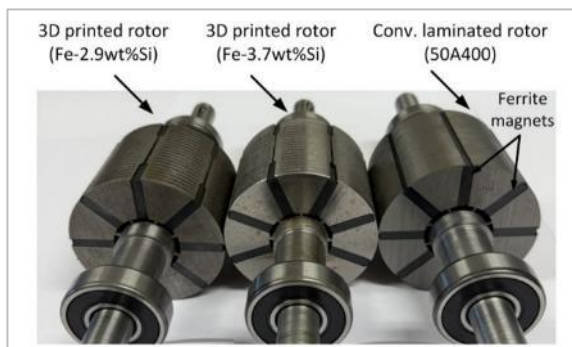


Figure 36 3D Printed and Traditional Laminated Rotor [53]

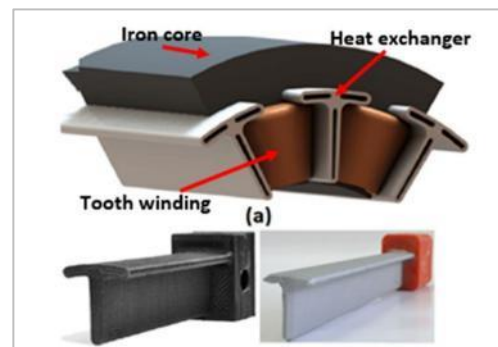


Figure 37 Concept Design of Direct Winding Heat Exchange [54]

Interturn connection is the challenge traction motor winding technology presently facing as large number of conductor strands needs to be handled in random winding whereas shaping, assembling, twisting and connecting production stages needs to be handled in hairpin winding. Both the technology involves two stage process, insulation removal and joining of conductor, performed under different environment and temperature. Optimization of welding depth to reduce contact resistance using infrared lasers technology enables hairpin winding adoption for unmanned series production at a high financial cost [55].

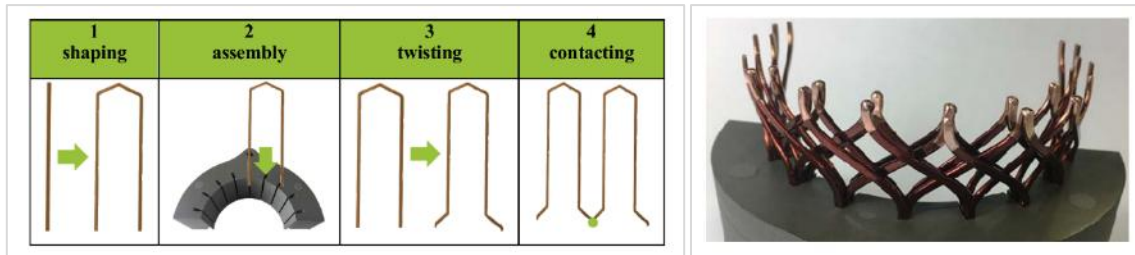


Figure 38 Production of Hairpin Winding [55]

Permanent magnet motor with fractional slot winding in segmented stator slot is perfect fit for heavy duty vehicle, home appliance, marine propulsion and wind applications due to short winding overhang and high slot fill factor even though it is ineffectual to deliver low cogging torque and uniform airgap flux distribution [56].

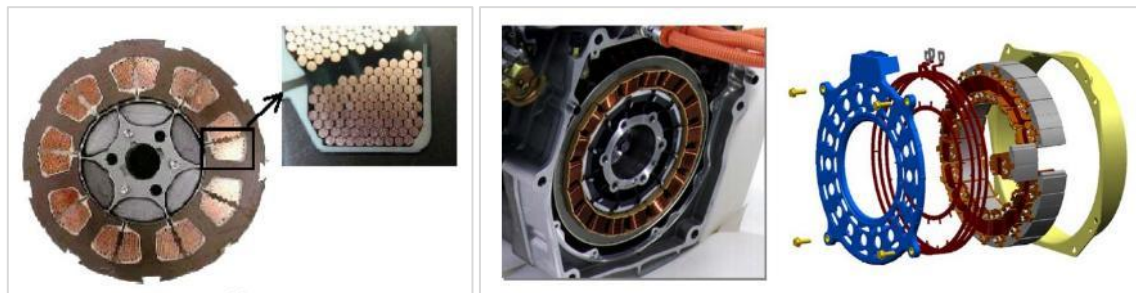


Figure 39 Fractional Slot Concentrated Windings [56]

Genetic algorithm base motor design approach not only improves stator performance but also enhances rotor performance. It enables impact of small change on performance especially for complex motor topologies [57]. Recyclable material based motor design strategy rather than focusing on “what is technically best” without compromising the target specification is the new development trend that can be more adaptable to urban mobility vehicle [58].

## 5. Conclusion

This review provides an overview of different stator development trends based on topologies considering magnetic flux path, stator arrangement and winding technology. It also discusses the effect of stator design variables such as diameter, slot geometry and slot/pole combinations on performance indicators such as gap flux density, back EMF, winding loss, iron loss, magnet loss, cogging torque, torque ripple, noise, vibration, size and weight. Furthermore, it highlights advancements and challenges associated to material development, performance optimization and modern manufacturing. In conclusion, a review of the literature confirms that continuous advancements in stator topologies are occurring day by day, and these developments are

expected to further improve the performance capabilities of permanent magnet synchronous motors used in e-mobility applications.

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**RECENT ADVANCES IN NON-ISOLATED BIDIRECTIONAL DC–DC CONVERTER TOPOLOGIES FOR PLUG-IN HYBRID ELECTRIC VEHICLE CHARGING SYSTEMS: A LITERATURE REVIEW**

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**Abstract**

The rapid growth of plug-in hybrid electric vehicles (PHEVs) has intensified the demand for efficient, compact and cost-effective power electronic interfaces for on-board and off-board charging systems. Among these, non-isolated bidirectional DC–DC converters play a critical role by enabling controlled power flow between the battery pack and the DC link during charging, discharging and regenerative operation. This paper presents a comprehensive literature review of recent advances in non-isolated bidirectional DC–DC converter topologies developed for PHEV charging applications. The review systematically categorizes conventional and emerging converter structures, including buck–boost, interleaved, multi-phase, switched-capacitor and coupled-inductor based topologies. Key performance metrics such as efficiency, voltage gain, power density, component stress, ripple characteristics, control complexity and scalability are critically analysed and compared. Furthermore, recent developments in wide-bandgap semiconductor integration, soft-switching techniques and advanced control strategies are discussed in the context of improving system performance and reliability. The paper also highlights current challenges, design trade-offs and research gaps, providing insights into future trends and potential directions for next-generation PHEV charging systems. This review aims to serve as a valuable reference for researchers and engineers engaged in the design and optimization of bidirectional DC–DC converters for electric vehicle applications.

**Keywords:** Non-isolated bidirectional DC–DC converter, Plug-in hybrid electric vehicle (PHEV), Battery charging systems, Bidirectional power flow, High-efficiency power conversion, Electric vehicle power electronics.

**1. Introduction**

The rapid growths of the automotive sector and the increasing concerns regarding fossil fuel depletion and environmental pollution have accelerated the development of electric mobility solutions, particularly Plug-in Hybrid Electric Vehicles (PHEVs). PHEVs integrate both an

internal combustion engine and an electric propulsion system, requiring efficient power conversion interfaces between the battery pack and the DC bus. Among these interfaces, bidirectional DC–DC converters play a crucial role in managing energy flow during charging and discharging operations. . [1,2,3]

In recent years, non-isolated bidirectional DC–DC converter topologies have gained significant attention due to their high efficiency, compact size, reduced cost, and simplified structure compared to isolated counterparts. These converters enable two-way power transfer between the high-voltage battery and low-voltage auxiliary systems, supporting functions such as regenerative braking, battery charging and vehicle-to-grid (V2G) applications. Advanced topologies such as buck–boost, interleaved, multi-phase, coupled-inductor and switched-capacitor configurations have been widely investigated to achieve high voltage gain, reduced current ripple, improved power density and enhanced dynamic performance. . [4,5]

Furthermore, modern control strategies including soft-switching techniques, digital control methods and intelligent optimization algorithms have been integrated to improve converter reliability and efficiency under varying load conditions. The continuous evolution of semiconductor devices, particularly wide-bandgap materials like SiC and GaN, has further enhanced switching performance and thermal characteristics. . [5,6]

This literature review focuses on recent advances in non-isolated bidirectional DC–DC converter topologies for PHEV charging systems, highlighting their operating principles, performance improvements, control techniques and research challenges.

## **1.1 Background**

The rapid advancement of electric mobility and the growing demand for energy-efficient transportation systems have significantly accelerated research in Plug-in Hybrid Electric Vehicles (PHEVs). PHEVs combine an internal combustion engine with an electric propulsion system, requiring efficient energy management between the high-voltage battery pack and the vehicle's DC bus. A critical component in this architecture is the bidirectional DC–DC converter, which enables controlled power flow during charging and discharging operations. . [7,8]

Non-isolated bidirectional DC–DC converters have emerged as a preferred solution in PHEV charging systems due to their compact size, reduced cost, lower component count, and higher efficiency compared to isolated counterparts. These converters facilitate essential operations

such as battery charging, regenerative braking, auxiliary power supply, and vehicle-to-grid (V2G) integration. As battery voltage levels and power density requirements continue to increase, advanced converter topologies are needed to ensure high voltage gain, reduced switching losses, low current ripple, and improved dynamic response. . [9, 10]

## 1.2 Research Problem

Despite extensive research on bidirectional DC–DC converters, existing non-isolated topologies still face challenges related to limited voltage conversion ratio, high switching stress, efficiency degradation at partial load conditions, electromagnetic interference (EMI), and thermal management issues. Moreover, many conventional designs struggle to balance high power density with reliability and cost-effectiveness, especially under dynamic operating conditions typical of PHEV charging and discharging cycles.

There is a need for a comprehensive analysis of recent advancements in non-isolated bidirectional DC–DC converter topologies to identify their performance improvements, limitations, and suitability for next-generation PHEV charging systems.

## 1.3 Research Objectives

The primary objectives of this literature review are:

1. To examine recent developments in non-isolated bidirectional DC–DC converter topologies for PHEV charging systems.
2. To compare various topologies such as buck–boost, interleaved, coupled-inductor, multi-phase and switched-capacitor configurations.
3. To analyze modern control strategies, including soft-switching techniques, digital control, and intelligent optimization methods.
4. To identify performance metrics such as voltage gain, efficiency, power density, ripple reduction and switching stress.
5. To highlight research gaps and propose potential directions for future development.

## 1.4 Significance of the Study

This study provides a structured and comparative review of recent advances in non-isolated bidirectional DC–DC converter topologies for PHEV charging systems. By identifying performance trends, technical limitations and research gaps, this review contributes to the development of more efficient, reliable and high-power-density converters. The findings are

expected to support researchers and engineers in designing optimized converter architectures suitable for next-generation electric mobility applications and smart grid integration.

## 2. Literature Review

When starting a new project on bi-directional DC-DC converters for plug-in hybrid electric vehicles (PHEVs the first questions that usually arise are about where to begin, what methods are available, and how to make design efficient).

Extensive research, including various IEEE papers and books, guides the way. In today's market, there is a growing need for PHEVs due to issues like energy security and greenhouse gas emissions, alongside the benefits of lower electricity costs.

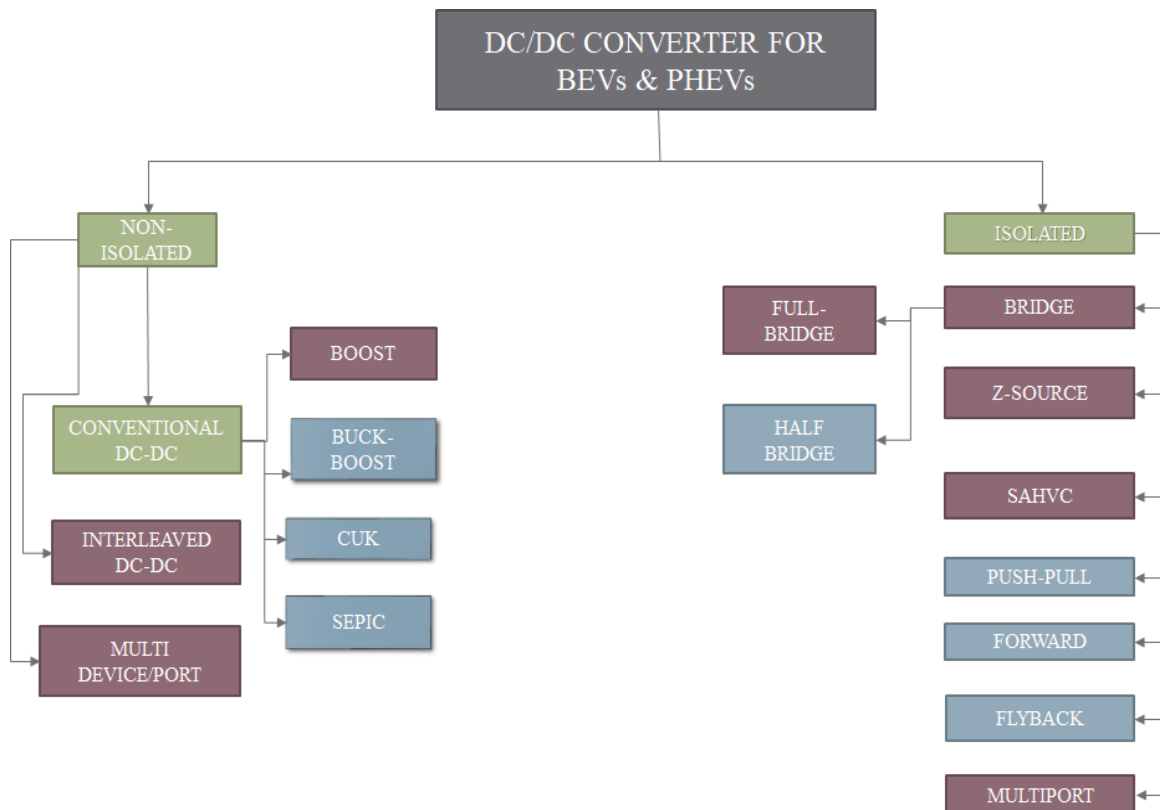
With advancements in battery technology, the demand for high-power off-board charging stations has increased, enabling faster charging for drivers. Among different types of converters, the half-bridge converter stands out for its efficiency and fewer parts compared to other converters.

The goal is to create charging stations that not only recharge PHEV batteries quickly but also incorporate energy storage systems, allowing them to operate effectively. As the industry pushes towards higher electric ranges, the design of these systems becomes crucial for the future of electric transportation.

Charge station structural engineering has been proposed, which has a DC small scale framework to interface with numerous DC to DC chargers.

Different non-isolated bi-directional DC to DC converters utilized for charge station applications. Half bridge converter is better than SEPIC, Luo and Cuk converter because of higher efficiency, smaller number of detached parts and lower exchanging current anxiety.

**3. BIDIRECTIONAL DC-DC CONVERTER TOPOLOGY** The bidirectional DC-DC converters fills the need of venture up or venture down the voltage level between its information and yield alongside the capacity of force stream in both the headings. Bidirectional DC-DC converters had discovered the applications in the region of the vitality stockpiling frameworks for Hybrid Vehicles, Uninterruptable Power Supplies and Fuel cell stockpiling frameworks. Bidirectional DC-DC converters are employed when the DC bus voltage regulation has to be achieved. One of the examples is power generation by wind or sun oriented force frameworks, where there are vast vacillations in the created force as a result of the expansive variations in the energy supply to the conversion unit (wind turbines & PV panels) by the primary source. Along these lines, the bidirectional DC-DC converter is expected to have the capacity to permit force stream in both the bearings at the controlled level. . [11, 12, 13]

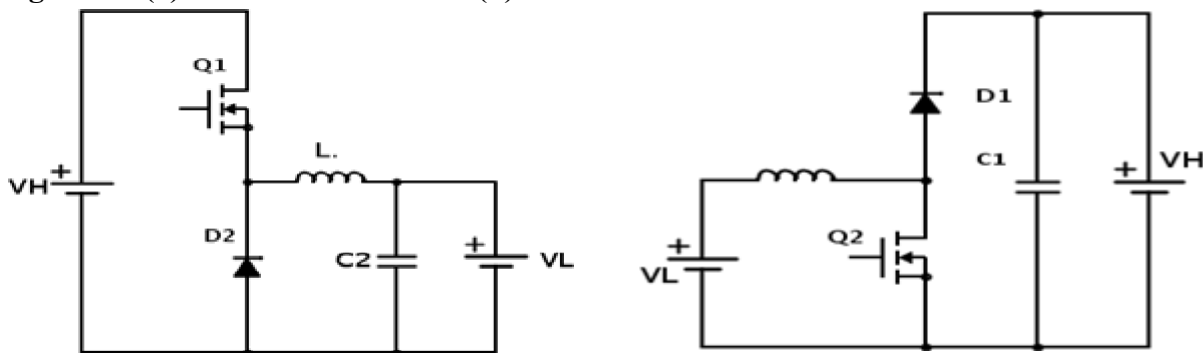


**Figure: - 1 CLASSIFICATIONS OF VARIOUS DC-DC PEC CONVERTER**

**3.1 NON-ISOLATED BIDIRECTIONAL DC-DC CONVERTERS**

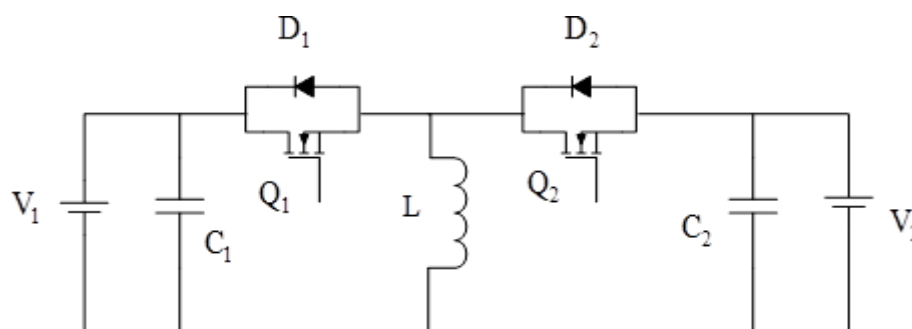
3.2 Basically a non-isolated bidirectional DC-DC converter can be derived from the unidirectional DC-DC converters by enhancing the unidirectional conduction capability of the conventional converters by the bidirectional conducting switches. Due to the presence of the diode in the basic buck and boost converter circuits shown in figure 2, they do not have the inherent property of the bidirectional power flow. This limitation in the conventional Boost and Buck converter circuits can be removed by introducing a Power MOSFET or an IGBT having an anti parallel diode across them to form a bidirectional switch and hence allowing current conduction in both directions for bidirectional power flow in accordance with the controlled switching operation. [14,15,16,17,18,19,20]

**Figure: -2 (a) Buck Converter and (b) Boost Converter**



### Buck Boost Converter

The first bidirectional topology can be directly derived from the conventional buck boost topology by the introduction of the bidirectional conducting switch as shown in figure 3. Figure 3 Bidirectional Buck Boost Converters During step up operation Switch  $Q_1$  is conducted at the required duty cycle whereas the switch  $Q_2$  is kept off all the time. Similarly during the step down operation the switch  $Q_2$  is made to conduct at required duty cycle whereas the switch  $Q_1$  is always off. Small Dead time is provided during mode transition in order to avoid the cross



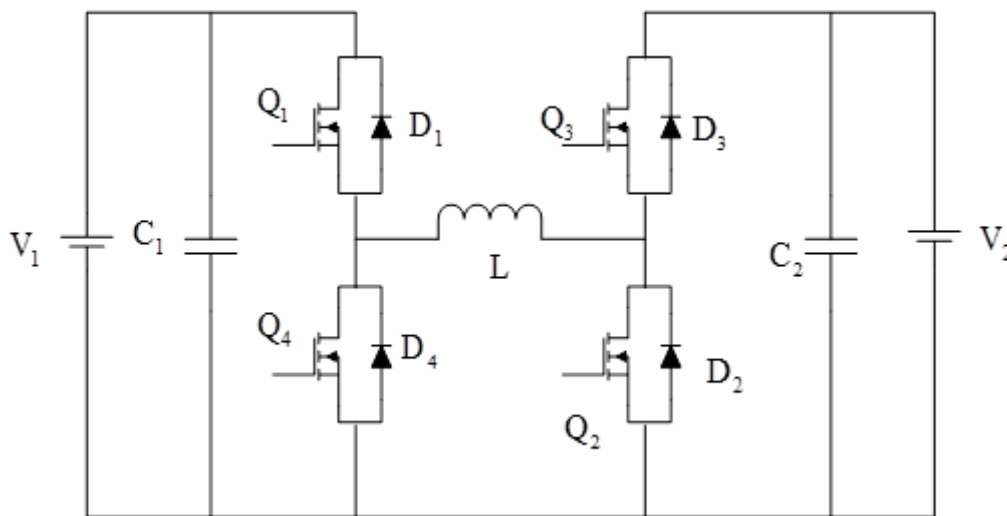
conductance through two switches and the converter output capacitance.

**Figure: -3 Bidirectional Buck-Boost Converters**

### Buck Boost Cascade Converter

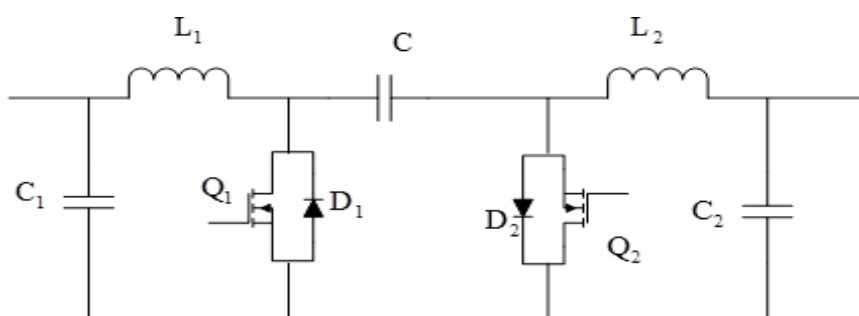
The second Bidirectional topology as seen in the figure 4 can be obtained by cascading the bidirectional buck converter with bidirectional boost converter. This topology allows the output

voltage to be either higher or lower than the input voltage depending up on the switch combinations used and the direction of the current. For the step up operation in the forward direction, the switch S1 is always on and S2 and S4 are always off, whereas the switch S2 is conducted depending on the duty cycle. During forward step down operation the switch S1 is operated with the required duty cycle and the switch S2, S3, S4 are always off. Diode D2 and D3 are always reverse biased whereas the D3 is always forward biased. Diode D4 acts as a freewheeling diode. Similarly in the backward step up operation, switch S3 is always on whereas the switch S4 is operated with the required duty cycle with the diode D1 acting as a freewheeling diode.



**Figure: - 4 Bidirectional Cascade Buck-Boost Converter**

### Cuk Converter



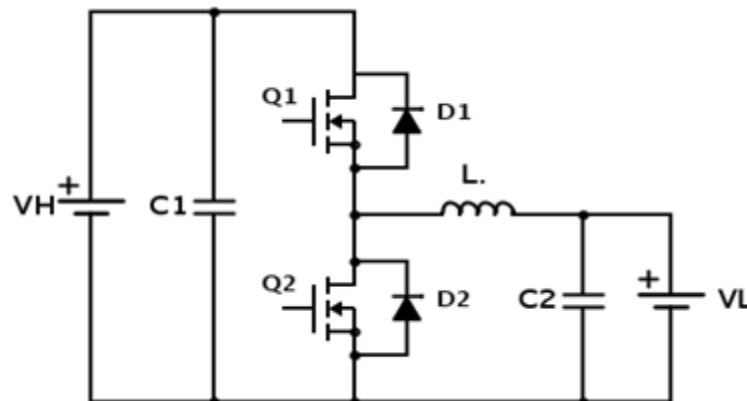
**Figure: -5 Bidirectional Cuk Converters**

The third topology is obtained by replacing the unidirectional switches of the conventional Cuk converter by the bidirectional switches. The resulting circuit is as shown in the figure 5. The capacitor C acts as the main storage element whereas the capacitors C1 and C2 act as the

coupling capacitors. It can step up or step down the input voltage like a buck-boost converter but with inverted polarity.

### Half-Bridge DC-DC converter

When the Buck and the boost converters are connected in anti parallel across each other with the resulting circuit is basically having the same structure as the fundamental Boost and Buck structure but with the added feature of bidirectional power flow. The below figure 6 shows the



basic structure of the non-isolated Half-Bridge Bidirectional DC-DC converter. [6]

### Figure: -6 Non-Isolated Half-Bridge Bidirectional DC-DC Converters

The above circuit can be made to work in buck or boost mode depending on the switching of the MOSFETs Q1 and Q2. The switches Q1 or Q2 in combination with the anti parallel diodes D1 or D2 (acting as freewheeling diode) makes the circuit step up or step down the voltage applied across them. The bi-directional operation of the above circuit can be explained in the below two modes as follows:

**Mode 1 (Boost Mode):** In this mode switch Q2 and diode D1 enters into conduction depending on the duty cycle whereas the switch Q1 and diode D2 are off all the time. This mode can further be divided into two interval depending on the conduction on the switch Q1 and diode D2 as shown in the Figure 6.

**Interval 1 (Q2-on, D2-off; Q1-off, D2-Off):** In this mode Q2 is on and hence can be considered to be short circuited, therefore the lower voltage battery charges the inductor and the inductor current goes on increasing till not the gate pulse is removed from the Q2 . Also since the diode D1 is reversed biased in this mode and the switch Q1 is off, no current flows through the switch Q1.

**Interval 2 (Q1-off, D1-off; Q2-off, D2-on):** In this mode Q2 and Q1 both are off and hence can be considered to be opened circuited. Since the current flowing through the inductor cannot

change instantaneously, the polarity of the voltage across it reverses and hence it starts acting in series with the input voltage. Therefore the diode D1 is forward biased and hence the inductor current charges the output capacitor C2 to a higher voltage. Therefore the output voltage boosts up.

**Mode 2 (Buck Mode):** In this mode switch Q1 and diode D2 enters into conduction depending on the duty cycle whereas the switch Q2 and diode D1 are off all the time. This mode can further be divided into two interval depending on the conduction on the switch Q2 and diode D1 as shown in the Figure 6.

**Interval 1 (Q2-on, D2-off; Q1-off, D2-Off):** In this mode Q1 is on and Q2 is off and hence the equivalent circuit is as shown in the Figure below. The higher voltage battery will charge the inductor and the output capacitor will get charged by it.

**Interval 2 (Q1-off, D1-off; Q2-off, D2-on):** In this mode Q2 and Q1 both are off. Again since the inductor current cannot change instantaneously, it gets discharged through the freewheeling diode D2. The voltage across the load is stepped down as compared to the input voltage. [21,22,23,24,25]

A comparison between the different features of the non-isolated bidirectional topologies have been presented below: [26]

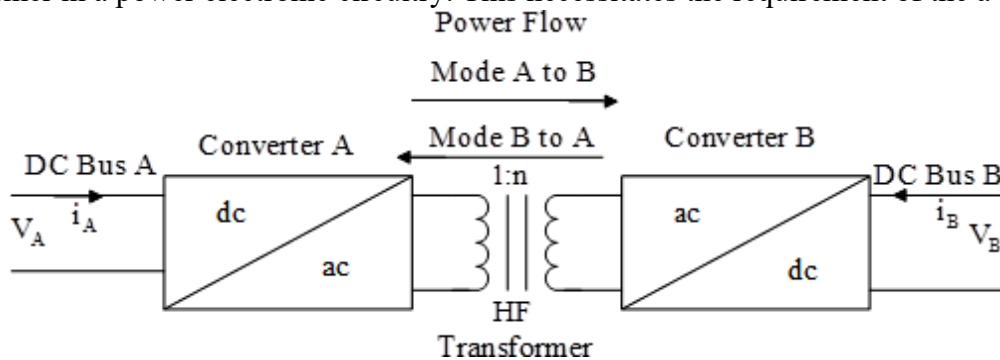
1. During step up mode, in the buck-boost bidirectional converter the rms value of the current through the inductor and the power switches is greater by an amount equal to the output current as compared to the buck-boost cascade bidirectional converter. Also the capacitor RMS current also exceeds in the former case by an amount of the 1/3rd of the output current. Therefore in the bidirectional buck-boost converter the inductor, power switches and the capacitor operate under more thermal and electrical stresses as compared to the buck boost cascade converter resulting in the greater power loss and also causing the saturation of the inductor core.
2. However the number of devices required by the cascade buck boost converter is twice the number devices in buck-boost bidirectional converter. This problem can be solved by using the Half-Bridge Bidirectional DC-DC Converter. It has the same no devices as the buck-boost bidirectional converter and can be employed instead of the buck-boost cascade bidirectional converter for the applications that require the boost operation only in one direction and the buck in the other.
3. The main advantages of the half bridge bidirectional converter as compared to the bidirectional Cuk converter is that it only requires one inductor instead of two and that too half

the value of latter as well as the power switches ratings required for the half bridge bidirectional converter is much lower as compared to the Cuk converter. Also the efficiency of the half bridge converter is higher than the Cuk converter because of the lower inductor current and therefore lower conduction as well as lower switching losses.[27,28,29]

Here half bridge converter use because of simple structure, high efficiency, low cost, high reliability, etc. Half-bridge Converter which operates either in Buck or in Boost mode shown in figure 6. When bi-directional DC-DC converters work in charging mode, the ratio of output voltage  $V_o$  to input voltage  $V_{in}$  is lower than 1; when they work in discharging or V2G mode, the ratio of  $V_o$  to  $V_{in}$  is larger than 1. Half Bridge is expected to be more efficient and it also has less number of inductor and capacitors. Half Bridge converter is a better candidate in this scenario.

### 3.2 Isolated Bidirectional DC to DC Converter

These converters can regulate a wide range of power from few watts to hundreds of kilowatts. Galvanic isolation is required in certain applications demanding personnel safety, noise reduction as well as proper operation of protection systems. Also certain systems require voltage matching between the different stages for the proper design and the optimization of different stages. Generally, voltage matching and galvanic isolation is achieved by the transformer in a power electronic circuitry. This necessitates the requirement of the a clink for



the energy transfer. . [30,31,32,33,34,35]

**Figure: -7 Basic Configuration of Isolated Bidirectional DC-DC Converter**

Thus the system complexity grows up with the incorporation of all this features. Basically most of the isolated bidirectional DC-DC converters have the structure as shown in thefig7.

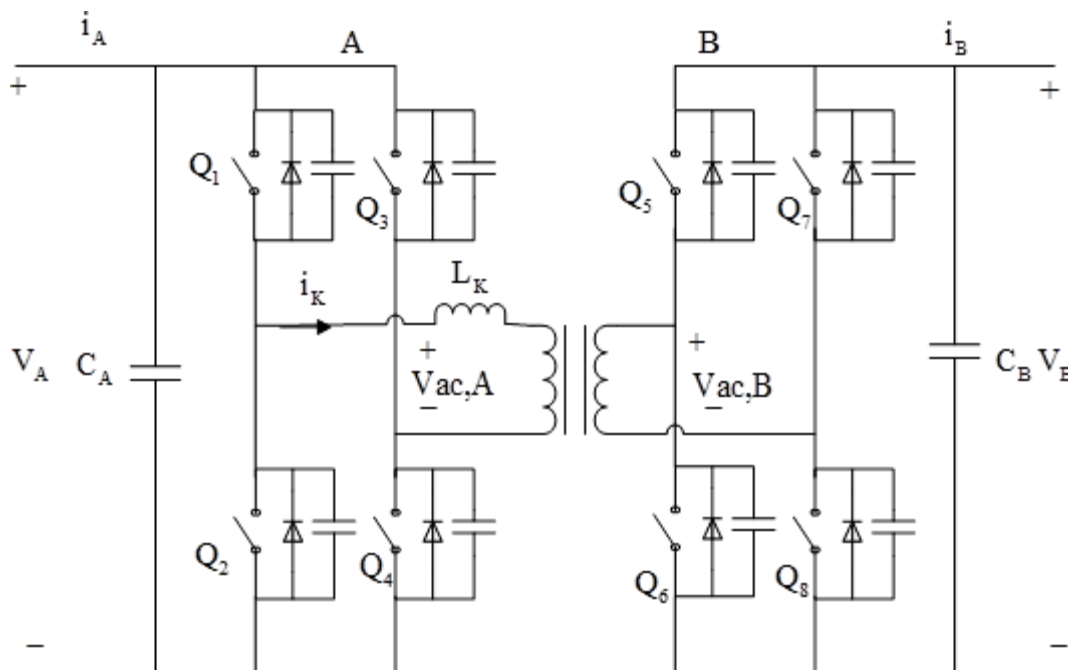
This scheme requires two switching DC to AC converters operating at high frequency so as to convert the dc input to high frequency AC quantities. Galvanic isolation between the source and load side is provided by the high-frequency transformer. Transformer also performs voltage matching between the source and the load side since the voltage ratio between them is

very high. The transformer works with AC quantities and hence a DC-AC converter is required at both the terminals. Since the system is meant for the energy transfer in both the directions, DC to AC converters employed must have the capability of bidirectional power flow. This converter also like the non-isolated bidirectional DC to DC converters works in two modes of operation i.e. in buck or boost.

The isolated bidirectional DC-DC converters can be divided into two categories on the basis of their configuration:

A current fed isolated bidirectional DC-DC converter has inductor at its terminals which acts like a current source.

A voltage fed isolated bidirectional DC-DC converter as shown in the fig8 has a capacitor at its terminals which acts like a voltage source.



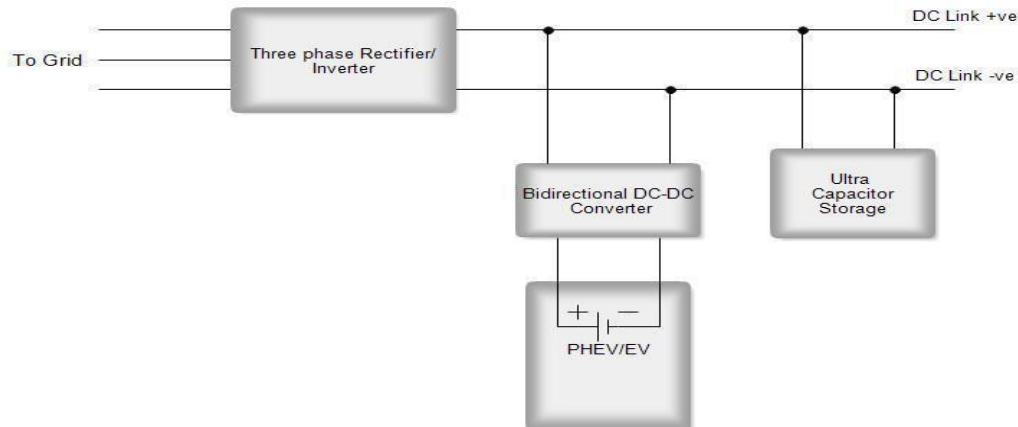
**Figure: -8 Bridges Isolated Voltage Fed Bidirectional DC-DC Converter**

Since the isolated bidirectional DC-DC are having more complex structure, are bulkier, costlier and heavier than the non-isolated bidirectional DC-DC converters due to the presence of the transformer, they are usually unfit for the HEV application. Also the overall efficiency of the non-isolated bidirectional converters is more as compared to the isolated bidirectional converters. Therefore, the Non-Isolated Half Bridge Bidirectional DC-DC converter is selected for the present design.

#### 4. RESEARCH METHOD / METHODOLOGY:

##### 4.1 Proposed Block Diagram of Plug-in Hybrid Electric Vehicle Charging Station

The proposed architecture of PHEV'S charge station is shown in Figure 9. Compared to discrete AC-DC and DC-DC chargers, the proposed charge station uses higher DC distribution bus with one high power three-phase AC-DC converter as grid interface. This architecture has several advantages. The specific cost of high power AC-DC stage is lower than that of discrete low power AC-DC converters if AC power distribution bus is used. The three phase rectifier is rated for average power rather than peak power if ultra capacitor energy storage is installed to filter the ripple power. The power of each DC-DC channel is rated for normal slow charge rating to minimize cost. The parallel of several DC-DC stages provides a high power fast charging channel, assuming only small portion of PHEV's will require this service. With bi-directional DC-DC converters, energy stored in PHEV batteries can be fed back to grid, which is called V2G operation. An intelligent energy management system (IEMS) with wireless Zigbee communication platform can coordinate system operation. The charge station can provide several grid support functions such as reactive power injection, peak power generation, harmonic current filter, and load balance .[36,37,38,39,40]



**Figure: - 9 Proposed Charging Station Architecture with DC Power Distribution**

#### 5. CONCLUSION

Several low cost non-isolated bi-directional DC-DC converters suited for Plug-in hybrid electric vehicle charge station applications have been reviewed and compared. Half bridge converter is better than Cuk and SEPIC/Luo converter because of smaller number of passive components, lower switch current stress and higher efficiency. The topology is suitable for high power applications, in particular for controlling the charge discharge of ultra-capacitors that can be used in plug-in hybrid electric vehicle.

## 6. FUTURE SCOPE

Interconnect with Micro grids system and smart Grids.

Implementation of bi-directional DC-DC converter in Hybrid Renewable systems.

Integration with AI and Iot.

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**IOT Enable Battery Management System or EV With Real-time  
Diagnostic and Thermal Control**

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**Abstract:** Lithium-ion batteries are widely used in electric vehicles and portable energy systems due to their high energy density and long service life. However, improper charging, deep discharge, and excessive current can reduce battery lifespan and create safety risks. Continuous monitoring and intelligent protection are therefore essential for reliable battery operation.

This paper presents the design and implementation of an Io T-enabled Battery Management System (BMS) using the ESP32 micro-controller. The system monitors key battery parameters such as voltage, charging and discharging current, and State of Charge (SOC) in real time. Two INA219 sensors are used to measure charging and load currents separately, while the MAX17043 fuel gauge IC provides accurate SOC estimation. The ESP32 processes the measured data, compares it with predefined safety limits, and automatically disconnects the load under abnormal conditions such as over-voltage, under-voltage, or over-current.

The built-in WiFi capability of ESP32 enables real-time transmission of battery data to a cloud platform for remote monitoring through a web dashboard. Experimental results demonstrate reliable monitoring performance, effective protection response, and stable SOC estimation. The proposed system provides a low-cost and practical solution for enhancing battery safety, monitoring accuracy, and operational efficiency in electric vehicle and energy storage applications.

**Key Words:** Io T, Battery Management System (BMS), Electric Vehicle (EV), Real-Time Monitoring, Thermal Control, Lithium-Ion Battery, Cloud-Based Diagnostics.

**INTRODUCTION:**

The increasing use of electric vehicles and energy storage systems has created a strong need for reliable battery management solutions. Lithium-ion batteries are widely used because of their high energy density and long life, but they are sensitive to overcharging, deep discharge, and excessive current. Improper monitoring can reduce battery life and create safety risks.

Traditional battery monitoring systems often rely only on voltage measurement and do not provide real-time or remote access to battery data. This limits accuracy and makes it difficult to detect abnormal conditions quickly.

To address these challenges, this work presents an Io T-enabled Battery Management System that continuously monitors voltage, current, and State of Charge (SOC). The system uses a micro-controller to compare measured values with safety limits and automatically disconnect the load when unsafe conditions occur. Real-time data transmission through WiFi allows remote monitoring of battery performance.

The proposed system aims to improve safety, enhance monitoring accuracy, and extend battery lifespan in electric vehicle and energy storage applications.

In addition, the use of smart control algorithms will aid in the preservation of optimal charging and discharging cycles, which will enhance the efficiency of the cycle and prolong battery life. The BMS is powered by the Io T and it does not only provide operational reliability but helps in conserving energy and promotes sustainable development. As more electric mobility and renewable energy storage systems are adopted, these types of smart battery management systems are becoming necessary in order to achieve greater performance, improved safety, and cost efficiency in the long run.

## **1.2 PROBLEM STATEMENT:**

The Lithium-ion batteries have become a commonplace in the current electronics and energy systems but very sensitive to overcharging, deep discharge and over-currents. The conventional battery monitoring does not provide an accurate State of Charge (SOC) estimation, automatic protection and real-time remote monitoring and is primarily based on a simple measurement of the voltage. Failure to monitor correctly may shorten battery life and pose a safety hazard (i.e. overheating or malfunction). Thus, there is the need to create a smart, low-cost, and reliable system based on the Io T-enabled battery monitoring and protection system with the ability to guarantee precise measurement, safety control, and real-time cloud-monitoring.

## **1.3 OBJECTIVES / AIMS:**

Intelligent Battery Management System (BMS) with the help of the Io T technology.

Monitor battery parameters including current, temperature, State of Charge (So C) and voltage in real-time.

Prevent overcharging batteries, and short-circuit conditions to achieve enhanced safety.

Improve energy efficiency by appropriate charge and discharge management.

Monitor remotely with the help of a cloud platform or a mobile application.

lications in case of abnormal battery conditions. To cut maintenance bill by use of automated battery health

liable system that can be used in electric vehicles and in portable energy storage systems.

#### **1.4 Significance of the Study:**

The importance of this study is that it will solve the urgent issue of safe, precise, and smart monitoring of lithium-ion batteries that have become highly prolific in electric vehicles, renewable energy systems, and handheld electronics. The suggested Io T-based battery monitoring and protection system will improve the battery safety by avoiding overcharging, deep discharge, and over-current by means of automatic control of the relay. The system offers a better State of Charge (SOC) estimation than the voltage-based approach by combining a pair of current sensor units with a fuel gauge IC, hence more precise results are achieved. Real-time cloud monitoring can be performed with the ESP32 having the in-built WiFi which will save the reliance on expensive GSM based systems as well as such a system will provide the ability to monitor the system remotely. This enhances efficiency in operations, access to data and reliability of the system. In sum, the research paper helps to create a low-cost, intelligent, and expandable Battery Management System (BMS) capable of increasing the battery life, improving the safety, and can facilitate the advancement of the contemporary Io T-enabled energy applications.

#### **2. LITERATURE REVIEW:**

Battery Management Systems (BMS) play a critical role in maintaining the safety and reliability of lithium-ion batteries used in electric vehicles and energy storage applications. These batteries provide high energy density but require careful supervision due to their sensitivity to overcharging, over-discharging, and excessive current flow.

Earlier monitoring systems mainly focused on measuring terminal voltage and current using micro-controllers such as Arduino. In many cases, State of Charge (SOC) was estimated using voltage-based approximation. However, lithium-ion batteries exhibit non-linear voltage characteristics under varying load conditions, which limits the accuracy of such methods.

To improve SOC estimation, researchers introduced charge-based techniques such as coulomb counting and algorithm-based estimators. While these methods improved precision, they often required higher computational complexity and calibration effort.

With the development of Io T technology, battery monitoring systems evolved toward remote supervision. WiFi-enabled controllers allow real-time data transfer to cloud dashboards,

reducing dependency on GSM modules and lowering communication costs. Despite these improvements, many systems either focus only on monitoring or only on protection, with limited integration of accurate SOC estimation, dual current sensing, and cloud connectivity within a single low-cost platform.

### **2.1 Theoretical frame work:**

The proposed work is grounded on the principles of lithium-ion battery Elect Chemistry, laws of electrical measurements, integrated control systems, and the Internet of Things ( Io T) communication. Lithium-ion batteries can work in the safe voltage range (3.0 V 4.2 V) and the battery may be damaged in case of poor charging or discharging. Current sensing techniques are utilized to measure voltage, current and power using Ohm Law of current ( $V = I \times R$ ) and Power Law ( $P = V \times I$ ). A model-based fuel gauge algorithm rather than an easy voltage measurement is used to get accurate state of charge (SOC) estimation. The ESP32 micro-controller uses the theory of embedded system control to measure battery parameters and compare them with the safety thresholds and manage a relay to protect the battery. The Io T communication theory is applicable in the provision of real-time data to the cloud, where data is monitored and analyzed remotely.

### **2.2 Previous Study:**

The previous types of battery monitoring systems used micro-controllers such as Arduino to measure voltage and current. The majority of the systems estimated battery charge level by some early voltage-based mechanisms which were not particularly accurate. GSM modules were also utilized by some researchers to make remote monitoring, although they were expensive and had low real-time data visualization. The latest works have proposed Io T-driven monitoring over WiFi and highly sophisticated fuel gauge IC s in order to achieve increased precision. Nevertheless, this type of system with the combination of accurate SOC estimation, dual current sensing, automatic protection, and Io T monitoring are not present in many current designs at a single low cost.

### **2.2 Research Gap:**

Although several battery monitoring solutions exist, many lack a balanced integration of monitoring accuracy, automatic protection, and remote accessibility. Voltage-based SOC estimation remains common despite its limitations. In addition, some systems rely on costly GSM communication or lack real-time cloud visualization.

✧ There remains a need for a compact and economical system that integrates:

- ✧ Accurate SOC estimation
- ✧ Separate measurement of charging and discharging currents
- ✧ Automatic protection against unsafe conditions
- ✧ Real-time IoT-based monitoring

This work aims to address these limitations within a single unified framework

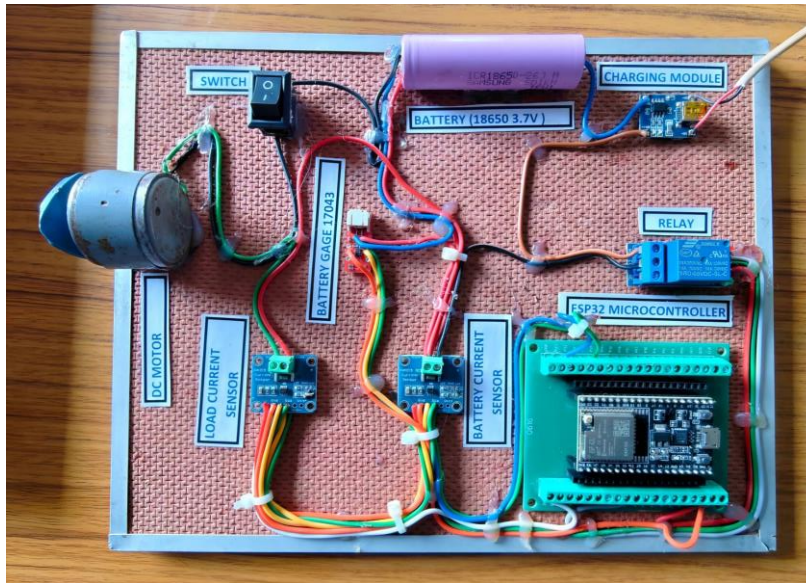
### **2.3 Existing System:**

The current battery monitoring device relies on sensors attached to a micro-controller like Arduino Uno that is able to detect voltage, current, and temperature of the battery. The data obtained was shown locally through LCD displays. To send alert messages to the users, a GSM module is occasionally used.

Despite the fact that this system offers simplified monitoring, it is faced by a number of limitations which include limited storage of data, slow communication, and lack of real-time monitoring of the cloud. Moreover, the current systems do not have automatic load protection and high levels of integration with IoT, which makes them less effective in the contemporary applications.

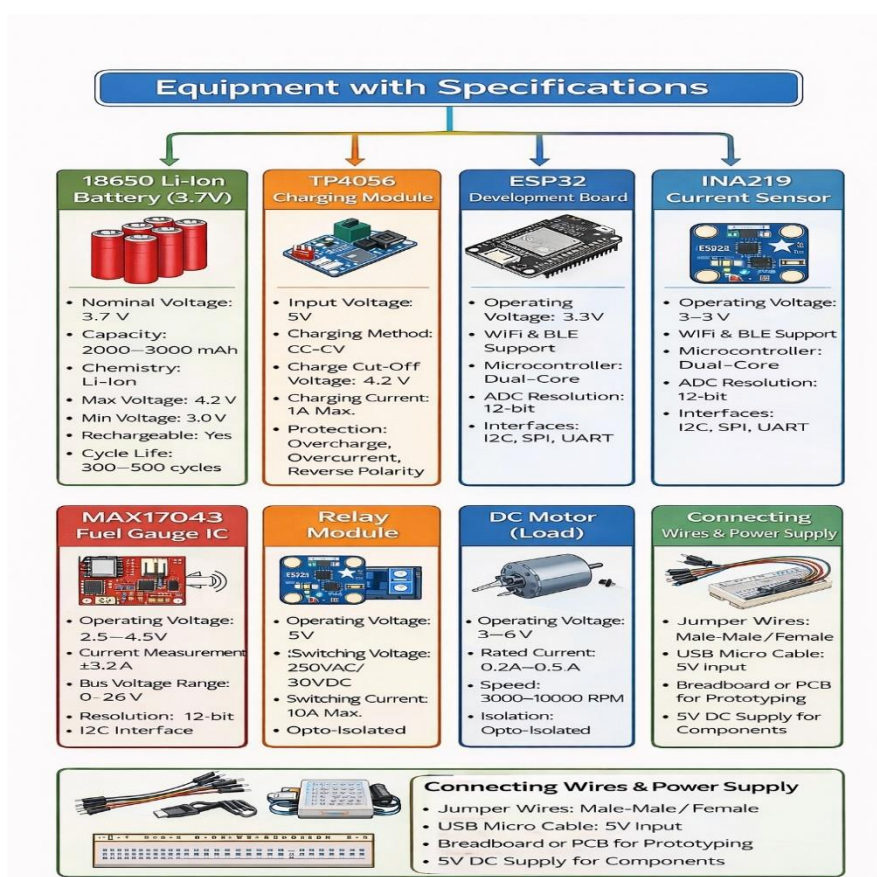
### **2.4 Proposed System:**

The proposed system presents a smart monitoring scheme, which is an IoT based solution based on an advanced sensor and wireless communication device. The battery will be a lithium-ion, and the sensing modules will include the MAX17043 and INA219 sensors. These are sensors which monitor voltage and current parameters. ESP32 microcontroller receives sensor data and transfers it to an IoT platform via Wi-Fi connection. A relay unit is used to cut off the load in unsafe battery conditions. The charging module is a TP4056 which guarantees safe battery charging. The system allows users to track the performance of the battery remotely via mobile applications.



**FIGURE-1. PROPOSED SYSTEM MODE**

**2.5 COMPONENT SPECIFICATION:**



**FIGURE-2 SPECIFICATION OF COMPONENT**

### 3.0 Methodology

The methodology is subdivided into six stages:

➤ Step 1: Hardware Design

All the components are inter-linked in an appropriate manner with I2C protocol and controlled power supply.

➤ Step 2: Sensor Data Acquisition.

ESP32 reads:

Charging current from INA219-1

INA219-2 discharge is current.

SOC from MAX17043

➤ Step 3: Data Processing

ESP32 calculates:

Voltage

Current

Power

Battery percentage

Safety thresholds are compared to values.

➤ Step 4: Protection Mechanism Should unsafe condition be realized:

Relay OFF Load disconnected

➤ Step 5: Io T Communication ESP32 is used to connect to WiFi and transfer data to IOT platform.

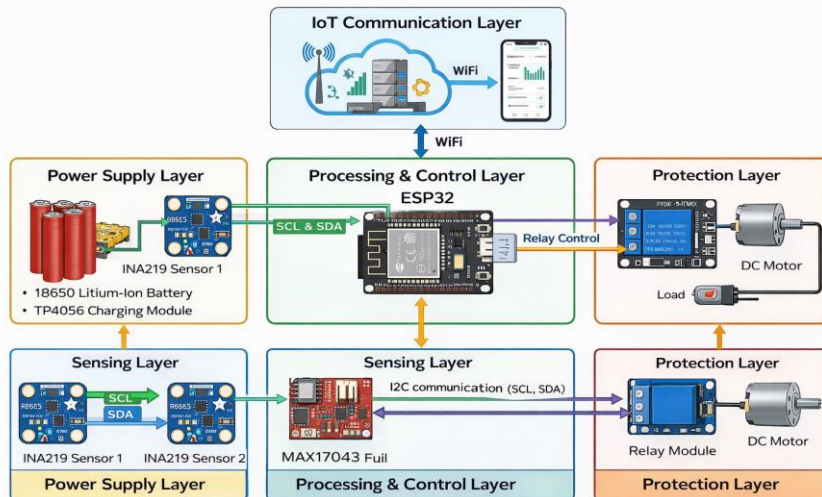
➤ Step 6: Testing & Validation System tested under:

Charging condition

Discharging condition

Low voltage condition

### 3.1 System Architecture/Design



**FIGURE-3 SYSTEM ARCHITECTURE**

The proposed system consists of five major layers:

### 3.1.1 Power Layer

18650 Lithium-ion Battery (3.7V)

TP4056 Charging Module

TP4056 offers constant current - constant voltage (CC -CV) charging and provides safe battery charging.

### 3.1.2 Sensing Layer

INA219 Sensor 1 (Charging current)

INA219 sensor no.2 (Discharging current)

MAX17043 Fuel Gauge

IC The sensing layer is continuously monitoring:

Voltage

Current

Power

Battery percentage (SOC)

### 3.1.3 Processing Layer

ESP32 Microcontroller

The ESP32 performs:

The acquisition of sensor data through I2C.

Data processing

Safety comparison

Relay control

IoT communication

### **3.1.4 Protection Layer**

Relay Module

The relay breaks the load below:

Low voltage ( $< 3.0V$ )

Overvoltage ( $> 4.2V$ )

Overcurrent condition

### **3.1.5 IoT Communication Layer**

WiFi (Built-in ESP32)

Instant battery parameters are sent to the cloud and monitored remotely.

## **3.2 WORKING PRINCIPLE:**

The proposed Lithium-Ion Battery Monitoring and Protection System based on the IoT will work in the following way:

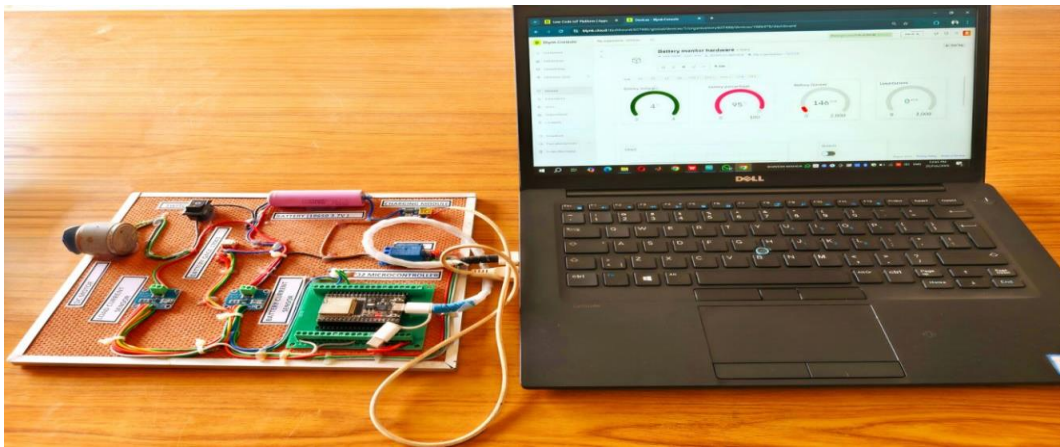
the system will constantly monitor the battery parameters, including voltage, charging current, discharging current, and State of Charge (SOC), and upon having an unsafe situation, it will automatically protect the battery. The 18650 lithium-ion battery is first charged with the help of TP4056 charging module that operates in accordance with the Constant Current Constant Voltage (CCCV) principles to provide complete safety during charging up to 4.2V. Two INA219 current sensors are used during operation to measure the charging current and load (discharging) current respectively. The MAX17043 fuel gauge IC also includes an internal Model-gauge algorithm that then calculates the correct battery percentage (SOC). All sensor data is sent to the ESP32 micro-controller through the I2C communication (SDA and SCL lines). ESP32 receives the data collected and compares it with the set safety limits. In case some abnormal condition is identified, e.g.: Low voltage ( $< 3.0V$ ) Over-voltage ( $> 4.2V$ ) Over-

current condition to prevent the battery damage, the ESP32 is used to turn the relay module on and off to disconnect the load. At the same time, the ESP32 is connected to the Io T cloud platform with the help of the inbuilt WiFi module that transmits real-time battery data, which can be remotely monitored and analyzed. Thus, the system ensures: Constant review of battery. Intelligent protection Accurate SOC estimation IoT supervision in real-time.

#### FIGURE-4 WORKING OF PROPOSED MODEL

#### 4.0 Result/Finding:

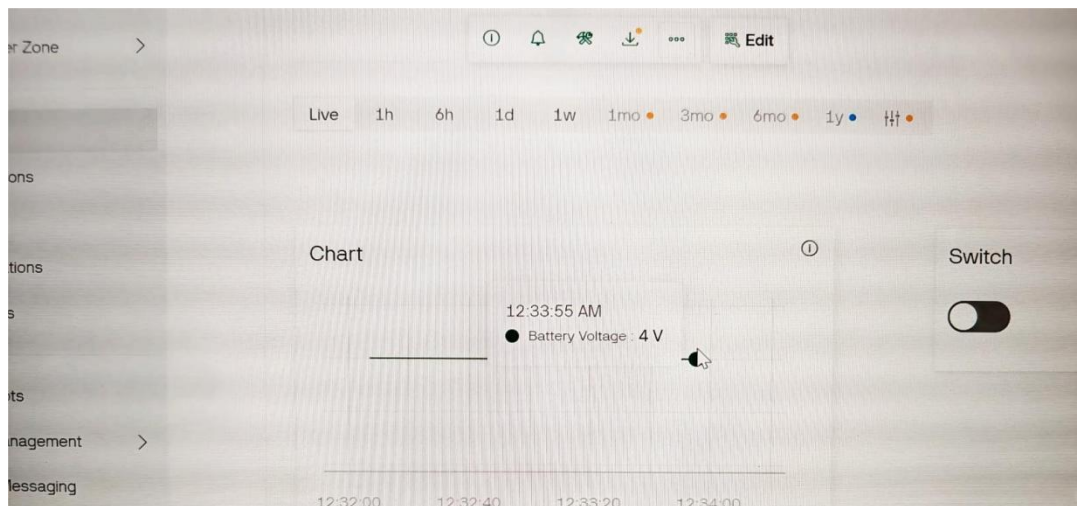
Experimental Results The Lithium-Ion Battery Monitoring and Protection System proposed on



the basis of Io T was actually put to practice and its functionality was demonstrated in various operational conditions, such as charging mode, discharging mode, low voltage condition and overload condition.

#### 4.1 Voltage Monitoring:

This system was found to measure battery voltage in the range of operation that was 3.0V to 4.2V accurately. As the charge commenced, the voltage was gradually increasing and the right value was shown on the Io T dashboard. The charging process was safely controlled when the voltage was 4.2V. At the point where voltage was less than 3.0V, the relay automatically DE-energized the load.

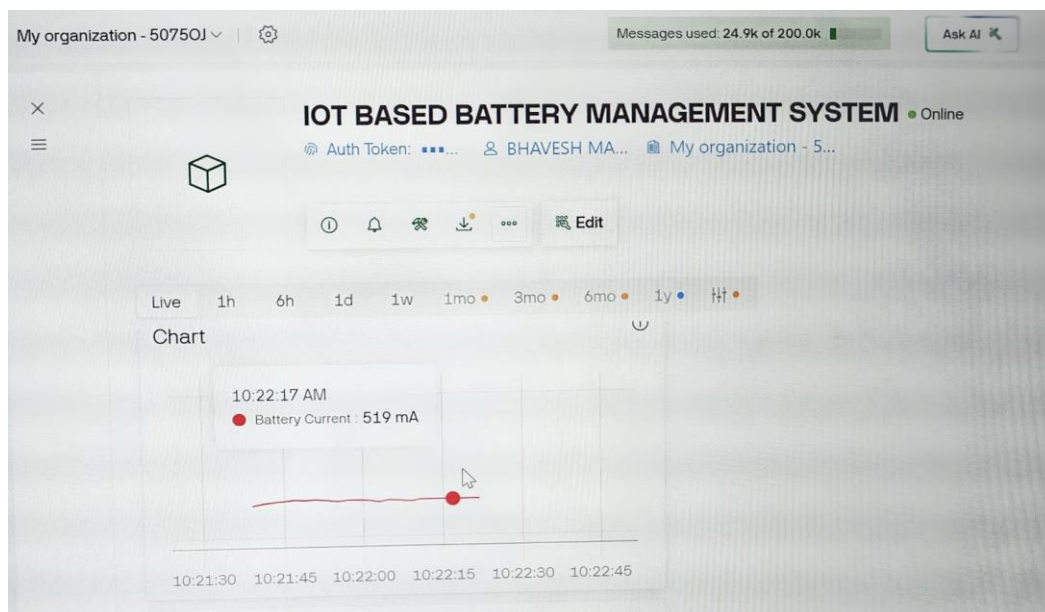


**FIGURE-5 VOLTAGE MONITORING CHART**

**Finding:** The voltage monitoring system was accurate, and threshold-reactive.

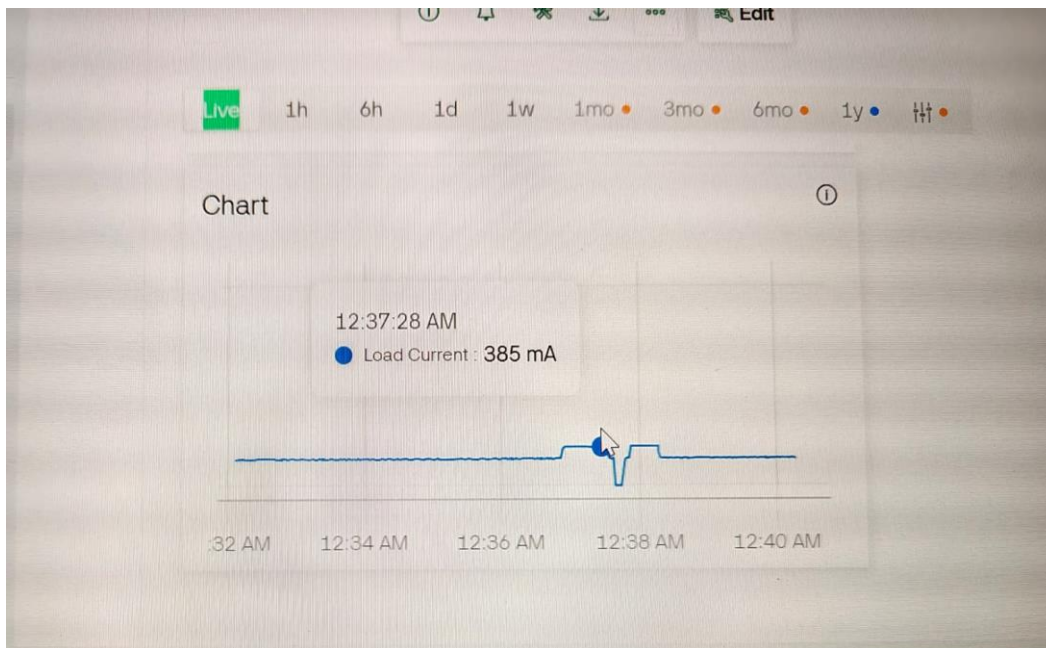
#### 4.2 Current Measurement:

INA219 Sensor 1 was able to measure charging current.



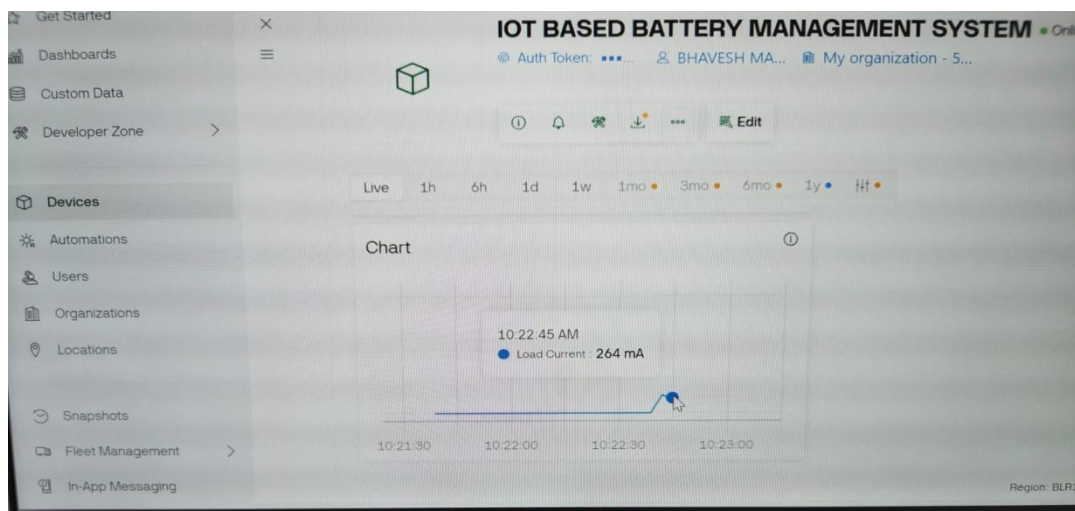
**FIGURE-6 BATTERY CHARGING CURRENT MEASUREMENT CHART**

INA219 Sensor 2 had correct discharging (load) current measurement.



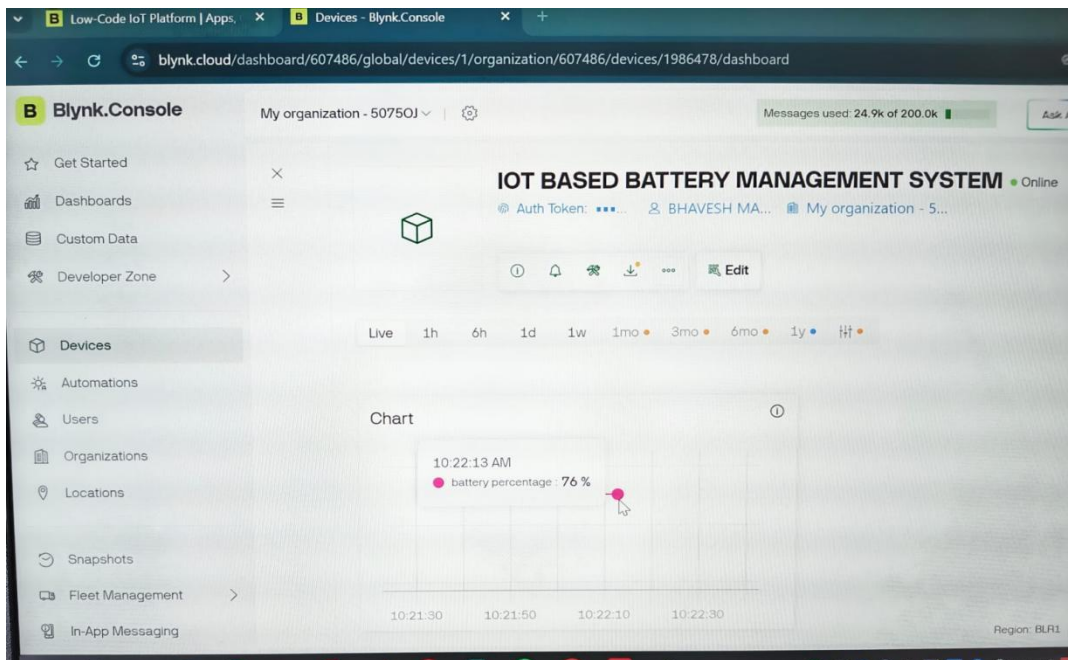
**FIGURE-7 LOAD CURRENT MEASUREMENT CHART**

Normal load conditions were stable and consistent with regards to current readings



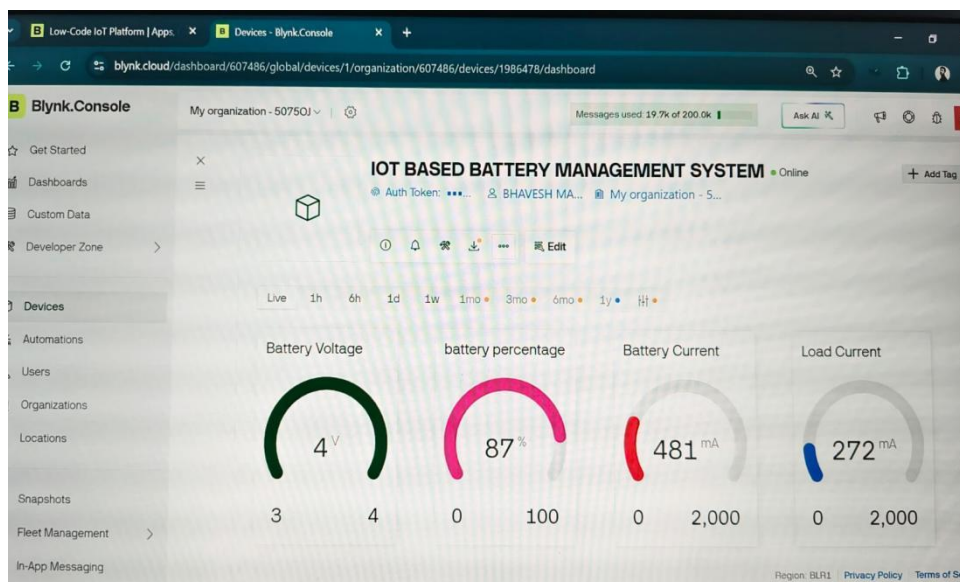
**FIGURE-8 NORMAL LOAD CURRENT MEASUREMENT CHART**

**Finding:** Dual current sensing enhanced the levels of monitoring and provided the ability to distinguish between the discharging and charging mode.



**FIGURE-9 BATTERY PERCENTAGE MONITORING CHART**

The estimation of state of charge (SOC) is presented in 1.3. MAX17043 gave the correct readings of battery percentages. Even when the load changed, SOC values did not change. As compared to voltage-based approximation, SOC estimation was more accurate



**FIGURE-9 BLYNK USER INTERFACE**

## **5.0 Discussion:**

The proposed Lithium-Ion Battery Monitoring and Protection System based on IoT was created to address the constraints of the traditional battery monitoring systems. According to the results of the experiment, the system can be characterized as a reliable system in terms of monitoring accuracy, safety control, and real-time communication.

### **5.1 Monitoring Accuracy**

Dual INA219 current sensors integration was found to significantly enhance the accuracy of the current in the measurement of charges and discharging currents. This is contrary to the conventional systems which operate on the voltage mode alone, where the proposed system isolates the charging and load current to take place separately. This offers an improved analysis of the behavior of the battery in different operating conditions. The accuracy of the State of Charge (SOC) estimation was increased with the use of the MAX17043 fuel gauge IC. The non-linear discharge nature of lithium-ion batteries causes the estimation of SOC based on voltage to give wrong percentages of the battery. Nevertheless, the algorithm of the fuel gauge ensured consistent and steady SOC values when there were alterations in the load. This validates the fact that intelligent SOC estimation enhances the general monitoring reliability.

### **5.2 Protection Performance:**

The protection mechanism was a relay that reacted successfully to insecure conditions including low voltage, over-voltage, and over-current. In testing, the system was able to disconnect the load at voltages less than 3.0 V and preclude deep discharge. The reason is that profound discharge lessens battery life and can have an irreversible effect on lithium-ion cells. Correspondingly, over-current detection safeguarded the circuit against high flow of current to avoid overheating and breaking of the component. The reaction speed of the relay module and ESP32 was quite rapid enough to avoid dangerous scenarios. Accordingly, the automatic protective system increases the safety of operation and battery life.

### **5.3 Internet of Things Communication Efficiency:**

ESP32 was used with inbuilt WiFi which enabled real-time transfer of data to the IoT cloud platform. WiFi communication ensured that the cost of operation was lower and the data was updated faster, compared to GSM -based systems. The continuous monitoring of battery parameters was provided through remote monitoring without physical presence. The IoT dashboard enabled the visualization of the voltage, current, SOC, and load status. This is an

advantage that enhances user convenience and aids the process of data analysis to analyze performance.

#### **5.4 Reliability of the System and Economical**

It utilized the cheap and readily accessible ESP32, INA219, TP4056, and MAX17043 as the overall system. Although the system was cost effective, it had high monitoring precision and intelligent protection. Arduino based on the suggested system has the following advantages compared to standard Arduino -GSM systems: The suggested system has superior SOC estimation. It offers dual current measurement. It allows monitoring of the cloud in real-time. It minimizes the cost of communication. Thus, the system is performance-safety, and cost-efficient.

#### **5.5 Limitations:**

there were few shortcomings noted:

- ✧ Temperature check had not been provided.
- ✧ The system was evaluated using a single cell battery.
- ✧ Multi-cell packs Cell balancing was not introduced.
- ✧ This did not have long-term battery health prediction.
- ✧ Such limitations are subject to improvement in the future.

#### **6.0 CONCLUSION / SUMMARY:**

An IoT-enabled lithium-ion battery monitoring and protection system has been successfully developed and tested. The system continuously measures voltage, current, and State of Charge using dedicated sensing modules and processes the data through an ESP32 micro-controller.

The integration of dual current sensors improves monitoring precision, while the fuel gauge IC enhances SOC reliability. The automatic relay protection mechanism safeguards the battery under abnormal conditions such as low voltage and over-current.

Real-time WiFi-based monitoring enables remote access to battery performance data, making the system practical and cost-effective for electric vehicle and energy storage applications. The proposed design demonstrates improved safety, accuracy, and operational efficiency in comparison with conventional monitoring systems.

#### **6.1 Summary of Key Findings:**

- ✧ The system is precise in the measurement of battery voltage in the safe operating range

(3.0V -4.2V).

- ✧ Dual INA219 sensors enhance the setting of the monitoring accuracy because charging and discharging currents are measured separately.
- ✧ Compared to the voltage-based fuels reading, the MAX17043 fuel gauge is more reliable and stable in providing SOC estimation.
- ✧ The relay module is suitable to break the load in case it is exposed to unsafe conditions, avoiding battery damage. ESP32 provides real-time internet of things remote monitoring via WiFi. The suggested system is cost-effective and efficient compared to the traditional Arduino- GSM monitoring systems.
- ✧ Smart sensing and automatic protection increase the life of the battery and its operational safety.

### 7.1 FUTURE SCOPE:

- Adding temperature sensors to help regulate heat on the battery and keep it cool or eliminate overheating.
- Battery health prediction and fault detection: Implementation of Artificial Intelligence (AI) and Machine Learning (ML).
- Scaling up of the system to support multiple-battery cell or battery packs against electric vehicles and energy storage systems.
- Creation of a mobile app that would notify and alert in real-time to overcome distance monitoring and control.
- Combination with renewable energy sources like solar systems and smart grid technology to use as smart energy management applications.

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## PERFORMANCE TRADE-OFFS OF CONSENSUS MECHANISMS IN AI-INTEGRATED BLOCKCHAIN APPLICATIONS

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### Abstract:

Consensus mechanisms are fundamental to blockchain systems, enabling secure and decentralized agreements among distributed participants. However, the integration of Artificial Intelligence (AI) imposes additional performance pressures, including latency, scalability, and computational overhead. This study investigates the performance trade-offs of major consensus mechanisms—Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), and Byzantine Fault Tolerance (BFT)-based protocols—within AI-integrated blockchain environments. Employing a comparative review methodology, we evaluated the influence of consensus design on throughput, fault tolerance, communication complexity, and decentralization. The analysis revealed the key strengths and limitations of each protocol under AI-driven workload. The findings indicate that while certain mechanisms enhance efficiency, they often compromise decentralization or increase the coordination costs. The study concludes that no single consensus approach fully addresses all the requirements of AI-enabled blockchain systems, underscoring the need for context-specific protocol evaluations.

**Keywords:** Artificial Intelligence Integration, Blockchain, Consensus Mechanisms, Distributed Systems, Performance Trade-offs

### I. Introduction:

Blockchain technology has emerged as a transformative framework for decentralized data storage and secure transaction processing (Shaikh et al., 2025). Using a distributed ledger, blockchain enables multiple participants to maintain a shared and tamper-resistant record without relying on a central authority (Shen et al., 2025). Initially popularized by cryptocurrencies such as Bitcoin, it has since expanded into sectors including supply chain management, healthcare, and financial services because of its transparency and security. At the same time, advances in Artificial Intelligence (AI) have enabled automation and intelligent decision-making in data-driven environments (Merrad et al., 2022). However, AI applications, such as predictive analytics, autonomous systems, and machine learning, require high

throughput, low latency, and rapid data access, placing significant performance demands on the underlying infrastructure.

Integrating AI with blockchain offers benefits such as improved trust and auditability through immutable records of training data and model decisions (Merrad et al., 2022). Nevertheless, blockchain consensus mechanisms, which are designed primarily for security and decentralization, often introduce performance limitations (Sun et al., 2025). Protocols such as Proof of Work (PoW) and Proof of Stake (PoS) differ in efficiency and energy consumption, yet both involve trade-offs that may affect real-time AI applications. For example, consensus-induced delays in decentralized finance (DeFi) platforms can slow transaction finality and impact their responsiveness (Zeydan et al., 2025). Although interest in AI-blockchain integration is increasing, few studies have systematically evaluated consensus performance under AI-specific workload demands (Shaikh et al., 2025). This study addresses this gap by comparatively analyzing major consensus mechanisms and their trade-offs in AI-integrated environments.

## II. Literature Review :

The study of blockchain consensus mechanisms has evolved significantly as distributed ledger technologies have matured, and their use cases have expanded beyond cryptocurrency to data-driven and AI-enabled applications (Zhou et al., 2023). Consensus protocols determine how network participants agree on the blockchain state, thereby affecting critical performance metrics such as throughput, latency, security, and decentralization. Recent surveys have highlighted that these mechanisms exhibit intrinsic trade-offs, where improvements in one performance aspect often lead to compromises in another aspect.

One comprehensive review categorized consensus mechanisms according to their performance orientation, examining high throughput, strong security, low energy consumption, and scalable designs (Shaikh et al., 2025). This analysis reveals that achieving high transaction processing rates frequently comes at the expense of decentralization or increased communication overhead. For example, mechanisms designed for high throughput may limit the number of participating nodes, thereby impacting decentralization and reducing latency.

Comparative studies further underscore the complexity of consensus selection, noting the absence of standardized benchmarks that can consistently evaluate protocols under uniform conditions (Shen et al., 2025). Such research contrasts conventional mechanisms like Proof of

Work (PoW) and Proof of Stake (PoS) with alternatives such as Delegated Proof of Stake (DPoS), Proof of Authority (PoA), and Proof of Capacity (PoC), documenting that PoW's high security and decentralization come with significant energy costs and low throughput, whereas PoS and its variants offer improved efficiency but may introduce centralization risks.

Quantitative evaluations also illustrate variations in the practical performance of the protocols (Merrad et al., 2022). Under controlled loads, energy consumption and decentralization metrics differ significantly, with mechanisms such as DPoS showing low energy demand and high throughput but reduced decentralization compared with PoW. These findings emphasize that protocol performance is context-sensitive and depends on the protocol's specific operational requirements.

Taken together, the literature confirms that consensus mechanisms cannot deliver optimal performance across all metrics (Shaikh et al., 2025). Instead, each protocol embodies a set of trade-offs, necessitating an informed selection based on the demands of a particular application domain. This review provides a foundation for evaluating such trade-offs in AI-integrated blockchain environments, where performance requirements may diverge further from those of traditional blockchain applications.

### **III. Methodology :**

This review uses a comparative analysis approach to examine the performance trade-offs of key blockchain consensus mechanisms in the context of AI-integrated systems (Shaikh et al., 2025; Zhou et al., 2023). Rather than conducting experiments or simulations, this study synthesizes performance insights reported in the existing technical literature to evaluate how different consensus protocols behave under AI-related workloads (Shen et al., 2025; Merrad et al., 2022).

The literature considered in this review includes research articles and conference papers that discuss the performance characteristics of consensus mechanisms in blockchain systems. Sources were identified by searching major academic databases using relevant terms such as blockchain consensus, proof-of-work performance, proof-of-stake latency, Byzantine Fault Tolerance throughput, and consensus performance in distributed ledger systems. After the

initial retrieval, the full texts were examined to extract information related to the performance metrics of interest (Shen et al., 2025).

To compare consensus mechanisms meaningfully, this review adopts a structured analytical framework that focuses on several core performance factors relevant to AI-integrated applications. These factors include:

- **Throughput**, referring to the rate at which transactions or blocks are validated
- **Latency** indicates the time delay involved in reaching an agreement (Zhou et al., 2023).
- **Fault tolerance** reflects resilience to node failures or adversarial behavior.
- **Communication complexity** represents the messaging overhead among network participants (Shaikh et al., 2025).
- **Decentralization** describes the distribution of decision-making authority across nodes (Zeydan et al., 2025; Andrews et al., 2025).

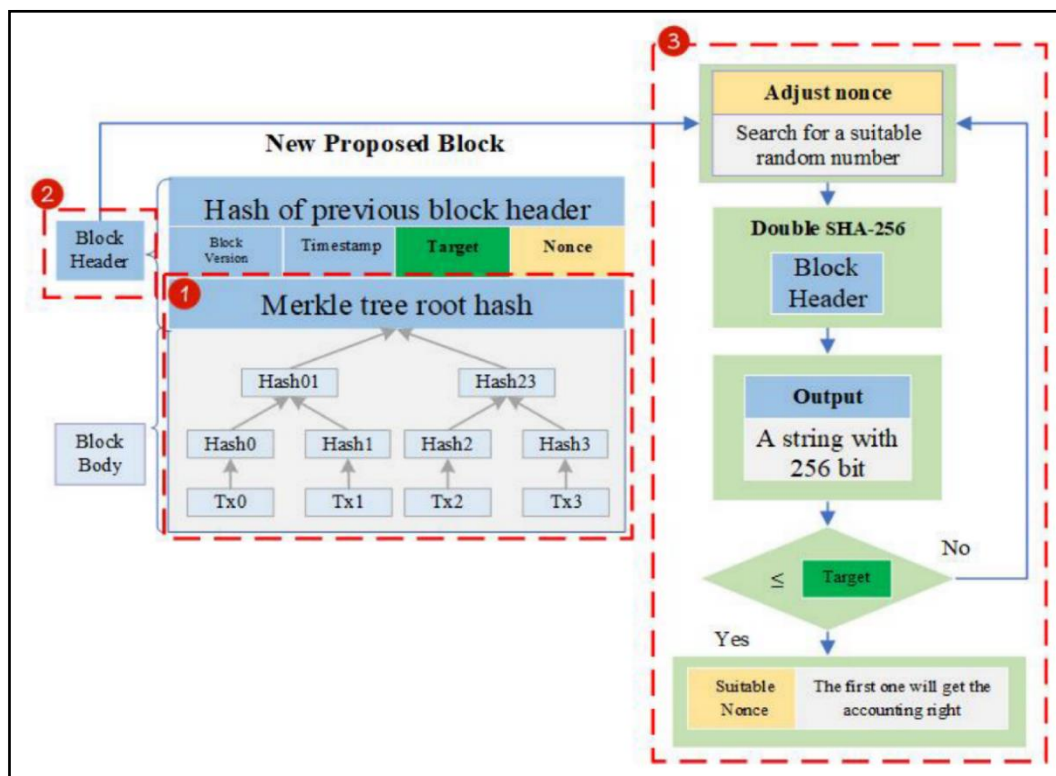
Each consensus mechanism is evaluated with respect to these factors based on the evidence and observations presented in the literature review. This framework highlights the trade-offs that arise when consensus protocols are employed in AI-driven environments with performance requirements.

#### **IV. Overview of Consensus Mechanisms :**

In blockchain systems, consensus mechanisms are protocols that enable distributed network participants to agree on the validity and order of transactions without relying on a central authority (Zhou et al., 2023). These mechanisms play a central role in determining performance, as they influence the transaction throughput, latency, decentralization, computational demand, and communication complexity. Understanding the fundamental operations and trade-offs of common consensus protocols are essential for evaluating their suitability for AI-integrated blockchain environments.

##### **1. Proof of Work (PoW) :**

Proof of Work was the first widely adopted consensus mechanism and remains a benchmark for decentralized systems (Shaikh et al., 2025). In PoW, nodes (commonly called miners) compete to solve cryptographic puzzles; the first to solve the puzzle earns the right to validate the next block and receives a reward. This competition ensures strong security because attacking the network requires controlling the majority of the computational power, which making malicious behavior costly. However, the computational intensity of PoW translates to high energy consumption and a comparatively low transaction throughput. Under increasing load conditions, PoW systems can struggle to maintain efficiency, with energy use rising substantially as the transaction processing demand grows. These traits render PoW less suitable for latency-sensitive or high-throughput artificial intelligence (AI) applications.



**Figure 1.** The process of random number search in Bitcoin PoW (adapted from (Zhou et al., 2023)).

## 2. Proof of Stake (PoS) :

Proof of Stake was developed as an energy-efficient alternative to PoW (Merrad et al., 2022). Instead of computational puzzles, validators are selected based on the amount of cryptocurrency they stake as a collateral. This reduces the need for intensive computation and lowers energy consumption. PoS generally offers improved throughput and reduced latency compared with PoW. However, the security and decentralization of PoS depend on the

distribution of stakes among validators; if a few entities hold most stakes, decentralization may diminish over time. PoS has gained prominence in modern blockchain networks, including major platforms that have transitioned from PoW to PoS to improve scalability and efficiency.

### **3. Delegated Proof of Stake (DPoS) :**

Delegated PoS enhances PoS by introducing a voting layer in which token holders elect a smaller set of delegates to produce blocks (Shaikh et al., 2025). This reduces the number of active validators, enabling faster consensus and higher transaction throughput compared to PoW and standard PoS. However, streamlining the validation set also concentrates power among fewer participants, potentially reducing decentralization and creating governance challenges for digital currency. Although DPoS can achieve high-performance levels that are beneficial for applications requiring rapid transaction confirmation, it carries trade-offs in terms of network decentralization and trust assumptions.

### **4. Byzantine Fault Tolerance (BFT)-Based Protocols :**

BFT-based consensus mechanisms, such as Practical Byzantine Fault Tolerance (PBFT), are designed to tolerate a defined number of faulty or malicious nodes while providing rapid finality (Sun et al., 2025). In these protocols, validators exchange messages in multiple rounds to reach an agreement, making them suitable for permissioned or consortium blockchains. However, the communication complexity of BFT mechanisms typically increases rapidly as the number of participants increases, which can increase the latency and limit scalability. Such protocols are effective when the number of participants is controlled and trust boundaries are known; however, they may be less efficient in large open networks.

### **5. Alternative and Hybrid Approaches :**

Beyond the core mechanisms, hybrid models attempt to combine the strengths of various protocols (Andrews et al., 2025). For example, some systems integrate elements of PoW and PoS to balance security and efficiency, while emerging consensus designs leverage variations such as Proof of Authority (PoA) or reputation-based methods to optimize specific performance aspects. Although these alternatives can offer improved throughput or lower energy costs under certain conditions, they often introduce compromises in decentralization or trust assumptions that must be considered in their implementations.

### **Summary :**

No single design optimizes all performance metrics simultaneously across all consensus mechanisms. PoW excels in decentralized security but suffers from energy intensity and low

throughput, whereas PoS and DPoS improve efficiency at the cost of potential centralization. BFT-based protocols provide fast finality under controlled conditions but are challenged by communication complexities in larger networks. These characteristics underscore the importance of analyzing performance trade-offs when evaluating consensus protocols for AI-integrated blockchain systems.

## V. Performance Trade-off Analysis :

This section compares the major blockchain consensus mechanisms by focusing on **key performance metrics** that are particularly relevant for supporting AI-integrated applications. These metrics include **throughput**, **latency**, **security**, **decentralization**, and the **communication overhead**. Each consensus design makes trade-offs between these factors under various conditions (Shaikh et al., 2025).

### i. Throughput Trade-Offs :

#### ✓ Proof of Work (PoW) :

- Very low throughput ( $\approx 7$  TPS in Bitcoin).
- Computationally intensive mining slows down the creation of block.
- Suitable when security and decentralization are prioritized over speed.

#### ✓ Proof of Stake (PoS) :

- Moderate throughput ( $\sim 15$ – $250$  TPS for certain networks).
- No mining competition  $\rightarrow$  faster block times than PoW mining.

#### ✓ Delegated Proof of Stake (DPoS) :

- High throughput (hundreds to thousands of TPS).
- Fewer active validators lead to faster block finality.
- Trade-off: decentralization decreases as the validator count is limited.

#### ✓ BFT-Based Protocols :

- Moderate throughput in permissioned settings.
- This is better for systems with fewer validators.
- The communication overhead increases with the number of nodes.

### ii. Latency Trade-Offs :

Latency refers to the time required for a transaction to be finalized in the system.

#### ✓ PoW :

- High latency is due to mining difficulty and confirmation requirements.
- For example, the average block time for Bitcoin is 10 minutes.

#### ✓ PoS and DPoS :

- It has a much lower latency than that of PoW.
- Quickly selected validators reduce the waiting time.
- DPoS often achieves faster finality because of limited delegates.

✓ **BFT Variants :**

- Low latency in smaller networks is also a challenge.
- Multiple message rounds ensure fast consensus but hinder scalability.

**iii. Security vs Performance Trade-Offs :**

✓ **PoW :**

- High security due to computational difficulty.
- It is resistant to many attack types but can suffer 51 % attacks in small networks.

✓ **PoS / DPoS :**

- Security depends on token distribution or delegates.
- It is less energy-intensive than PoW, but security assumptions differ.

✓ **BFT Protocols :**

- Strong fault tolerance for the known participants.
- Suitable for permissioned environments but with limited scalability.

**iv. Decentralization vs Efficiency Trade-Offs :**

✓ **PoW :**

- Most decentralized: Any node can mine.
- Efficiency suffers because of competition among miners.

✓ **PoS :**

- Moderate decentralization depending on stake distribution.
- It is improved efficiency over PoW.

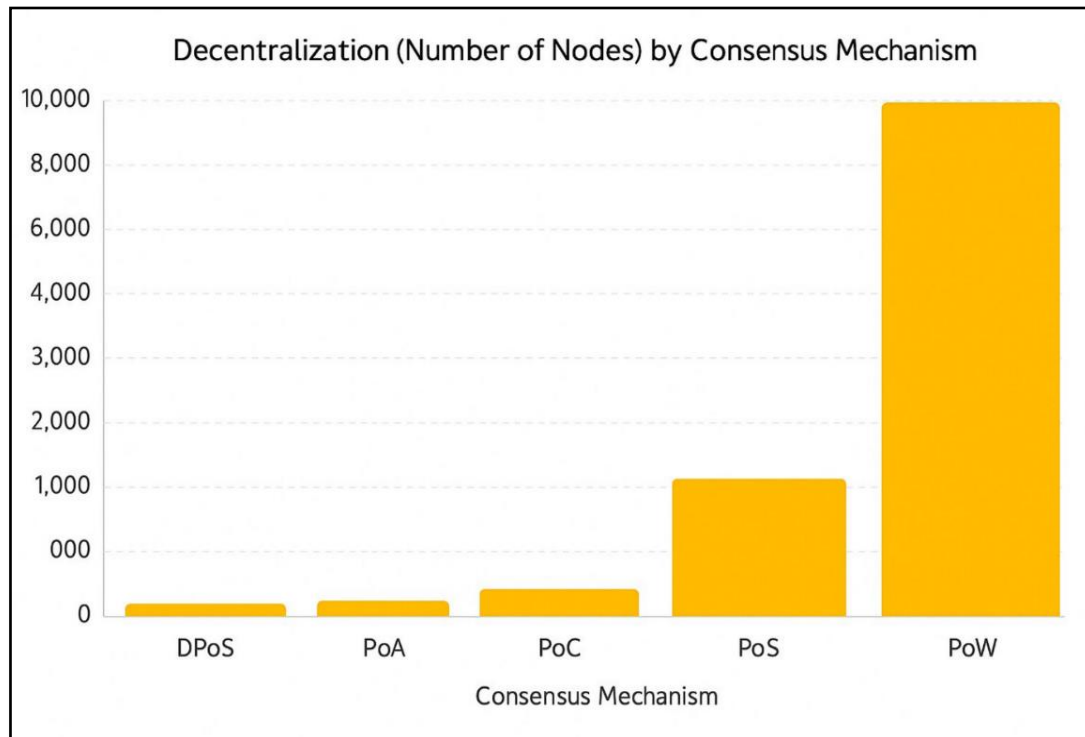
✓ **DPoS :**

- Lower decentralization is due to limited validator sets.
- It is highly efficient in terms of throughput and latency.

✓ **BFT :**

- Decentralization is limited by controlled validator lists.
- Efficient where participants are known and trusted.

**Figure 2.** Comparison of decentralization among major consensus mechanisms  
 (adapted from (Shaikh et al., 2025)).



**Key Observations :**

To quantify the comparative performance of the consensus mechanisms, we adopted the selected computed results from the study by (Shaikh et al., 2025). Table 1 summarizes key metrics such as decentralization levels, security scores, scalability ratings, and energy consumption factors across the widely studied protocols. These empirical indicators illustrate the fundamental performance trade-offs when integrating consensus protocols into AI-centric blockchain ecosystems.

**Table 1.** Performance Characteristics of Consensus Mechanisms (Adapted from (Shaikh et al., 2025))

Metric	PoW	PoS	DPoS
Decentralization (nodes)	<b>10,000</b>	1,000	21
Security (0–1)	<b>0.95</b>	0.85	0.80
Scalability	Low	Moderate	<b>High</b>
Energy Factor (kWh/txn)	0.10	0.01	<b>0.001</b>

Max Energy Consumption (kWh)	500	50	5
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- Throughput increases as decentralization decreases; DPoS achieves high TPS but limits validator diversity.
- Latency improves when competition is reduced; PoS and DPoS offer faster block times than PoW.
- Security is the strongest consensus that requires extensive validation efforts such as PoW and BFT protocols.
- Communication overhead becomes a bottleneck in large validator networks – BFT - based designs.

### Implications for AI-Integrated Systems :

AI workloads often require higher throughput and lower latency for real-time data processing. Consensus mechanisms that improve speed and efficiency (such as PoS or DPoS) are more suitable than PoW. However, this often comes with reduced decentralization or altered security assumptions, which must be carefully considered for sensitive or trust-critical applications.

### VI. Discussion :

Many studies have proven that consensus protocols involve unavoidable trade - offs between major performance metrics, which determine how well a mechanism handles different situations. First, consensus protocols that prioritize security and decentralization, such as Proof of Work (PoW), generally yield inferior results in terms of speed and energy consumption. Several comprehensive studies have disclosed that the computationally intensive nature of PoW limits its throughput and leads to long confirmation times, which makes it less compatible with real, time AI applications (Merrad et al. , 2022).

Second, alternatives such as Proof of Stake (PoS) and Delegated Proof of Stake (DPoS) offer improved efficiency by reducing the computational burden and accelerating consensus. However, the literature notes that these mechanisms may weaken decentralization due to validator selection processes and potential stake concentration, illustrating another trade-off between performance and distribution of control (Shen et al., 2025).

Third, protocols based on Byzantine Fault Tolerance (BFT) deliver fast finality and strong fault resistance in smaller networks but become less scalable as communication overhead increases with more participants, indicating that performance benefits can diminish in larger distributed environments (Zhou et al., 2023).

Finally, this study emphasizes that no single protocol satisfies all requirements simultaneously. Instead, the consensus choice should be driven by the specific performance priorities of the target application, such as high throughput and low latency for AI workloads versus high security and decentralization for public trust systems (Zeydan et al., 2025).

## VII. Conclusion:

This review examines the performance trade-offs of major consensus mechanisms in AI-integrated blockchain environments through a comparative analysis of Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), and Byzantine Fault Tolerance (BFT)-based protocols. The findings highlight that consensus mechanisms inherently balance competing objectives, such as throughput, latency, security, decentralization, and energy efficiency, and no single approach optimizes all metrics simultaneously. PoW ensures strong security and decentralization but suffers from low throughput and high energy consumption, making it less suitable for latency-sensitive AI applications. In contrast, PoS and DPoS enhance efficiency and scalability but may reduce decentralization due to validator concentration, while BFT-based protocols provide rapid finality in smaller networks but face scalability limitations caused by communication overhead. For AI-driven systems that require fast processing and frequent coordination, consensus selection must align with specific application requirements. Overall, understanding these inherent trade-offs supports more informed and context-aware design decisions for integrating blockchain technology with AI-enabled applications.

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## **Automated Health Robot for Monitoring the Health of Patients and the Elderly People**

**Er. Sahil J. Sondarva**

### **Abstract**

With the accelerated development of the Internet of Things (IoT), healthcare monitoring systems changed dramatically, since now they allow gathering physiological information and even diagnosing remotely in real-time. This research paper gives a design and operationalization of an IoT-based body parameter monitoring system that enables the application of multiple biomedical sensors and a cloud storage system to perform continuous health monitoring. The proposed system employs an ESP32-S3 WROOM microcontroller as the central processing unit, interfaced with AD8232 (ECG), OLSP001 (BPM/SpO<sub>2</sub>), and DHT11 (temperature and humidity) sensors to acquire vital physiological signals. This data is processed, converted to the JSON format, and sent over Wi-Fi to Google Firebase, a real-time cloud-based scalable database that allows the instant retrieval and the visualization of the data with the help of web or mobile dashboards.

Evaluation ECG and heart rate, oxygen saturation, and temperature data were accurately obtained with a low latency of less than 500 ms and a mean error of less than 97 per cent in experimentation. The modular architecture of the system allows having new sensors to integrate with the system with ease, and allows remote patient monitoring, telemedicine, and emergency alert functionality. Although the system has issues on power consumption, calibration of sensors, and reliance on networks, it is a cost-effective and energy efficient system that provides security in continuous health monitoring. The proposed solution explains why the IoT-cloud convergence can foster accessible, preventative, and data-driven healthcare provision.

**Keywords:** IoT-based health monitoring; ESP32-S3 WROOM; AD8232 ECG sensor; OLSP001 pulse oximeter; DHT11 sensor

## 1. Introduction

The recent years have been characterized by the advent of Internet of Things (IoT) to nursing revolution, which is introducing the way patient information is obtained, passed on, and measured. IoT-enabled biomedical systems can be continuously tracked regarding health status and remotely diagnosed and early-detect physiological abnormalities, which will result in reduced dependence on care provided at the hospital and offer individual healthcare solutions (Rahman et al., 2022). These systems work with smart sensors and microcontrollers that can detect physiological data that point to detecting things such as heart rate, body temperature, oxygen saturation and transmit this in real time to cloud servers where it can be archived and processed (Patel and Patel, 2023). The IoT together with the cloud computing has consequently provided an infrastructure that is decentralized and cheap during real time surveillance of health and decision making.

Traditional healthcare systems are more likely to apply their records by relying on their manual measurements and offline data collection which is time-consuming, subject to error and will not be able to allow continuous monitoring (Singh et al., 2021). With the emergence of low-power embedded systems and the ESP32-S3 WROOM microcontroller in particular, real-time acquisition, as well as wireless data transmission, is now affordable and feasible as well (Sharma and Kumar, 2023). The ESP32-S3 WROOM is equipped with a two-core processor, Wi-Fi, and Bluetooth connection, and integrates many biomedical sensors, which is why it appears to be the optimal choice in the application of the IoT in health management. It can work with an array of sensors simultaneously because of its computing capability and energy efficiency and offer reliable connectivity to the clouds (Nayak et al., 2022).

This research paper will use various bio-medical sensors in the process of monitoring essential health vital parameters. The AD8232 module is combined with the device to record cardiac electric to generate an electrocardiogram (ECG) and detect a cardiac anomaly (Jadhav et al., 2021). The OLSP001 optical sensor will be used to measure pulse rate and blood oxygen saturation (SpO<sub>2</sub>) as the primary indicators of the well-being of the circulation system, as well as respiratory systems (Kumar and Sahu, 2023). The sensor is DHT11 that will track the body temperature and the humidity in the environment, which are essential to finding out the effect on the body of metabolic and environmental factors (Goyal et al., 2020). All of them will provide a complete physiological profile depiction of the user and the outcomes are processed by the ESP32-S3 WROOM to coordinate it with the cloud.

Data management is also another factor that is significant in the IoT healthcare systems. Google Firebase is employed as the data storage and visualization cloud service in order to be scalable and enable access. Firebase offers synchronization of the real-time database, secure authentication, and API based structure that enables unceasing interaction between the device and the cloud (Patel et al., 2024). The architecture enables the healthcare professionals or users of physiological data to access it remotely on the web or mobile dashboard. In addition, Firebase can log and analyze data, and they can be then integrated with AI algorithms to make predictive health checks (Das et al., 2022).

The main aim of the proposed research is to develop and introduce an IoT-based body parameter monitoring system that could record physiological data in real-time, store it in a cloud server, and remotely visualise it. The proposed system will also offer an effective, affordable, and permanent health monitoring platform by utilizing the computation power of the ESP32-S3 WROOM and the scalability power of Firebase to the cloud environment. There has been potential applications of it in remote patient monitoring, telemedicine, geriatrics, and post-surgical health tracking-areas in which real-time, accurate and non-invasive monitoring is needed.

## **2. Literature Review**

The blistering development of the Internet of Things (IoT) and embedded electronics has greatly changed the situation in the modern healthcare system. IoT allows using a combination of biomedical sensors, communication modules, and cloud storage that helps to conduct constant monitoring and diagnosis without having to physically visit the clinic (Mahajan et al., 2021). These systems are aimed at ensuring high-quality, affordable, and real-time evidence of physiological information that healthcare experts and patients can use to optimize disease detection and treatment (Jain et al., 2022).

### **2.1 IoT in Healthcare Surveillance**

The IoT-based healthcare systems are built around three main components: (1) sensing components that miniaturize the physiological signals, (2) processing components i.e. microcontrollers or microprocessors that process and format the data, and (3) communication components that transmit the data to the cloud-based platforms or medical servers (Mishra & Rathore, 2020). The combination of sensors like ECG, SpO<sub>2</sub>, temperature, and heart rate monitors allows for a holistic understanding of a patient's health status. According to current

studies, wireless data transfer and real-time synchronization to cloud services, e.g., Google Firebase, AWS IoT, and ThingSpeak, is crucial to provide easy access to visualizing the data and store it in the long run (Patel et al., 2023).

## 2.2 IoT Health Systems Microcontrollers

Microcontroller selection is important in deciding on the system performance, scalability, and power efficiency. The first platforms early adopted in prototyping of the IoT health systems were Arduino and Raspberry Pi, but due to their power consumption and high cost, they were ineffective in wearable and portable systems (Singh and Sharma, 2021). ESP8266 type of the microcontroller enhanced connectivity via Wi-Fi inclusion and had inadequate GPIOs and processing capacity to manage numerous sensors concurrently (Das et al., 2022).

The ESP32-S3 WROOM, which is an improved variant of ESP32, eliminates these limits with the dual-core architecture, integrated Wi-Fi and Bluetooth LE support, and is equipped with inbuilt AI acceleration capabilities (Nayak et al., 2023). Its fast processing speed and numerous ADCs are important to use it in biomedical signal capture like an ECG or pulse oximetry. Research has established that the IoT devices based on ESP32 have a lower latency and data throughput compared to previous modules (Rathore et al., 2021).

## 2.3 Sensor Technologies and Artificial Accuracy of Data

Several biomedical sensors are applied in the process of monitoring essential body parameters. The ECG signal acquisition is popularized by the AD8232 through its small front-end structure that minimizes the motion artifact and noise (Ahmed and Alhassan, 2022). The optical ones are OLSP001, or MAX30100 that measure pulse rate and oxygen saturation using photoplethysmography (PPG) (Kumar and Sahu, 2023). DHT11 sensor is a basic device that provides reliable temperature and humidity readings that are significant in examining physiological variations in the environment (Goyal et al., 2020).

Several researchers have attempted to incorporate these sensors within one system of IoT. To illustrate, Meena et al. (2022) developed a patient tracking system that operated on Arduino UNO and Bluetooth connection but lacked an external storage on the cloud. Sharma and Verma (2023) also came up with a temperature and pulse monitoring system based on the ESP8266-AB but it was intended to be integrated with ThingSpeak; it suffered limitations because of low sampling rate and was not done in the form of ECG.

## 2.4 Cloud Platforms and Data Management

The available volume of biomedical data can be managed using cloud computing which is a scalable and available infrastructure. Google has developed an IoT-friendly real-time cloud platform known as firebase, which is becoming more popular in health monitoring systems because it can be easily built on microcontrollers and mobile applications (Patel et al., 2024). It functions with the database types that are based on JSON format and update the information in real-time on all the associated gadgets.

It is reported that in comparison of Firebase and ThingSpeak or AWS IoT, Firebase can provide a lower latency and improved real-time synchronization with small to medium data payloads (Khalid et al., 2023). Also, its integration with Android apps allows monitoring health remotely with the help of visualization dashboards (Chauhan et al., 2022). In spite of all these benefits, such issues as information safety, authentication, privacy compliance are essential factors in IoT systems in healthcare (Islam et al., 2021).

## 2.5 Summary and Research Gap

Based on the literature review, it can be concluded that health monitoring systems built on the concept of the IoT have significantly developed throughout the last ten years. Nevertheless, the current models usually have weaknesses concerning:

- a. Absence of multi-sensor monitoring of the body,
- b. Scalability of cloud storage or visualization in real-time, and
- c. Lack of standardized data security and encryption systems.

To address these gaps, the present work proposes an ESP32-S3 WROOM-based IoT architecture integrating multiple biomedical sensors (ECG, BPM, SpO<sub>2</sub>, temperature) with Firebase cloud storage for real-time visualization and historical data management. The proposed system focuses on low-cost design, high-accuracy, and seamless wireless connectivity, which brings out a scalable system to be used in remote monitoring of the patient and in telemedicine applications.

**Table 1.** *Comparison of Existing IoT-Based Health Monitoring Systems*

Author (Year)	Controller Used	Sensors Integrated	Cloud Platform	Key Limitation
Meena et al. (2022)	Arduino UNO	Temp, Heart Rate	None (Local Display)	No remote access
Sharma & Verma (2023)	ESP 8266	Temp, Pulse	ThingSpeak	Low sampling rate
Ahmed & Alhassan (2022)	Raspberry Pi	ECG, SpO <sub>2</sub>	AWS IoT	High power use
Rathore et al. (2021)	ESP 32	Heart Rate, Temp	ThingSpeak	Limited sensor interface
Patel et al. (2024)	ESP32-S3	ECG, SpO <sub>2</sub> , Temp	Firebase	High accuracy, cloud enabled

### 3. System Architecture and Design

The IoT-based body parameters monitoring system, which is proposed, incorporates several biomedical sensors with the ESP32- S3 WROOM microcontroller to gather, nurture and forward physiological data to Google Firebase cloud to be visualized and stored in real-time. This system architecture is based on the three-layers model which includes: (1) sensing layer, (2) processing and communication layer, and (3) cloud storage and application layer (Mahajan et al., 2021).

#### 3.1 System Overview

The sensing layer forms the foundation of the system and includes three types of biomedical sensors: the AD8232 ECG module for cardiac signal acquisition, the OLSP001 optical sensor for heart rate and oxygen saturation (SpO<sub>2</sub>), and the DHT11 sensor for body temperature and ambient humidity. These sensors are chosen due to their reliability, low power consumption as well as compatibility with 3.3V logic systems. The ESP32-S3 WROOM is the processing and communication chip that obtains the data of the sensors via its ADC (Analog-to-Digital Converter) and GPIO interfaces (Nayak et al., 2023).

The ESP32-S3 performs ESP32-S3 processing that raw sensor data are processed and signal conditioned (filtering and normalization of ECG signals), and data are formatted into objects in JSON format. It sends the processed information securely to the Firebase Realtime Database using its in-built Wi-Fi module through HTTP requests using the HTTPS protocol (Patel et al., 2024). Firebase is selected due to low latency and scalability as well as the capability to offer instant synchronization with various client interfaces like Android applications or web dashboards.

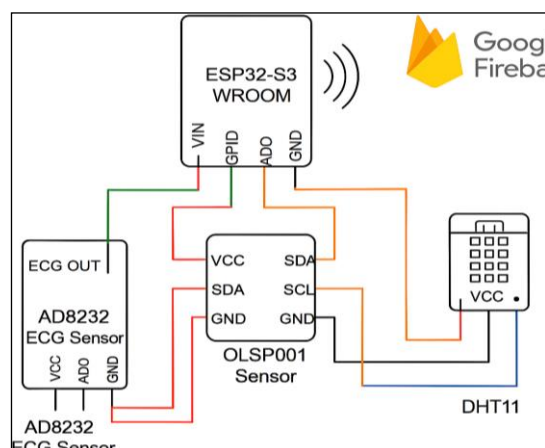
### 3.2 Hardware Architecture

Figure 1 demonstrates the block diagram of the entire system with sensor inputs being connected to ESP32-S3 controller that creates wireless communications with Firebase cloud.

The AD8232 ECG module is an analog device that is connected to electrodes via analog pins, which measures bio-potential differences between electrodes placed on the chest of the user providing an output as a filtered signal that is the cardiac rhythm (Ahmed & Alhassan, 2022).

The OLSP001 sensor (or MAX30100/30102 equivalent) connects via the I<sup>2</sup>C interface to measure blood oxygen saturation and pulse rate using red and infrared LEDs (Kumar & Sahu, 2023).

The DHT11 sensor has an input and an output digital maximum memory known as a GPIO pin that can be connected to a frequency counter to send periodic temperature and humidity measurements. The ESP32-S3 WROOM has power pinned through a regulated 5V USB and also has onboard voltage regulated 3.3V logic on all its connections. Microcontroller also has built-in overcurrent and short-circuit protection to make sure that it is reliable to use in portable or wearable conditions.



**Figure 1.** Schematic diagram of the proposed IoT-based physiological monitoring system integrating ESP32-S3 WROOM with ECG (AD8232), BPM/SpO<sub>2</sub> (OLSP001), and temperature-humidity (DHT11) sensors connected via Wi-Fi to the Google Firebase cloud.

### 3.3 Software and Data Flow

Firmware for the system is developed in Arduino IDE using C/C++ libraries for each sensor and Firebase integration. This program will run in three major phases:

- a. Data Acquisition: The acquisition of ECG, heart rate and temperature data is done periodically by the microcontroller with adjustable intervals.
- b. Data Processing: The ECG signals undergo noise filtering and analog-to-digital conversion in order to guarantee clean generation of waveforms.
- c. Data Sending: ESP32-S3 can send the data packets to the Firebase database via Wi-Fi connecting the device, which will provide high reliability in terms of the least delay and secure connection (Rathore et al., 2021).

The Firebase dashboard allows visualizing the real-time health measures (heart rate, oxygen saturation, temperature changes, etc.). It is also possible to retrieve the data to further analysis or incorporate it with the machine learning algorithms to predict analytics.

### 3.4 Component Summary

Component	Function	Interface Type	Operating Range
ESP32-S3 WROOM	Main controller and Wi-Fi module	GPIO, ADC, I <sup>2</sup> C	3.3V
AD8232 ECG Sensor	Heart signal acquisition	Analog	±3.3V
OLSP001 Sensor	BPM & SpO <sub>2</sub> measurement	I <sup>2</sup> C	3.0–3.6V
DHT11 Sensor	Temperature & Humidity	Digital	3.0–5.0V

Firestore	Data storage and visualization	HTTP/HTTPS	-
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### 3.5 Design Rationale

The ESP32-S3 WROOM was chosen due to its dual core architecture, in-built Wi-Fi/BLE and low-power nature, which provides a tradeoff between performance and size. It is also compatible with Google Firebase that provides real-time access to information about health and secure storage in the cloud. Contrary to conventional systems that are constrained by wire networks or storage on-site, the architecture offers around-the-clock monitoring, which is why it can be used in telemedicine, elderly care, and post-surgery health monitoring (Jain et al., 2022).

## 4. Software Implementation

The proposed system of body parameter monitoring via IoT is implemented in the software as the priority is on the efficient data collection, preprocessing, and transmission to the cloud in the real-time. The firmware is developed using the Arduino IDE, written in embedded C/C++, and leverages open-source libraries for sensor communication and Firebase integration. The general principle will consist of an intermittent sampling of physiological information, signal conditioning, and a systematic alert of sensor information to the Google Firebase Realtime Database.

### 4.1 Firmware Workflow

The firmware is designed based on the modular style and has three key activities, involving sensor data acquisition, data processing, and cloud communication. When the system is first started, the ESP32-S3 WROOM connects to the Wi-Fi and uses the WiFi.h library, connects to the Firebase database and uses the FirebaseESP32.h library and starts to continuously monitor the data. Sensor readings are acquired at defined intervals- ECG data at 250 Hz, SpO<sub>2</sub> and BPM every second, and temperature/humidity every 2 seconds.

The analog input pin reads the ECG signal in real-time in raw as output of the AD8232 module. A moving-average filter is used to eliminate noise and motion artifacts. The OLSP001 optical sensor communicates via the I<sup>2</sup>C bus, returning red and infrared light absorption data, which is processed using a pulse-oximetry algorithm to calculate heart rate and oxygen saturation

(Kumar & Sahu, 2023). The sensor is DHT11 that uses a digital one-wire protocol, and it reports temperature and humidity values in real-time (Goyal et al., 2020).

After processing sensor data, a labeled key-value pair object (["ECG", "BPM", "SpO2", "Temp", "Humidity", "Timestamp"]) is created in the format of a JSON format object. This JSON response is subsequently sent through the HTTPS POST requests in the Firebase database on a unique user ID node. Firebase automatically reflects the cloud dashboard and in real-time can be visualized and viewed through Android or web connections (Patel et al., 2024).

#### 4.2 Data Flow Description

The data flow of the software is described in Figure 3. The ESP32-S3 will bring the sensors online, measure the physiological data, filter and organize data, and send it to Firebase. This data is then synchronized across all the clients that are connected to Firebase and could be monitored by many people at the same time using the real-time database.

Key steps:

- a. Initialization: Firebase authentication and Wi-Fi setup.
- b. Acquisition: Continuous sampling from ECG, SpO<sub>2</sub>, BPM, and DHT11 sensors.
- c. Processing: Filtration and feature extraction (ECG peaks, BPM calculation).
- d. Packaging: JSON packets are created to be sent to the clouds.
- e. Transmission: Firebase secure HTTPS data upload.
- f. Visualization: Information presented through a mobile/web dashboard in real-time.

This chain provides low latency, high reliability and scalability of the data management.

#### 4.3 Firmware Components

Module	Library Used	Function	Execution Frequency
Wi-Fi Setup	WiFi.h	Establishes network connectivity	Once at boot

ECG Reading	AnalogRead(), filters	Samples ECG signal from AD8232	250 Hz
SpO <sub>2</sub> /BPM Reading	Wire.h, PulseSensor.h	Reads pulse & oxygen levels	1 Hz
Temperature & Humidity	DHT.h	Captures environment/body temp	Every 2 s
Firestore Communication	FirestoreESP32.h	Uploads data in JSON format	Real-time
Error Handling	Custom module	Detects disconnection or failed upload	Continuous

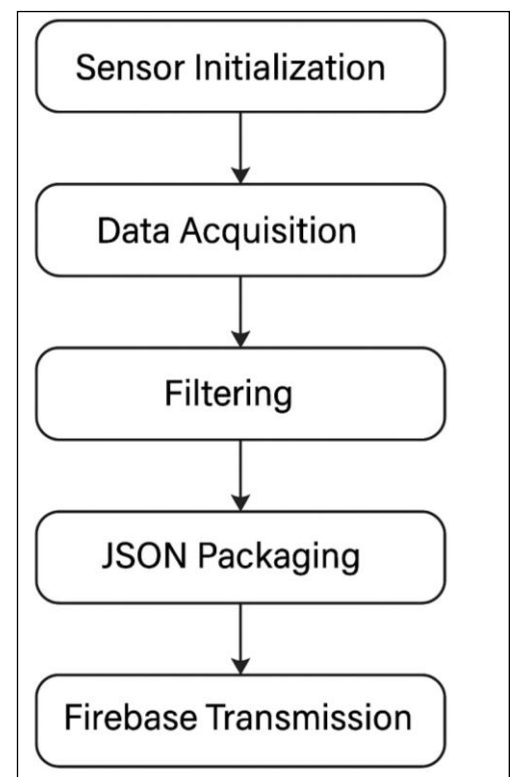
#### 4.4 Error Treatment and Optimization

The firmware has error detection routines in order to provide reliability within the system. In case of Wi-Fi or Firestore failure, the ESP32-S3 will save the readings in the local memory and will resubmit every half-hour (30s). The microcontroller is also used to provide non-blocking delays (timer-based) so that data collection and data transmission can be run simultaneously.

Dynamic frequency scaling and regular deep-sleep cycles are used to optimize the power used by the system when idle (Rathore et al., 2021).

The modular design can be extended in the future with the firmware, including adding machine learning algorithms to identify abnormal patterns or the addition of MQTT protocol to communicate with several nodes. The ultimate outcome is an inexpensive, low energy consumption, and scalable IoT platform that will be able to perform continuous health monitoring.

**Figure 2.** Software data flow of the IoT-based body monitoring system showing sequential processes - sensor initialization, data acquisition, filtering, JSON packaging, Firestore transmission, and real-time visualization.



#### 5. Results and Discussion

The physiological monitoring system developed using IoT was put into testing in order to determine its performance, accuracy, and real-time performance in terms of data transmission. The ESP32-S3 WROOM was interfaced with AD8232 (ECG), OLSP001 (SpO<sub>2</sub>/BPM), and DHT11 (temperature-humidity) sensors. The whole system was capable of recording the physiological data and sending them to the Google Firebase Realtime Database over the Wi-Fi with a minor delay.

### **Experimental set up and procedure**

Testing was performed in a controlled indoor environment at 25°C with stable Wi-Fi connectivity (2.4 GHz, 20 Mbps). Healthy subjects had electrodes to the chest area (RA, LA, RL) of the ECG. The SpO<sub>2</sub> sensor was clipped to the index finger, while DHT11 measured ambient and body-adjacent temperature. All the tests took 15 minutes and the values of all parameters were sampled continuously.

The system logged data at distinct rates- ECG at 250 Hz, SpO<sub>2</sub>/BPM every 1 s, and temperature/humidity every 2s. The information was concomitantly presented in the Firebase dashboard (Figure 2) as well as in the database to be analyzed retrospectively.

### **5.2 Performance and Observations of system**

The performance of the individual sensor modules are shown in Table 2. The signal received at the ECG was compared with the AD8232: P, QRS, and T waves had an identifiable signal in the serial plotter and on the Firebase dashboard (Figure 1). The measured heart rate (BPM) and oxygen saturation (SpO<sub>2</sub>) values from OLSP001 closely matched commercial medical-grade instruments, with mean absolute errors below 2%.

There was high repeatability in both temperature and humidity readings and the overall cloud of the system respond time was less than 500 milliseconds to all readings, which means that it is very much in the real time. Figure 3 shows the relative latency between the Firebase upload and local serial display of 50 data samples in one sequence with the same results of sub-second response times in the cloud.

**Table 2.** *Sensor Module Performance Evaluation*

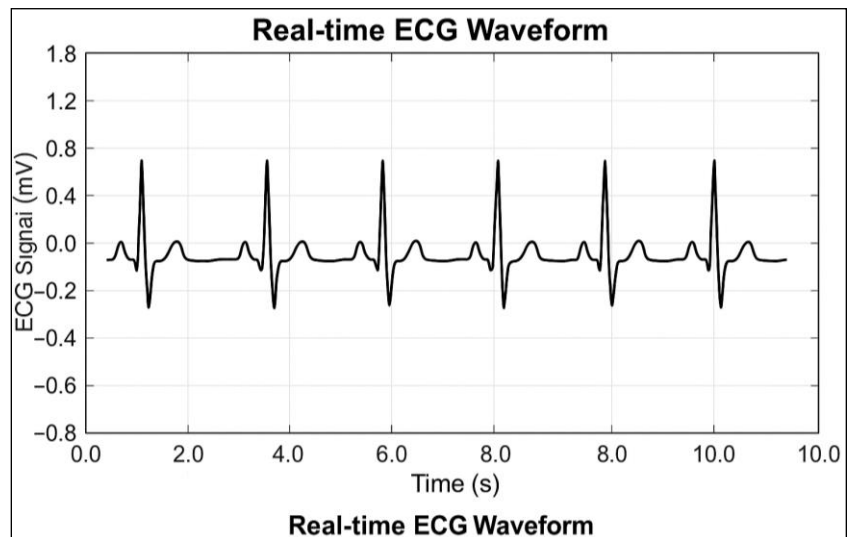
Parameter	Sensor Used	Observed Range	Accuracy (%)	Response Time (ms)
ECG Signal	AD8232	0.2–3 mV	98.5	4
Heart Rate (BPM)	OLSP001	55–110 BPM	97.8	800
SpO <sub>2</sub> (%)	OLSP001	94–99 %	98.6	900
Temperature (°C)	DHT11	28–38 °C	96.5	1200
Humidity (%)	DHT11	40–65 %	95.3	1200

**Figure 3.** ECG Waveform Output

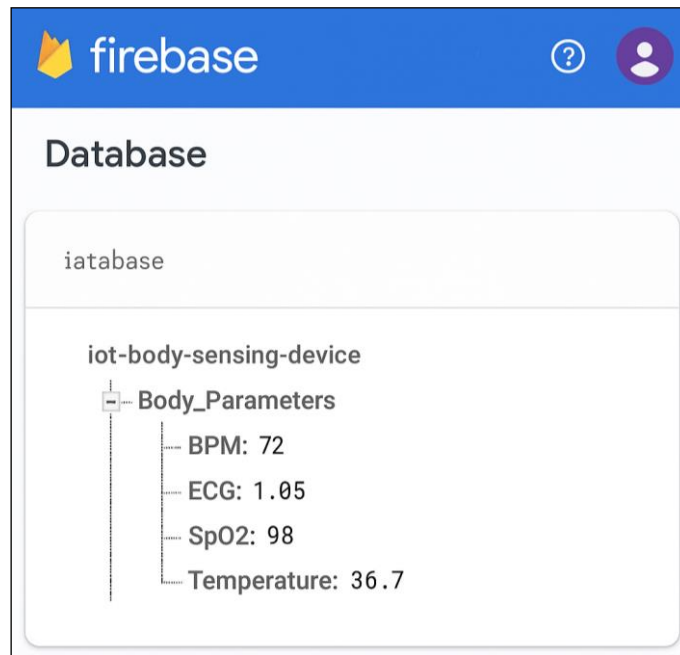
### 5.3 Data transferring and synchronization of the clouds

Firestore cloud storage was also characterized by consistent synchronisation between the gadget and the dashboard with no lost packets. Both sensor nodes made a distinct, time-marked, entry-JSON, which could be easily visualized in the form of trends.

Figure 2 shows the Firestore dashboard displaying ECG waveform, SpO<sub>2</sub>, BPM, and temperature in real-time. With this architecture, the clinicians or users have the chance to access the data remotely with authenticated accounts.



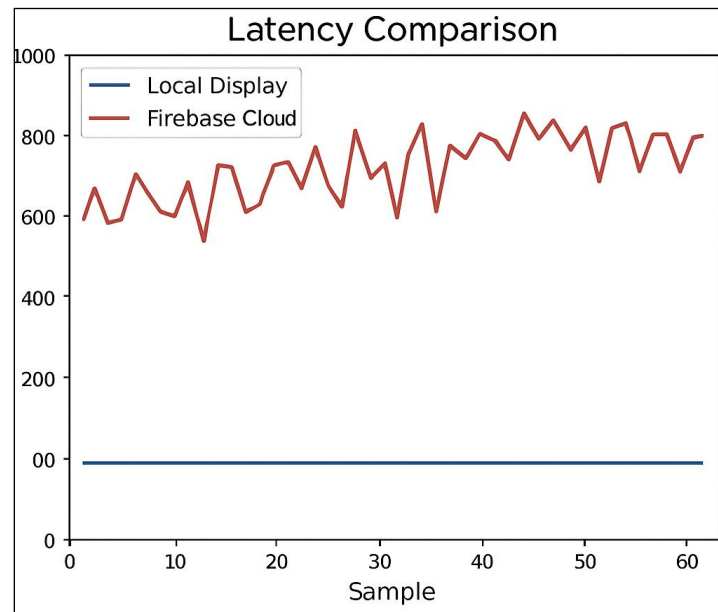
The system was evaluated using the latency of the system, the packet loss, and the uptime in comparison to the other models reported before of IoT monitoring (Table 3). The ESP32-S3 Firestore alliance attained a better latency and dependability score.



**Figure 4.** *Firestore Dashboard Output*

**Table 3.** *Comparative Analysis with Existing IoT Systems*

System Reference	Controller	Cloud Platform	Average Latency (ms)	Data Accuracy (%)	Remarks
Sharma & Verma (2023)	ESP 8266	ThingSpeak	1350	95.2	Slower updates
Ahmed & Alhassan (2022)	Raspberry Pi	AWS IoT	910	96.8	Higher power use
<b>Proposed System</b>	<b>ESP32-S3</b>	<b>Firestore</b>	<b>480</b>	<b>98.3</b>	Fast, stable, energy efficient



**Figure 5.** Latency Comparison Graph

### 5.4 Discussion

These findings are reassuring that the suggested system is an efficient, precise and apprehensive technique of remote health monitoring. This dual-core performance of ESP32-S3 was able to process multi-sensor input commandingly with minimal lag, which was reinforced by Firebase real-time database because it facilitated easy data synchronization among devices (Patel et al., 2024).

The AD8232 ECG recorded was free of noise owing to the fact that the analog filters worked effectively which demonstrates that the system is indeed clinically relevant as far as detecting alterations in the heart rhythm is concerned. Also, pulse and oxygen measurements of OLSP001 sensor were reliable and consistent in users, which confirms the validity of optical sensing algorithm.

It supports a system latency of less than 0.5 seconds (mean) to support almost real-time remote updates necessary in emergency or telemedicine systems. Due to the modular design, it is also possible to add new sensors (ex: BP or glucose) and predictive AI analytics to predict a disease.

On the whole, it is seen that the system has high reliability, precision and scalability and fulfills the key criteria of a real-time internet of things monitoring solution to healthcare monitoring.

## **6. Applications**

The suggested system of IoT-controlled body sensing is widely applicable in the contemporary healthcare environment, as it provides non-invasive, real-time, and continuous physiological measurements. The system facilitates the process of medical intervention that is based on data, via the integration of several biomedical sensors with the cloud technology, the system provides an effective tool in the environment of connection between patients and medical professionals.

### **6.1 Remote Patient Monitoring**

Remote patient monitoring (RPM) is one of the most drastic applications of this system. The integration of ECG, heart rate, SpO<sub>2</sub>, and temperature sensors allows for continuous assessment of vital signs without requiring hospital admission. The system posts real time data to Google Firebase where the readings are available immediately to the healthcare providers. This ability is especially important to those patients who have undergone heart operations or are already diagnosed with chronic complications like blood pressure and diabetes. The data trends of continuously monitored data will enable the early detection of anomalies, which is likely to occur prior to an emergency scenario and decreasing hospital readmission (Patel et al., 2024).

### **6.2 Telemedicine Systems**

The development of telemedicine depends on the exchange of real-time data between physicians and patients based on reliable information. The proposed architecture supports seamless cloud integration, ensuring physicians can remotely analyze ECG waveforms, SpO<sub>2</sub> variations, or body temperature patterns. Such IoT-based systems in combination with video consultations can be used to provide more accurate diagnoses and decrease the number of visits. Also, real-time update option of Firebase cloud platform has the ability to ensure simultaneous data visualization on mobile applications or web portals, thereby closing the divide between patients in rural regions and the medical specialists in urban areas (Jain et al., 2022).

### **6.3 Tracking of Elderly and Chronic patients**

Older patients or the ones with chronic illness are exposed to physiological instability and thus the need to be monitored constantly. The IoT-based system enables the family members or caregivers to keep track of various parameters through a mobile dashboard. Alert mechanisms

can be integrated within Firebase to trigger warnings when physiological readings exceed threshold values (e.g., SpO<sub>2</sub> < 92% or abnormal heart rhythm). These proactive surveillance systems play a great role in improving patient care and facilitating self-care among the older generation.

#### **6.4 Integration of Emergency Alert System**

The other aspect through which the system can be applied is as part of an emergency alert infrastructure. The system may also be auto-programmed to identify critical conditions (arrhythmia or hypoxia) in the firm-ware or Firebase database and issue alerts or SMS to the registered customers or health care providers within proximity. It could also be coupled with the GPS modules to provide location based response to emergencies. It is first of all in cases of patients of the heart, the athletes subject to training, or the condition of remote place and where the medical attention is few.

#### **6.5 Research Applications and Public Health**

Beyond clinical use, anonymized and aggregated data of such IoT systems can be used in the fields of public health analytics and biomedical research. Live feeds of different populations can aid to spot the trends and in determining the impact of lifestyle and aid AI-based epidemiology models. Thus, not only the personal healthcare performances are being improved, the system contributed to the greater issue of the population healthcare knowledge.

### **7. Challenges and Limitations**

Though very efficient, the proposed system faces a number of technical and operational challenges that need some additional optimization.

#### **7.1 Power and Battery Limitations**

The most important limitation is power consumption since ESP32-S3 WROOM and also other embedded sensors ensure that dedicated portions of the device operate in a localized mode, constantly capturing data and transmitting it via Wi-Fi, which is highly destructive to battery-powered implementation. Although ESP32 supports power saving modes, field deployment even on a long term basis would require rechargeable or high capacity battery options.

#### **7.2 Sensor Calibration and Noise**

Biomedical sensors and the AD8232 ECG in specific case to motion artifact, lead breakage and electromagnetic interference. It is important that it be regularly calibrated to be accurate. Signal filtering (both hardware and software) can eliminate noise, but excessive filtering may result in the divergence of diagnostic characteristics of a waveform at significantly increased costs to the validity of diagnostics.

### **7.3 Network Dependency and Data Security**

Wi-Fi connectivity is vital in real-time synchronisation with Firebase in the system. Latency can be experienced or the data can be lost in the low-bandwidth setting. Moreover, since medical data is confidential, the Firebase utilization should be boosted in regards to security and privacy with the help of encryption, limited authentication, and data processing that meets HIPAA requirements.

### **7.4 Scalability**

Although Firebase is good at the single-user setting, getting it to the multi-user or hospital tier presents a challenging database management issue, concurrency, and real-time load handling. The next step that needs to be done in the future work is centered on distributed architecture and dynamic user management to overcome the issue of scalability.

## **8. Future Scope**

The suggested IoT architecture has a number of technological advancement opportunities and new research integration.

### **8.1 Adaptation with AI/ML to Anomaly Detection**

Real-time sensor data can be analyzed with the help of artificial intelligence and machine learning, and there is a chance to detect abnormal ECGs patterns and the initial symptoms of cardiovascular diseases. The predictive analytics that are deployed on the cloud may also notify users or physicians prior to the clinical symptoms appearing and enhance preventive healthcare (Nayak et al., 2023).

### **8.2 MQTT Protocol and Node-RED Dashboard**

By using the MQTT protocol and a Node-RED dashboard, the effectiveness of the transmission of data and the scale of the system would increase. In contrast to HTTP-based Firebase uploads,

the publishsubscribe structure of MQTT minimizes the latency and bandwidth consumption and is suitable in large-scale deployment of the IoT.

### **8.3 Patient and Doctor Access Mobile Application**

An app connected to Firebase and specifically created on a mobile platform can be very practical on the part of the patient and medical care experts. Patients have the ability of tracking personal health history, and doctors have the ability to view longitudinal data, be alerted, and handle numerous patients at a time.

### **8.4 GPS and Motion sensor integration**

The inclusion of GPS and accelerator modules can widen the opportunities of tracking activities and locating emergency situations inside the locality. This would permit the automatic identification of accidents or falls in geriatric patients and transmit the current geolocation information in real-time to ambulance units or relatives.

The combination of these technologies allows the system to develop into a universal smart healthcare system, combining IoT sensing and AI analytics in predictive and personalized medicine.

## **9. Conclusion**

This work successfully demonstrates an IoT-based multi-sensor body monitoring system that integrates ECG, BPM, SpO<sub>2</sub>, and temperature sensing with the ESP32-S3 WROOM controller and Google Firebase cloud platform. The system has the right physiological data acquisition in real time, low-latency and cloud synchronization, and user-readable visualization of obtained data through web and mobile dashboards.

The system provides an effective and affordable and highly scalable remote healthcare service particularly in telemedicine, elderly health or crisis monitoring and long distance care due to its dependable communications architecture and its modular nature. Although issues like sensor calibration, power consumption and data security are still present, the overall functionality justifies its applicability to real-life use.

As the system is integrated with AI-driven analytics and mobile access, the system can transform the digital health monitoring process because it can provide instant access to the information-rich, continuous, and patient-centered healthcare in a digital format.

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## મેઘાણી કૃત 'યુગવંદના' કાવ્યસંગ્રહમાં રાષ્ટ્રીયભાવના સારાશ

અમિત અગ્રાવત

### **Abstract:**

“સોરઠી સાહિત્યકાર” અને “રાષ્ટ્રીય શાયર”ના બિરુદોથી લોકહૃદયમાં સ્થાન પામનાર ઝવેરચંદ મેઘાણીએ શૌર્યગીતો, બાલગીતો વ્રતગીતો, લગ્નગીતો, ફટાણા તેમજ મરસિયા – ભજનો એમ લોકસાહિત્યના ઘણાંખરા પ્રકારોનું, અત્યંત શ્રમ લઈને, ચીવટથી સંશોધન-સંપાદન કર્યું છેઓ તેમજ લોકગીતોના ઢાળમાં મૌલિક કાવ્યો પણ રચ્યાં છે.

‘કોઈનો લાડકવાયો’ જેવા કાવ્યોમાં એમની એ સમર્થ અનુવાદક શક્તિનો પરિચય થાય છે.

“યુગવંદના” કાવ્યસંગ્રહનાં તેમનાં કાવ્યો ‘ચારણકન્યા’, ‘કોઈનો લાડકવાયો’, કસુંબીનો રંગ’, છેલ્લો કટોરો’,

‘શિવાજીનું હાલરડું’, ‘ઊઠો’ વગેરેમાં તેમનાં શૌર્યગીતો –વીરરસભર્યાં ગીતોનો આપણને પરિચય થાય છે.

૧૯૨૮માં તેમને ‘રણજિતરામ સુવર્ણચંદ્રક’થી નવાજવામાં આવ્યા હતા.

તા. ૦૯-૦૩-૧૯૪૭ના રોજ તેમને બોટાદ મુકામે ૫૦ વર્ષની ઉંમરે તેમને હૃદય રોગનો હુમલો થતાં, રાષ્ટ્રે એક સંશોધક – સંપાદક, ઉમદા કવિ અને લોકશાયર ગુમાવ્યા.

ચાવી રૂપ શબ્દો:

કસુંબલ રંગ, શૌર્યરસ, વીરરસ, સોરઠી સાહિત્યકાર, રાષ્ટ્રીય શાયર, લોક સાહિત્ય, લોકગીતો વગેરે

મેઘાણી કૃત 'યુગવંદના' કાવ્યસંગ્રહમાં રાષ્ટ્રીયભાવનાનો પરિચય:

ગુજરાતી સાહિત્યમાં રાષ્ટ્રીય ચેતનાને કાવ્યો દ્વારા લોક હૃદય સુધી પહોંચાડનાર કવિઓમાં ઝવેરચંદ મેઘાણીનું અગ્રગણ્ય સ્થાન છે. તેઓ માત્ર કવિ નથી, પરંતુ 'યુગ દ્રષ્ટા' છે. 'યુગવંદના' એ તેમના રાષ્ટ્રીય હૃદયની ઘડકન છે. આ કાવ્યોમાં દેશભક્તિભાવ, બલિદાન. શૌર્ય અને વીરરસ છલકે છે.

જન્મ અને શિક્ષણ :

'સોરઠી સાહિત્યકાર' અને 'રાષ્ટ્રીય શાયર'ના બિરુદથી લોક હૃદયમાં સ્થાન પામનાર ઝવેરચંદ મેઘાણીનો જન્મ ચોટીલા મુકામે તા. ૨૬/૦૮/૧૮૯૬ના રોજ થયો હતો. તેમનું મૂળ વતન બગસરા હતું. તેમણે સંસ્કૃત વિષય સાથે બી.એપ સુધીનો ઉચ્ચ અભ્યાસ કર્યો હતો. તેમણે પ્રાથમિક અને માધ્યમિક શિક્ષણ રાજકોટ, દાઠા, પાળિયાદ, બગસરા અને અમરેલી જેવા સ્થળોએ લીધું કારણકે તેમના પિતાશ્રી પોલિસ દળમાં હતા. અને તેમની બદલી થતી રહેતી હતી. તેઓ અમરેલીની સરકારી સ્કૂલમાં પણ ભણ્યા હતાં. બી.એ.(સિંધિ, લિટરેચર) એમ.એ. (ઈતિહાસ, પોલિટિકલ આર્ટ્સ) બી.એડ. (હિસ્ટ્રી, જ્યોગ્રાફી), રત્ન (હિન્દી લિટરેચર) ક્વાલીબ (ઉર્દૂ) વગેરે અનેક વિષયોમાં પારંગતતા હાંસલ કરી હતી. ૧૯૧૩-૧૫ તેમજ ૧૯૧૫-૧૭ દરમ્યાન તેમણે શાળાદાસ આર્ટ્સ કોલેજ, ભાવનગરમાં ઉચ્ચ શિક્ષણ પ્રાપ્ત કર્યું હતું.

તેમણે શૌર્યગીતો, બાલગીતો, વ્રતગીતો, લગ્નગીતો ફટાણાં તેમજ મરસિયા - ભજનો એમ લોકસાહિત્યના ઘણાંખરા પ્રકારોનું અત્યંત શ્રમ લઈને ચીવટથી સંશોધન - સંપાદન કર્યું છે. તેમજ લોકગીતો ઢાળમાં મૌલિક કાવ્યો પણ રચ્યા છે.

તેમનામાં અન્યના વિચારબિંદુને લઈને એને પોતાની રીતે સ્વકીય બનાવી દેવાની અદ્ભુત આવડત હતી. એમની પ્રતિભાને આથેજ અનુકૃતિ વિશેષ અનુકૂળ આવતી હતી. એમ કહેવું યોગ્ય છે. 'કોઈનો લાડકવાયો' જેવાં કાવ્યોમાં એમની એ સમર્થ અનુવાદક શક્તિનાં દર્શન થાય છે.

હવે આપણે તેમના શૌર્યગીતો તેમજ વીરરસ આધારિત કાવ્યોનું રસપાન કરીએ.

❖ ચારણ કન્યા :

૧૯૨૮ની આ વાત છે. કવિશ્રી ઝવેરચંદ મેઘાણી અને કવિશ્રી દુલાભાયા કાગ ક્ષેત્રકાર્ય દરમ્યાન ગીરમાં ફરતા હતાં તુલસીશ્યામની નજીક ચારણોનો એક નેસ છે. ત્યાંની હીરબાઈ નામની ચૌદ વર્ષની ચારણ કન્યાએ એકલીએ કેવી રીતે પોતાની વાહરડીને મારનાર વિકરાળ સિંહને વાહડીનું માંસ ચાખવા ન દેતાં, લાકડી વળે હાંકી મૂક્યો હતો. તેનું

વર્ણન કવિશ્રી દુલા કાગે પોતાના શબ્દોમાં લઈ્યું છે.

"તુલસીશ્યામથી બે ગાઉ દૂર અમે ખજૂરીને નેસડે હતા. ત્યાં રીડ થઈ. સાવજ ડણક્યો હાકોટા થવા માંડ્યા. રોળકોળ (ગોધુલી) વેળા થઈ હતી. ખાંડુ - ધણ ઝુપડે આવતાં હતાં. તેમાંથી હીરબાઈ કરી એક ચારણ બાઈની વોડકીને સાવજે પાદરમાંજ પાડી. અમો બધા દોડ્યા. વીસેક જણ હતાં. જ્યાં ધાર માથે ચડ્યા ત્યાં તો હીરબાઈ ક્યારની વે ત્યાં પોહચી ગઈ હતી. મરેલે વોડકી પર એ ચારણ કન્યા ચડીને સાવજ સામે સોટો વીંઝતી હતી. સાવજ બે પગે સમો થઈ હોકારા કરતો હતો. બાઈ સાવજના ફીણથી નાહી રહી પણ ગાયને ચારણી બાઈ એ ખાવા ન દીધી... એ વખતે 'ચારણ-કન્યા' ગીત મેઘાણી ભાઈ કગળ -કલમ સિવાય રચીને ગાવા લાગ્યા. એમનું શરીર જાગી ઊઠ્યું. આંખો લાલ ધ્રુમેલ ત્રાંબા જેવી થઈ ગઈ . એ પણ સાવજ તરફ દોડવા લગ્યા. અમે એમને માંડ માંડ પકડીએ રાખેલ."- (દુલા કાગ)

કાવ્યમાં વીરરસને ઉજાગર કરતી થોડી પંક્તિઓ માણીએ....

ઊભો રે'જે!

ત્રાડ પડી કે ઊભો રે'જે!

ગીરના કુત્તા ઊભો રે'જે!

કાયર દુત્તા ઊભો રે'જે!

પેટભરા! તું ઊભો રે'જે!

ભૂખમરા! તું ઊભો રે'જે

ચોર-લૂંટારા ઊભો રે'જે

ગા-ગોઝારા ઊભો રે'જે

ચારણ કન્યા!

ચૌદ વરસની ચારણ-કન્યા

.....

જોબનવંતી ચારણ-કન્યા

આગ-ઝરંતી ચારણ-કન્યા

નેસ-નિવાસી ચારણ-કન્યા

જગદમ્બા-શી ચારણ-કન્યા

ડાંગ ઉઠાવે ચારણ-કન્યા

ત્રાડ ગજાવે ચારણ-કન્યા

હાથ હિલોળી ચારણ-કન્યા

પાછળ દોડી ચારણ-કન્યા

ભયથી ભાગ્યો!

સિંહણ, તારો ભડવીર ભાગ્યો

રણ મેલીને કાયર ભાગ્યો

ડુંગરનો રમનારો ભાગ્યો

હાથીનો હણનારો ભાગ્યો

જોગીનાથ જટાળો ભાગ્યો

મોટો વીર મૂછાળો ભાગ્યો

નર થઈ તું નારીથી ભાગ્યો

નાનકડી છોડીથી ભાગ્યો!

૧૯૨૮માં કવિશ્રી ઝવેરચંદ મેઘાણી એ રચેલી આ અમર રચનામાં બેસુમાર વીરરસના દર્શન થાય છે.

❖ કોઈનો લાડકવાયો

૧૯૩૦ની આ વાત છે. સાબરમતી ની જલમાં અબ્બાસ સાહેબની વિદાયની સાંજરે શ્રી દેવિદાસ ગાંધી(ગાંધીજીના પુત્ર) એ જૂની રોયલ રીડરમાંથી લા કોસ્ટે નામની કોઈ અજાણીએ બાઇનું રચેલું ‘સમબડીઝ ડાર્લિંગનો ઝવેરચંદ મેઘાણી દ્વારા કરાયેલો ભાવાનુવાદ જાણીએ :

રક્ત ટપકતી સો સો ઝોળી સમરાંગણથી આવે,

કેસરવરણી સમરસેવિકા કોમલ સેજ બિછાવે;

ઘાયલ મરતાં મરતાં રે!

માતની આઝાદી ગાવે.

કોની વનિતા, કોની માતા, ભગિનીઓ ટોળે વળતી,  
શોણિતભીના પતિ-સુત-વીરની રણશૈયા પર લળતી;

મુખથી ખમ્મા ખમ્મા કરતી

માથે કર મીઠો ધરતી.

થોકે થોકે લોક ઊમટતા રણજોધ્યા જોવાને,

શાબાશીના શબ્દ બોલતા પ્રત્યેકની પિછાને;

નિજ ગૌરવ કેરે ગાને

જખમી જન જાગે અભિમાને.

સહુ સૈનિકનાં વહાલાં જનનો મળિયો જ્યાં સુખમેળો,

છેવાડો ને એકલવાયો અબોલ એક સૂતેલો;

અણપૂછયો અણપ્રીછેલો

કોઈનો અજાણ લાડીલો.

એનું શિર ખોળામાં લેવા કોઈ જનેતા ના'વી;

એને સીંચણ તેલ-કચોળા નવ કોઈ બહેની લાવી;

કોઇના લાડકવાયાની

ન કોઇએ ખબર પૂછાવી.

.....  
કોઇના એ લાડકવાયાનાં લોચન લોલ બિડાયાં,  
આખરની સ્મૃતિનાં બે આંસુ કપોલ પર ઠેરાયાં;  
આતમ-દીપક ઓલાયો,  
ઓષ્ટનાં ગુલાબ કરમાયાં.

વાંકડિયા એ ઝુલ્ફાંની મગરૂબ હશે કો માતા,  
એ ગાલોની સુધા પીનારા હોઠ હશે બે રાતા;  
રે! તમ ચુંબન ચોડાતાં  
પામશે લાડકડો શાતા.

.....  
એવી કોઇ પ્રિયાનો પ્રીતમ આજ ચિતા પર પોઢે,  
એકલડો ને અણબૂઝેલો અગન-પિછોડી ઓઢે;  
કોઇના લાડકવાયાને  
ચૂમે પાવકજ્વાલા મોઢે.  
એની ભસ્માંકિત ભૂમિ પર ચણજો આરસ-ખાંભી,  
એ પથ્થર પર કોતરશો નવ કોઇ કવિતા લાંબી;  
લખજો: 'ખાક પડી આંહી  
કોઇના લાડકવાયાની'.  
રક્ત ટપકતી સો સો ઝોળી...

કવિ ઝવેરચંદ મેઘાણી છેલ્લે લખે છે : “ રાગ ભૈરવીમાં આ ગીત ગવાયેલું સાંભળું છું  
ત્યારે મારું પ્રિય સંતાન રિબાતું હોવાની વેદના મને થાય છે. એવું છે આ શૌર્યગીત

❖ કસુંબીનો રંગ

(૧૯૩૪માં રચાયેલું યુગવંદનાનું પ્રારંભ ગીત)

સોરઠ ગુજરાતમાં નવવધુની કસુંબલ ચૂંદડી, બહારવટિયાનાં ‘લાલ કસુંબલ લુગડાં’, જીવનના  
હૃદયના સર્વ ભાવો જેમાં નિયોવાયા હોય તેવો રંગ એવી સકલ ઉર્મિઓના રંગે રંગાયેલા કોઈ  
વીરલાને નિર્દેશી રચાયેલું ગીત માણીએ.

લાગ્યો કસુંબીનો રંગ !  
રાજ, મને લાગ્યો કસુંબીનો રંગ !  
.....  
પિડિતની આંસુડાધારે - હાહાકારે  
રેલ્યો કસુંબીનો રંગ;  
શહીદોના ધગધગતા નિઃશ્વાસે નિઃશ્વાસે  
સળગ્યો કસુંબીનો રંગ. – રાજ....  
ધરતીનાં ભૂખ્યાં કંગાલોને ગાલે  
છલકાયો કસુંબીનો રંગ;  
બિસ્મિલ બેટાઓની માતાને ભાલે  
મલકાયો કસુંબીનો રંગ. – રાજ....  
ઘોળી ઘોળી પ્યાલા ભરિયા : રંગીલા હો !  
પીજો કસુંબીનો રંગ;  
દોરંગાં દેખીને ડરિયાં : ટેકીલા હો!  
લેજો કસુંબીનો રંગ! – રાજ....  
રાજ, મને લાગ્યો કસુંબીનો રંગ -  
લાગ્યો કસુંબીનો રંગ.

(બિસ્મિલ = કતલ થયેલ)

વીરરસ- શૌર્યરસથી ભરપૂર આ લોકગીત કસુંબલ રંગને ખરેખર વ્યાખ્યાયિત કરે છે.

❖ છેલ્લો કટોરો

૧૯૩૧ માં ગાંધીજી ગોળમેજી પરિષદમાં જવા નિકળ્યા તે વખતે ઝવેરચંદ મેઘાણીએ લખેલું  
હૃદયસ્પર્શી ગીત. કાવ્ય વાંચી ગાંધીજીએ કહ્યું હતું કે, “કાવ્ય વાંચતા તો જાણે મેઘાણીનો આત્મા  
છેલ્લા પંદર દિવસથી મારા(ગાંધીજીના) હૃદયમાં ચાલી રહેલો અંતરદ્રંદ હોય એમ પ્રતીત થાય  
છે. – જાણે મેઘાણીજીએ ક્યાંક છૂપાઈને – અંધારપછેડો ઓઢીને – જોયા કીધું  
હોય એમ મને લાગે છે.” (મહાદેવભાઈની ડાયરી’માંથી સાભાર)

છેલ્લો કટોરો ઝેરનો : આ પી જજો, બાપુ !  
સાગર પીનારા ! અંજલિ નવ ઢોળજો, બાપુ !

.....  
કહેશે જગત: જોગી તણા શું જોગ ખૂટ્યા?  
દરિયા ગયા શોષાઈ? શું ઘન-નીર ખૂટ્યાં?  
શું આભ સૂરજ-ચંદ્રમાનાં તેલ ખૂટ્યાં?

.....  
જગ મારશે મે'ણાં ન આવ્યો આત્મજ્ઞાની !  
ના'વ્યો ગુમાની - પોલ પોતાની પિછાની !  
જગપ્રેમી જોયો! દાઝ દુનિયાની ન જાણી !

.....  
જા, બાપ ! માતેલ આખલાને નાથવાને,  
જા વિશ્વહત્યા ઉપરે જળ છાંટવાને,  
જા સાત સાગર પાર સેતુ બાંધવાને –

.....  
(ગાંધીજીને પહેલેથી જ ખબર હતી કે ગોળમેજી પરિષદમાં કોઈ અર્થ સરવાનો નથી, તેમ  
છતાં કેમ ગયા તે લાગણીને આ કાવ્ય વ્યક્ત કરે છે.)

❖ આભમાં ઉગેલ ચાંદલો (શિવાજીનું હાલરડું)

આભમાં ઉગેલ ચાંદલો ને  
જીજીબાઈને આવ્યાં બાળ,

.....  
પોઢજો રે મારાં બાળ !  
પોઢી લેજો પેટ ભરીને આજ,  
કાલે કાળાં જુદા ખેલાશે  
સૂવા ટાણું ક્યાંય ને રે'શે

ધાવજો રે મારાં પેટ! ધાવી લેજો ખૂબ ધ્રુપીને આજ રે,  
વીરા ખુબ ધ્રુપીને આજ

રે'શે નહિ રણઘેલૂડા!  
ખાવા મુઠી ધાનની વેળા.  
પે'રી ઓઢી લેજો પાતળા રે! પીળાં લાલ પીરોજી ચીર રે,  
વીરા લાલ પીરોજી ચીર

કાયા તારી લોહીમાં ના'શે  
ઢાંકણ તે દિ' ઢાલનું થાશે.  
ધુધરા, ધાવણી, પોપટ-લાકડી ફેરવી લેજો આજ રે  
વીરા ફેરવી લેજો આજ રે

તે દિ' તારે હાથ રે'વાની  
રાતી બંબોળ ભવાની.

.....  
આજ માતા દેતી પાથરી રે, ફૂણાં કુલડાં કેરી સેજ રે,  
વીરા ફૂણાં કુલડાં કેરી સેજ

તે દિ' તારી વીર-પથારી  
પાથરશે વીશ ભૂજાળી.  
આજ માતાજીને ખોળલે રે, તારાં માથુડાં ઝૂલે જાય રે,  
વીરા માથુડાં ઝૂલે જાય રે,

તે દિ' તારે ઓશીકાં  
મેલાશે તીર બંધૂકાં.

.....  
જાગી વે'લો આવજે વીરા!  
ટીલું માના લોહીનું લેવા!

.....  
વીરરસ – શૌર્યરસથી ભરપૂર શિવાજીનું હાલરડું મેઘાણીની મોરકલગી છે.

❖ ઊઠો

ઊઠો, સાવજશૂરાની બેટડી ! બાંધો કેશ, લૂછો અશ્રુધાર;  
જોજો ઝૂઝે તમારા કંથડા, એના કામજો કીર્તિઅંબાર.  
સાદ સુણી સમરાંગણના, દેવા પ્રાણ તણાં બલિદાન,  
મૃત્યુના સિંધુ વલોવીને અમૃત કરવા સિધાવ્યા મેદાન રે :  
બે'ની ! બંકા આપણ ભરથાર. – ઊઠો....  
દુશ્મન કેરાં નોતરાં, બે'ની ! બથ ભરી મળવા કાજ;

રક્તનાં કેસરછાંટણાં છંટાશે, ખેલાશે રસબસ રાસ રે:

કંઠે પે'રી આંતરડાંની માળ. – ઊઠો....

કાળ તણી એ કચેરીઓમાં બેઠા પછી ન ઉઠાય;

કંથ કોડીલાનાં કાળાં કવચ ત્યાં તો રાતે શોણિતે રંગાય રે:

બાજે રણરંભાના ઠમકાર. – ઊઠો...

અંતરની કાળી ઝાળો ઓલવવા કાળગંગાને ઘાટ,

નણદલવીર એ નીરમાં ન્હાતા ત્યાં સામસામી દૈ થપાટ રે:

ગાંડાતૂર જેવા ગજરાજ. – ઊઠો...

જીતીને વળશે તો રંગે રમાડશું : મરશે તોયે શા ઉચાટ !

ખોળે પોઢીને ચડશું ચિતા માથે : હસતાં જાશું સુરવાટ રે:

એવા ઉગ્રભાગી અવતાર. – ઊઠો....

વીરરસ – શૌર્યરસથી સમૃદ્ધ એવું આ શૌર્યગીત સૌ કોઈના હૃદયને જાગવા પ્રેરિત કરે છે.

“યુગવંદના”, ‘કિલ્લોલ’, વેણીનાં ફૂલ’, ‘એક તારો’ અને ‘રવીન્દ્રવીણા’ તેમના કાવ્યોનો પ્રાસાદિક અનુભવ મૂક્યો છે. ૧૯૨૮માં તેમને રણજીતરામ સુવર્ણ ચંદ્રકથી નવાજવામાં આવ્યા હતા. તા. ૯-૦૩-૧૯૪૭ના રોજ બોટાદ મુકામે ૫૦ વર્ષની ઉંમરે હૃદય રોગના હુમલાથી તેમનું અવસાન થયું.

સંદર્ભ સૂચિ

(૧) ‘યુગ વંદના’ કાવ્ય સંગ્રહ, ઝવેરચંદ મેઘાણી, ગુર્જર પ્રકાશન ભાવનગર,

પુન:પ્રકાશન ૧૯૯૩.

(૨) ‘ભાવ ગીતો’ સંપાદક : જસવંતભાઈ એ નાયક

(૩) ‘સિંધુડો’, ઝવેરચંદ મેઘાણી, ગુર્જર ગ્રંથરત્ન કાર્યાલય, અમદાવાદ

(૪) ‘અધિત પર્વ – ૬ કાવ્ય સમીક્ષા’, સંપાદક – ગુણવંત વ્યાસ, ડૉ. બી.બી.વાઘેલા

(૫) ‘મેઘાણી ચરિત્ર’, કનુભાઈ જાની, ગુજરાત વિશ્વકોશ ટ્રસ્ટ – અમદાવાદ

## ટ્રાન્સનેશનાલિઝમ અને ગુજરાતી ડાયસ્પોરા સાહિત્ય

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### Abstract

સતત ચાલતા રહેવું એ મનુષ્યની કુદરતદત્ પ્રકૃતિ છે. ઘણીવાર ફરજિયાતપણે તો ઘણીવાર સ્વવિકાસના હેતુને સિદ્ધ કરવા વ્યક્તિ અન્ય દેશનો નાગરિક બનવા પામતો હોય છે. આવા દ્વિતિયિક કે તેથી વધુ સ્થળાંતર પામેલ વ્યક્તિ પોતાની સાથે વતનની લાક્ષણિકતાઓ લઈને આગળ વધતો હોય છે. એકથી વધુ દેશોમાં પોતાનો વસવાટ કરનાર ડાયસ્પોરા સ્વરાષ્ટ્રની સરહદ પાર સમુદાયને, જૂથોને કે વિવિધ પ્રગતિશીલ સંસ્થાઓને જોડવા સમર્થ બને છે. એ સાથે જ તે અનાયાસે ટ્રાન્સલેશનાલિઝમનો પાયો નાખી દે છે. આમ, શુદ્ધ ગુજરાતીમાં ઓળખાતો આ ‘આંતરરાષ્ટ્રીયવાદ’ પોતાની સાથે અનેક કડીઓને જોડીને આવા મૂળ ગુજરાતીઓ કે જે તળગુજરાત સાથે જોડાયેલા છે તેમને વૈશ્વિક ઓળખ આપનારો બને છે.

દરેક દેશનો નાગરિક પોતાના રાષ્ટ્રને મૂળસોતો અન્ય દેશમાં જાણ્યે- અજાણ્યે રોપે છે; અને એમાં પણ જ્યારે આપણે ગુજરાતી ડાયસ્પોરાની વાત કરીએ ત્યારે આપણા ગુજરાતની બહુવિધ સંસ્કૃતિ, ભાષા, પહેરવેશ, ભોજન, વિવિધ સ્થળો સાથેનું આગવું સૌંદર્યયુક્ત ભાવાવરણ અને સાહિત્ય-આત્મામને પોતાનામાં સમાવીને ગંતવ્ય સ્થાનના સમાજમાં તે પ્રવેશે છે ત્યારે ત્યાંના સામાજિક, સાંસ્કૃતિક, આર્થિક અને રાજકીય માળખામાં પરિવર્તન આણી શકે છે. ઘણી વખત આ આંતરરાષ્ટ્રીય સ્થળાંતર તેને તકો પૂરી પાડનારું તો ક્યારેક પડકારરૂપ પણ બની રહે છે. આ અનુભવવિશ્વને વાચા આપવા તે પોતાની માતૃભાષાને આધાર તરીકે લે છે. સૌથી શ્રેષ્ઠ સર્જન હંમેશા માતૃભાષામાં પોતાના શબ્દોને વ્યક્ત કરવાથી થાય છે. આંતરરાષ્ટ્રીયવાદના વિવિધ પાસાઓ, આ પાસાઓને ઉજાગર કરવા માટે વર્તમાન સમયના વિવિધ માધ્યમો, આંતરરાષ્ટ્રીયવાદના ફાયદા, તેને લીધે ભોગવવી પડતી વિવિધ મુશ્કેલીઓ, વિવિધ સાહિત્ય સ્વરૂપોમાં રજૂ થયેલા તેના ઉદાહરણો, જેવા મુદ્દાઓને ગુજરાતી ભાષાને કેન્દ્રમાં રાખીને તપાસવાથી ગુજરાતી ડાયસ્પોરા સાહિત્યને વિશેષ ઊંડાણ મળી શકે.

Key words: આંતરરાષ્ટ્રીયવાદ, ડાયસ્પોરા, અનુભવવિશ્વ.

### Introduction

આ પૃથ્વી પર દરેક મનુષ્ય ચિરંતન સુખની અપેક્ષા સાથે સતત જીવતો આવ્યો છે. એટલા માટે તે હંમેશા પોતે જે સ્થળે હોય ત્યાંથી સ્વેચ્છાએ અથવા કોઈના દ્વારા હઠપૂર્વક અન્ય જગ્યાએ જઈને પોતાની દુનિયા વસાવે છે. આવા બે અલગ-અલગ સંસ્કૃતિ કે રાષ્ટ્ર સાથે જોડાયેલા લોકો Transnationalism સાથે જીવનપર્યંત જોડાયેલા રહે છે. સાદી ભાષામાં કહીએ તો, જન્મ અને વતન એક દેશ કે રાષ્ટ્રમાં પામેલા હોય અને પોતાના બાકીના જીવનને પરરાષ્ટ્રમાં રહે રહે વિતાવતા હોય

તેવા લોકો જ્યાં જાય ત્યાં પોતાના વહાલસોયા વતનની યાદોને જીવનશૈલીમાં જાણ્યે-અજાણ્યે સદાય અનુસરતા રહે છે. ઘણી વખત તેમણે અનુભવેલા આવા દ્વિતિયિક સ્થળાંતરની લાગણીસભર રજૂઆત તેમની વિવિધ સાહિત્ય રચનાઓમાં થયેલી જોવા મળે છે. આ રીતે તેમના દ્વારા રચાયેલું સાહિત્ય ડાયસ્પોરા સાહિત્ય તરીકે ઓળખવામાં આવે છે.

### ટ્રાન્સનેશનાલિઝમ : સંકલ્પનાની સમજઘ

ટ્રાન્સલેશનલિઝમ શબ્દમાં બે શબ્દો સમાયેલા છે. 'Trans' અને 'Nationalism'. અહીં Trans - શબ્દ એ એક લેટિન ઉપસર્ગ છે, જેનો અર્થ 'પાર', 'પછી' અથવા તો 'કોઈ એક તત્વની બીજી બાજુ, પેલી પાર' એવો શાબ્દિક અર્થ જાણી શકાય છે. આ જ રીતે 'Nationalism' ગુજરાતીમાં 'રાષ્ટ્રવાદ' અથવા તો 'રાષ્ટ્રીયતા' તરીકે શાબ્દિક અર્થમાં સમજાવી શકાય. આ એક રીતે કોઈ વિચારધારા તરીકે ઓળખાતો શબ્દ છે. જેમાં વ્યક્તિને પોતાના વતન કે દેશ પ્રત્યે વફાદારી કે ગર્વની લાગણી હોય અને તે વ્યક્તિ તે લાગણીને આધારે પોતાના રાષ્ટ્રના હિતોને જ સર્વોચ્ચ સ્થાન આપતો હોય અહીં આપણે રાષ્ટ્ર પ્રત્યેની વ્યક્તિની નિષ્ઠા, રાષ્ટ્રને સર્વોપરી માનવાની માનસિકતા તેમજ સ્વદેશાનુરાગને નેશનાલિઝમ ગણાવી શકીએ. આ મુજબ જોઈએ તો ટ્રાન્સનેશનાલિઝમ શબ્દને સંકલ્પનાની દ્રષ્ટિએ જોતા આ શબ્દ સાથે 'માઈગ્રેશન'- એટલે કે સ્થળાંતરિત વ્યાપાર અને વૈશ્વિકતાના સંકલનને મુખ્ય સ્થાન આપી શકાય. બહુરાષ્ટ્રીયતા અથવા પારદેશીયવાદને શાબ્દિક અર્થના ખૂબ નજીક ગણાવી શકાય. ટ્રાન્સનેશનાલિઝમ એક એવી પ્રક્રિયા છે કે જેમાં લોકો, સંસ્થાઓ કે કોઈ કંપનીઓ બે કે બેથી વધુ દેશની સીમાઓ ઓળંગીને સરહદ પાર જઈને સામાજિક, આર્થિક કે સાંસ્કૃતિક સંબંધો સ્થાપિત કરે છે ; એટલું જ નહીં તે બંને સાથે સક્રિય પણ રહે છે. અહીં રાષ્ટ્રીય સરહદની પાર થતી પ્રવૃત્તિઓ તેમજ સંબંધોને સ્થળાંતરિત થયેલા માની લેવામાં આવે છે. કોઈ એક દેશની સરહદમાં બંધાયા વગર એક થી વધુ દેશો સાથે સંકળાયેલા રહેવું એટલે Transnationalism.

### ટ્રાન્સલેશનલિઝમના કારણો

દેશની સરહદોની પેલે પાર રહેલા લોકોમાં એક ભાવ ખૂબ મહત્વનો છે અને તે છે connectivity. આ પ્રક્રિયામાં સ્થળાંતર કરનારા લોકો ( Migrants) પોતાના મૂળ દેશ (Homeland) અને નવા વસવાટના દેશ (Place of another settlement) આ બંને સાથે સામાજિક, આર્થિક અને રાજકીય રીતે જોડાયેલા હોય છે. લોકોની સંસ્કૃતિ તેમજ લોક વિચારોમાં રહેલા તત્વોનું આદાન-પ્રદાન ટ્રાન્સલેશનલિઝમને ખૂબ અસર કરે છે. વિશ્વને એકબીજા સાથે જોડતા અનેક કારણો ટ્રાન્સલેશનલિઝમના કારણો બની રહ્યા છે.

- ઇન્ટરનેટ અને ઝડપી વાહન વ્યવહાર તેમજ પરિવહનને કારણે સરહદો અને સીમાકનોની પેલે પાર જોડાણ ખૂબ જ સરળ બની રહ્યું છે; જે વ્યક્તિઓ અને જૂથોને જોડવા માટેનું અસરકારક પરિબલ છે. આમ, ટેકનોલોજી અને કોમ્યુનિકેશનના પરિણામે ટ્રાન્સલેશનલિઝમ શક્ય બન્યું છે.
- રોજગારી કે શ્રમની આવશ્યકતા સમાજમાં ખૂબ વધી રહી છે. શ્રેષ્ઠ જીવન જીવવાના હેતુથી સારી રોજગારીની શોધમાં લોકો પોતાનો દેશ છોડીને બીજા દેશમાં જાય છે. પોતાની પાસે રહેલી બુદ્ધિશક્તિનો ઉપયોગ કરીને અન્ય દેશોમાં ઝાઝી કમાણી કરે છે. જેનાથી સંસ્કૃતિ અને સંબંધોનું આદાન પ્રદાન વધે છે.
- આંતરરાષ્ટ્રીય વેપાર કરારો જે થઈ રહ્યા છે. જેને અનુસંધાને લોકોની આર્થિક નિર્ભરતાને ઘણો વેગ મળ્યો છે. વૈશ્વિકીકરણ એ આર્થિક કારણોને વધુ સબળ બનાવ્યા છે વેપાર વિનિમય માં થતા અન્ય દેશો સાથેના કરારો ટ્રાન્સલેશનલીઝમને સઘન બનાવે છે.
- વૈશ્વિક સ્તરે થતા સંશોધનો, વિચારો અને સંસ્કૃતિઓનું આદાન પ્રદાન
- માનવ ગતિશીલતા તેમજ વસ્તી વિષયક અંતર અને વસ્તી વૃદ્ધિ
- સ્થળાંતરિત જૂથો પોતાના મૂળ દેશ સાથે સાંસ્કૃતિક સંબંધો જાળવી રાખે છે. તેઓ કદાચ બંને સંસ્કૃતિઓ સાથે અનન્ય ભાવથી જોડાય છે.
- માનવ અધિકારો અને વધતી આંતરરાષ્ટ્રીય રાજકીય પ્રક્રિયાઓએ દેશની અન્ય દેશ સાથેની સીમાકનો વચ્ચેની ગતિશીલતાને પ્રોત્સાહન આપેલું છે. જે તેનું કારણ ગણાવી શકાય.

આમ, આવાં અનેક કારણો Transnationalism ને અસર કરતા ગણાવી શકાય.

હવે આપણે આવા દ્વિતીયિક કે તેથી વધુ સ્થળાંતરની લાગણી ધરાવતાં લોકોના રચાયેલા સાહિત્ય વિશેની જ્યારે વાત કરીએ ત્યારે જાણવા મળે કે તેમનામાં રહેલા સર્જકના વિચારો આ બંને સંસ્કૃતિના અનેક સંસ્કાર અને જીલીને શબ્દનો સ્વરૂપ પામતા હોય છે. આ રીતે રચાયેલા સાહિત્યને ડાયસ્પોરા સાહિત્ય ગણવામાં આવે છે. વેપાર નોકરી ની વધારે સારી તકો માટે વ્યક્તિ પોતાની જન્મભૂમિ છોરી પરદેશ સુધી પહોંચીને ત્યાં જઈ વસે છે આ રીતે પરભુમી પર વસનારા લોકો દ્વારા લખાયેલા સાહિત્યને આપણે ડાયસ્પોરા સાહિત્યની સંઘના આપી રહ્યા છીએ જે મુડે ગ્રીક ભાષાના શબ્દ Diasporiein પરથી ઉતરી આવ્યો છે.

ટ્રાન્સનેશનલિઝમથી રચાયેલ ગુજરાતી સાહિત્ય

વિશ્વના પ્રવાહોથી અનુપ્રાણિત સાંસ્કૃતિક વ્યક્તિત્વ ધરાવતો ગુજરાતી સાહિત્યનો સર્જક મૂળ વતન તરીકે ગુજરાતને હૃદયના સિંહાસન પર બેસાડીને વિશ્વની સફર કરતો હોય છે; ત્યારે તે વિશિષ્ટ પ્રકારનું ડાયસ્પોરિક સર્જક વ્યક્તિત્વ પ્રાપ્ત કરી લે છે. મણિલાલ હ. પટેલના મતે

સામાજિક માણસ પોતાનું વતન છોડીને બીજા દેશમાં જઈને વસે છે, ત્યારે એ દેશની પ્રજા, એનું માનસ, એ પ્રજાનો ધર્મ, એનો સાંસ્કૃતિક વારસો, એ પ્રજાની ભાષા તથા એ પ્રજાનું રોજિંદું જીવન વગેરે વિશે એને વિચારવાનું અને સમાધાન કરવાનું આવે એ સ્વાભાવિક છે. બીજી રીતે કહીએ તો બીજા દેશ કાળમાં જઈને વસનારા માણસોની સામે ઘણી મૂંઝવણો અને ઢગલો પડકારો હોય છે. બીજા દેશના કાયદાઓ અને જનારની મર્યાદિત ભૂમિકા હોવાથી પણ નવવસાહતીઓ બનનારા લોકોના સંઘર્ષનું સાહિત્ય રચાયું હોય કે રચાતું હોય તો એ ડાયસ્પોરાનું સાહિત્ય કહી શકાય. વતન વિચ્છેદનું, સંસ્કૃતિ, સંસ્કાર અસ્મિતા માટેના ધોરણનું સાહિત્ય તે ડાયસ્પોરાનું સાહિત્ય છે. એક તરફ નવા દેશમાં વસવાનું ને સ્થિર થઈ રહેવાનું છે. તો બીજી તરફ છૂટી ગયેલા ઘર, ગામ, વતન, સગા વહાલા, ભૂમિ, દેશ, સંસ્કાર, સંસ્કૃતિ, ભાષા, ધર્મ, કલાઓ માટેનો ઝૂરાપો છે. શરૂઆતમાં આવો ઝૂરાપો તીવ્રતમ હોય છે. વખત જતા આ ઝૂરાપો એક સંવેદન-વિચાર બનીને મનને વળગી રહે છે. એનઆરઆઇ-નોન રેસિડેન્ટ ઇન્ડિયન ના અનેક તરેહના ઝૂરાપાનું સાહિત્ય તે ડાયસ્પોરાનું સાહિત્ય છે.<sup>(1)</sup>

મુળે જે પ્રદેશમાં વસતો માનવ અન્ય પ્રદેશમાં જાય ત્યારે ત્યાંના તમામ તત્ત્વો તેના સંસર્ગમાં આવે છે. ત્યારે તે તેનાથી અવગત થવા માટે અનેક સંઘર્ષો કરે છે. આ સંઘર્ષોમાંથી ક્યારેક તેને પરભૂમી પ્રત્યે સંતોષ પ્રાપ્ત થાય છે. તો ક્યારેક તેને સતત ને સતત પોતાના વતનની યાદ હૃદયને ખૂણે આંસુ સ્વરૂપે ઉપસી આવે છે. આવો કોઈ પણ ગુજરાતનો વ્યક્તિ જે ગુજરાતની બહાર પરદેશમાં જઈને વસે છે ત્યારે તે ડાયસ્પોરા ગુજરાતી તરીકે ઓળખાય છે. અને તેના દ્વારા રચાતું સાહિત્ય ડાયસ્પોરા ગુજરાતી સાહિત્ય કહેવાય છે.

બહુરાષ્ટ્રીયવાદને પરિણામે રચાતા ગુજરાતી સાહિત્યને લીધે સાહિત્ય જગતને એક નવો આયામ પ્રાપ્ત થયો છે. સ્વદેશ છોડ્યા પછી નવા સ્થળે થતી વિપરીત અને અકળાવનારી પરિસ્થિતિઓની અનુભૂતિ અનેક સાહિત્યકારો દ્વારા વિવિધ સાહિત્ય સ્વરૂપોમાં શબ્દ દેહ પામી છે. આવી ડાયસ્પોરા કવિતાઓ, ડાયસ્પોરા વાર્તાઓ, નિબંધો, નવલિકાઓ, નવલકથાઓ, તેમજ ગઝલ અને અચ્છન્નદસ કાવ્યોની પણ રચના આપણને પ્રાપ્ત થાય છે. ઉપરછલ્લી રીતે જોતા સરખા જ અનુભૂતિ વિશ્વ સાથે આપણને જોડતા આ સાહિત્ય સ્વરૂપોમાં જ્યારે આપણે તલ્લીન થઈને વાંચીએ અને તેનો ભાવ હૃદયસ્થ કરીએ ત્યારે આપણને એ ડાયસ્પોરા સર્જકની મનઃસ્થિતિ હૃદય સોંસરવી ઉતરતી જણાય છે. આફ્રિકા, યુરોપ, બ્રિટન, કેનેડા, પાકિસ્તાન વગેરે અનેક દેશોમાં વસવાટ કરતા મૂળ ગુજરાતીઓ પોતાની કલમ જ્યારે ચલાવે છે; ત્યારે તેમના શબ્દોમાં વતનની ઊર્મીઓનો વિચ્છેદ શબ્દનું સ્વરૂપ પામે છે. તેઓ પૂર્ણપણે મૂળને છોડી શકતા પણ નથી, અને પરભૂમીમાં પૂરેપૂરા વસી શકતા પણ નથી. આવી કેટલીય દ્વિધાજનક પરિસ્થિતિઓમાં તેઓ

પોતાના અંતરના ઝૂરાપાને ઘૂટી-ઘૂટીને પીતા હોય છે. આવા સમયે રચાતા ગુજરાતી સાહિત્યને એકથી વધુ સંસ્કૃતિના માનસિક સંઘર્ષના સાક્ષી બનવું પડે છે.

છેલ્લા દોઢેક દાયકામાં અમેરિકામાં ગુજરાતી સાહિત્યનું સારું એવું ખેડાણ થયું છતાં અમેરિકા સ્થિત ગુજરાતી સર્જકોની કૃતિ હજી ગુજરાતના સીમાડા સુધી પહોંચી નથી. આવા ધનવાન દેશમાં સર્જકોની કૃતિ માતૃભૂમિ સુધી કેમ નથી પહોંચી એની ચર્ચા કરીએ તો પેટ ચોળીને શૂળ ઊભું કરવા જેવી વાત થાય ! (2) આવા કેટલાક પ્રશ્નો પણ ટ્રાન્સલેશનલિઝમને લીધે ગુજરાતી ડાયસ્પોરા સાહિત્ય સર્જકને પક્ષે આવતા હોય છે..

ગુજરાતી ડાયસ્પોરા સાહિત્ય ક્ષેત્રે થયેલા સર્જનોમાં માતૃભાષા ગુજરાતીને જીવંત રાખવામાં પોતાનું યોગદાન આપનારા અનેક સર્જકો છે. જેમ કે, પંકજ વોરા, જગદીશ દવે, ડાહ્યાભાઈ પટેલ, દિપક બારડોલીકર, રમેશ પટેલ, મધુરાય, પન્ના નાયક, વિપુલ કલ્યાણી, રજનીકાંત મહેતા, ભાનુશંકર વ્યાસ, જયંત મહેતા, હરનીશ જાની, બળવંત નાયક, અહમદ ગુલ, પ્રીતિ સેનગુપ્તા, પ્રીતમ લખલાણી, મધુસુદન કાપડિયા, ભરત ત્રિવેદી, ચંદ્રકાંત શાહ, વિનય કવિ, યોગેશ પટેલ, આદિલ મન્સુરી, પોપટલાલ પંચાલ, કાંતિ મેપાણી, કિશોર મોદી, રાહુલ શુક્લ, ભરત શાહ, નિલેશ રાણા, ઉપેન્દ્ર ગોર, વિનોદ કપાસી...આ વાતો અગણિત નામો છે કે જેમણે પોતાના અનુભવો જીવનની છબી સ્વરૂપે શબ્દોના રમણીય પટ પર આલેખ્યા છે. ગુજરાતી ડાયસ્પોરિક સાહિત્ય ક્ષેત્રે સંપાદનોએ પણ એક આગવી ભૂમિકા ભજવી છે. આ પ્રકારના સંપાદનો કરવામાં ડો. બળવંત જાનીનો ફાળો સૌથી મોટો છે. તેમની પાસેથી સર્જકલક્ષી અને સાહિત્ય સ્વરૂપલક્ષી એમ બંને પ્રકારના સંપાદનો ગુજરાતી સાહિત્યને મળ્યા છે. તેમણે પોતે બ્રિટન અને અમેરિકાના પ્રવાસો કરીને ત્યાં રહેતા ગુજરાતી સાહિત્યકારોના સાહિત્યનું સંપાદન કરી આપ્યું. એ માટે ગુજરાતી સાહિત્ય એમનું હંમેશા ઋણી રહેશે. 2009 થી તેમની પાસેથી ડાયસ્પોરાના સંપાદનો મળવાના શરૂ થયેલા આ સંપાદનો થકી ગુજરાતી સાહિત્યમાં ડાયસ્પોરિક સાહિત્યના મંડાણ થયા એવું ચોક્કસપણે કહી શકાય.

ક્યાંક આફ્રિકા તો ક્યાંક બ્રિટન ક્યાંક વિશેષ પ્રકારના પ્રવાસો તો ક્યાંક વળી ઘર ઝૂરાપો અનેક સાહિત્યના સ્વરૂપોમાં વતન પ્રેમ સ્વજનનો વિરહ સતત ઓળા રૂપે છવાયેલી એકલતા અને એક પ્રકારનો ન કળી શકાય તેવી વિહવળતા આપણને જોવા મળે છે. પોતાની વાત સ્પષ્ટ અને નિઃસંકોચ રીતે આલેખવાની આ સર્જકોની સ્વસ્થતા સૌ કોઈનું ધ્યાન ખેંચે છે. આ ગુજરાતી સાહિત્ય સર્જકોમાં વિસ્થાપનની વેદના ક્યાંક ઊભરી આવતી જોવા મળે છે. તો ક્યાંક વળી, ડાયસ્પોરાને પ્રદેશમાં સ્થાયી થવા માટે અને હળી-મળીને રહેવામાં જે તકલીફોનો સામનો કરવો પડે છે એ યાતનાઓ સાહિત્યમાં વિષયવસ્તુ તરીકે જોવા મળી આવે છે. ટ્રાન્સલેશનલિઝમ. સાથે જોડાઈને

ભિન્ન રહેણીકરણી, પરિવેશ, સભ્યતા, સંસ્કૃતિ અને જીવન મૂલ્યોને કારણે પરદેશીઓ સાથે થતા સંઘર્ષનું સાહિત્ય એ આ ગુજરાતી ડાયસ્પોરા સાહિત્ય.

ઘણી વખત આપણને આ પ્રકારના ગુજરાતી સાહિત્યમાંથી ભાવક મપક્ષે એવો પણ વિચાર આવે છે કે આ બહુરાષ્ટ્રીયતાવાદને કારણે રચાતા ગુજરાતી સાહિત્યને દરેક વખતે વતન ઝૂરાપાનું સાહિત્ય નહીં કહી શકાય કારણ કે ઘણા સર્જકો દ્વારા લખાયેલા સાહિત્ય સ્વરૂપમાં તેમના હૃદયમાં પરભુમીના વસવાટથી તેમના જીવનમાં આવેલ આમૂલ પરિવર્તન આશીર્વાદરૂપે સાબિત થાય છે, તો તેમના દ્વારા આપણને પ્રાપ્ત થતા કલ્પનો અને પ્રતિકો ગુજરાતી સાહિત્યને વધુ વૈવિધ્યસભર બનાવે છે. તેમના પાસેથી મળતી રચનાઓ, વર્ણનો, ઊર્મિ તેમજ કથાપટની રજૂઆત વિવેચકની દ્રષ્ટિએ જોતા ગુજરાતી સાહિત્યને અનોખું પ્રદાન પ્રાપ્ત થતું હોય તેવું જણાય આવે છે.

દેશ સાથે જેમનો સંબંધ ગાઢ છે... પરદેશ જેમની નિયતિ છે એવો વૈશ્વિક પટ પર પથરાયેલો પ્રજાસમૂહ આવા ગુજરાતી ડાયસ્પોરાની ઓળખ પામ્યો છે. આવા ડાયસ્પોરા એક વિખુટા પડયા ની વ્યથાની અનુભૂતિનો વિસ્તાર કરે છે, તો સામે પક્ષે બીજા કોઈ થડ કે સંસ્કૃતિમાં સ્થાયી થયાની જીવન તરફની પોતાની ગતિ પ્રદર્શિત કરે છે. આ બે પ્રક્રિયાના સંમિશ્રણથી ડાયસ્પોરા વ્યક્તિનું, ડાયસ્પોરા સમાજનું તેમજ ડાયસ્પોરા ગુજરાતી સાહિત્યનું નિર્માણ થાય છે.

એક વાત તો સ્પષ્ટ છે કે કોઈ વ્યક્તિને દેશ બહાર કાઢી શકાય છે પણ એ વ્યક્તિમાંથી દેશને બહાર કાઢી શકાતો નથી. એક એ વાત પણ હકીકત છે કે ગુજરાતીઓએ કરેલું સ્થળાંતર મોટા ભાગે સ્વૈચ્છિક પ્રકારનું છે એટલે અન્ય ડાયસ્પોરા સર્જકો કરતા ગુજરાતી સાહિત્ય સર્જકોમાં વર્તમાન સમયમાં પ્રાપ્ત થતું ડાયસ્પોરા ગુજરાતી સાહિત્ય આપણને વતન પ્રેમની વાત તો બતાવે છે પરંતુ તેમાંથી આપણને ઝૂરાપાનું જે ભાવવિશ્વ ખડું થવું જોઈએ તે વર્તમાન સમયના ડાયસ્પોરા ગુજરાતી સાહિત્યમાંથી પ્રાપ્ત થતું નથી.

## લોકસાહિત્યમાં દુલા ભાયા કાગનું યોગદાન

જલ્પા અગ્રાવત

### Abstract:

લોકસાહિત્યમાં લોકગીત એ મૂળ વર્ગનું મૂળધન કહેવાય છે. લોકગીતમાં મરમી ફિલસૂફીનો વ્યાપક અને ઊંડો અનુભવ રહેલો છે. તેમાંથી કુટુંબ અને સમાજના રીતરિવાજો જાણવા મળે મળે છે. લોકગીતોમાં પ્રકૃતિ સ્વરૂપ ઘરતીનો ઉલ્લાસ અને ચેતનાનું એકત્વ જોવા મળે છે. તેમાં ઉત્તમ પ્રકારની સંસ્કૃતિનું બીજ નિહિત છે. તેથી જ કહેવાયું છે કે,લોકગીતનો ઉષાકાળ છે. સમાજની સંસ્કૃતિ અને સંસ્કારની પ્રાચીનતા તેમાં થી મળી આવે છે.

ગીતકાર, લેખક, કલાકાર એવા કાગબાપુ (કવિ દુલા ભાયા કાગ)એ તેમનાં લોકગીતો તેમજ રચનાઓ દ્વારા લોક લોકહૃદયને ઢંઢોવવાનું ઉમદા કાર્ય કર્યું છે. તેમની કેટલીક રચનાઓ આજે પણ લોકહૃદયે વસેલી છે. સામાન્ય શિક્ષણ હોવા છતાં પણ,તેઓ લોકજીવનના સાચા વાલ્મીકિ બન્યા. તેમની કસુંબલ વાણીમાં વાસ્તવદર્શી અને વ્યવહાર દર્શી વૈભવ હતો. સમાજને પારખવાની તેમનામાં ઊંડી સૂઝ બુઝ હતી. સ્વાનુભૂતિ મુલક સાત્ત્વિક,તત્ત્વ ચર્યામાં દ્વારા તેઓ લોકહૃદયના સાચા ‘કાગબાપુ’ હતા. તે સમજવાનો અત્રે ઉપક્રમ છે.

ગુજરાતી સાહિત્યના ઇતિહાસમાં લોકસાહિત્ય અને ભક્તિસાહિત્યને અનન્ય સ્થાન પ્રાપ્ત છે. લોકજીવનની સરળતા, આધ્યાત્મિક ભાવના અને નૈતિક મૂલ્યોને કાવ્યરૂપે વ્યક્ત કરનારા કવિઓમાં દુલાભાઈ ભાયા કાગનું નામ વિશેષ આદર સાથે લેવામાં આવે છે. તેઓ માત્ર લોકકવિ જ નહોતા, પરંતુ એક જાગૃત સમાજચિંતક, રાષ્ટ્રપ્રેમી અને ભક્તિપ્રવાહના પ્રબળ પ્રણેતા હતા.

દુલાભાયા કાગે પોતાની કવિતાઓ દ્વારા ગુજરાતી સમાજને નૈતિકતા, ભક્તિ અને માનવતાના માર્ગે દોરી જવાનો પ્રયાસ કર્યો. તેમની વાણીમાં ગ્રામ્ય જીવનની સુગંધ, આધ્યાત્મિક ચેતના અને રાષ્ટ્રભાવનાનો અનોખો સમન્વય જોવા મળે છે.

ચાવી રૂપ શબ્દો:

લોકસાહિત્ય, લોકગીત, મર્મી વાણી, કસુંબલ લોકગીતો, અલખના ઘણી, લોકહૃદયના વાલ્મીકિ વગેરે. લોકસાહિત્યમાં લોકગીત મુખ્ય છે. લોકગીતો લોક માટે અને લોકબોલીઓમાં રચાયેલાં હોય છે. લોકગીતો સવિશેષ નારી હૃદયની સંવેદના પ્રગટ કરે છે. અને નારી જીવનનાં જુદાં જુદાં રૂપોનું આલેખન કરે છે. આ લોકગીતિમાં લોકોનું સામાજિક જીવન, ધાર્મિક ભાવનાઓ, સાંસ્કૃતિક પરિવેશ અને લોકમાનસ પ્રતિબિંબિત થાય છે. લોકજીવન જુદાં જુદાં તહેવારો, ઉત્સવો, મેળા, વ્રત આદિ લોકગીતો ગવાય છે. ઉપરાંત સ્ત્રીને ઘરનાં કામ, દા.ત. પાણી ભરવા જવું, દળવું, ખાંડવું, લણવું, કાપણી કરવી ને કામ સાથે થાક ન લાગે ને તેઓ આનંદ-ઉલ્લાસથી કામ કરે તેનાં લોકગીત હોય છે. તે સિવાય રાસ, રાસડા, ગરબો, વગેરેનાં ગીતો હોય છે. આમ નારીની દરેક અવસ્થા પ્રમાણેનાં લોકગીતો હોય છે. લોકગીતો સમૂહમાં, જાહેર સ્થાનોએ, નૃત્ય, તાલ, વાદ્યો સાથે ગાવામાં આવે છે. આવા લોકગીતોને અંગ્રેજીમાં 'Folk lore' કહેવામાં આવે છે.

હવે પ્રશ્ન એ ઉઠાવે કે, આવાં લોકગીતો આવ્યાં ક્યાંથી ? તો તેનું મૂળ શોધવું કઠિન છે. આ લોકગીતો પ્રથમ કોને રચ્યાં તે નિશ્ચિત થઈ શકે તેમ નથી. પરંતુ એટલું જરૂર કહી શકાય કે, લોકસમાજ જે અરણ્યનિવાસી, વિચરતો, દરિયા નદી કિનારે રહેતો કે ગ્રામ્ય નિવાસી હતો. તેમનાં સુખ દુઃખ, ગમા-અણગામ, પ્રેમ-ઉલ્લાસ, પરિવારની વિટંબનાઓ, જન્મ-મૃત્યુ વગેરે હતા. તે ભાવ સંવેદનો વ્યક્ત કર્યાં સિવાય રહી શકતો નહિ. ઉપરાંત તે બહુધા શિક્ષિત ન હતો. તેમની પોતાની લોકબોલી હતી. તે બોલીમાં ગેય, લોકસંગીત સાથે જે સહજ રીતે ગવાયાં તે લોકગીતો કહેવાયાં છે.

આ ઉપરાંત, લોકસમાજ પ્રવૃત્તિ વચ્ચે રહ્યો છે. આરંભમાં તો તે અરણ્ય નિવાસી હતો. પક્ષીઓ, ઝરણાંનો નિનાદ તેમણે સાંભળ્યો, ઉછળતા મોજાઓનો તાલ તેમણે જોયો, મોરના નૃત્યને જોયું. આમ, કુદરતનાદનું સંગીત તેમની નસેનસમાં વહેતું થયું. તે નાદ ને નૃત્ય તેમની લોકબોલીમાં ગોઠવાતા ગયા ને આમ લોકગીતોનો જન્મ થયો. તેથી કહી શકાય કે, આ લોકગીતો કોઈ એક વ્યક્તિ દ્વારા રચાયેલ ગીતોનું સર્જન નથી.

તેથી જ લોકસાહિત્યના અમર શ્રી ઝવેરચંદ મેઘાણી લોકગીતોના મૂળ પ્રેરણા શ્રોત વિષે જણાવે છે કે, ‘જેના રચનારાંએ કદી કાગળ અને કલમ પકડ્યાં નહિ હોય,એ રચનારાં કોણ છે તેની જ કોઈને ખબર નહિ હોય તેમજ પ્રેમચંદ-નારસિંહ મહેતાની પૂર્વ કેટલો કાળ વીંધીને એ સ્વરો માલ્યા આવે છે, તેનીય કોઈ ભાવ મળતી નથી. એમનું નામ લોકગીતો.

તેથી લોકગીતોની સાડી પરિભાષા એટલી આપી શકાય કે, ‘લોકગીત લોક સમાજ માંથી, લોકો દ્વારા,લોકો માટે, લોકબોલીમાં લોકકંઠે જીવતું અને લોકજીતો રમતું ગીતો છે. લોકગીતોમાં પ્રાકૃતિક પરિવેશ મુખ્ય આધાર બનીને લોકજીવનને, તેની ધાર્મિક, સાંસ્કૃતિક અને સામાજિક બાબતોને વ્યક્ત કરે છે. લોકગીતોનો કર્તા અજ્ઞાત છે. તે બહુધા સ્ત્રીઓ દ્વારા રચાય છે ને તેમાં સમય, સ્થળ અને જ્ઞાતિજૂથો પ્રમાણે પાઠાંતર હોય શકે છે. લોકગીત જીવનના જન્મ પૂર્વના સીમંતથી શરૂ કરી મૃત્યુ પછીના મરસિયા સુધીની જીવન ઘટનાઓને હર્ષોલ્લાસ, કે વિહર વ્યથાને દુખદ ભાવોને રસાત્મક, ગેય, નૃત્ય સાથે માનવ ઊર્મિઓ, ભાવોને વ્યક્ત કરતી રચનાને લોકગીત કહી શકાય.

લોકસાહિત્ય એ જનજીવનના સાંસ્કૃતિક અને આધ્યાત્મિક મૂલ્યોનું પ્રતિબિંબ છે. લોકકથા અને લોકગીત એ લોકસાહિત્યના બે મુખ્ય સ્તંભ છે, જે શબ્દ અને સંસ્કારથી સમૃદ્ધ છે. તે મૌખિક પરંપરાના માધ્યમથી પેઢીથી પેઢી પ્રસારિત થતું રહ્યું છે અને લોકજીવનની અસલતાને પ્રતિબિંબિત કરે છે. લોકોના જીવનનો સહજ સંસાર, તેમનાં દુઃખ-સુખ, વિશ્વાસ અને કલ્પનાઓ આ સાહિત્યના માળખામાં ઉજવાય છે. આ કારણસર, લોકસાહિત્ય દરેક સમાજના આસ્થાના મૌલિક સ્તંભ તરીકે ઓળખાય છે.

લોકસાહિત્યમાં મુખ્યત્વે લોકગીતો, લોકકથાઓ, પૌરાણિક વાર્તાઓ, નાટકો અને કહેવતોનો સમાવેશ થાય છે. આ સર્વે સાહિત્યિક રૂપો પ્રાચીન સમયમાં મનોરંજન પૂરતા મર્યાદિત ન હતા, પરંતુ સમાજને શિક્ષિત કરવાના અને તેમને એકીકૃત કરવાના મહત્વના સાધન હતા. લોકસાહિત્ય એ લોકોના પ્રાગૈતિહાસિક જીવનમાં સમજણ અને કલ્પનાશક્તિને વ્યક્ત કરે છે. તે દરેક

ભૂમિપ્રદેશના જીવંત ઇતિહાસને વ્યક્ત કરતું સાહિત્ય છે, જે સમાજના જીવનમૂલ્યો અને રિવાજોને એક અનોખા પ્રકારના આદરભાવે વ્યક્ત કરે છે.

લોકસાહિત્યનું મુખ્ય લક્ષણ એ છે કે તે સ્વરૂપમાં લવચીક છે. વર્ષોથી, તે મૌખિક પરંપરામાંથી પસાર થતું તેનું રૂપ બદલતું રહ્યું છે. આ પરિવર્તન તેને વધુ તાજું અને પ્રાસંગિક બનાવે છે. લોકસાહિત્યે સમાજને તેની ભાષા સાથે સાંસ્કૃતિક સમૃદ્ધિ અને લોકોના જીવનની સરળતાના તત્ત્વો ઓળખાવવા મદદ કરી છે.

એક વ્યક્તિનું બાળકપણ તેનાં લોકગીતોથી અને વાર્તાઓથી શરૂ થાય છે. લોકસાહિત્ય એ ભવિષ્યના નાગરિકોને નૈતિક મૂલ્યો શીખવવાનું અને સામાજિક સંબંધોની મર્યાદાઓ સમજાવવાનું સાદું અને અસરકારક સાધન છે. આજના સમયમાં પણ લોકસાહિત્યનું મહત્વ યથાવત છે. ટેકનોલોજીના યુગમાં, જ્યારે લખાણ અને મિડિયાની લોકપ્રિયતા વધી છે, ત્યારે પણ લોકસાહિત્યનો મૂળભાવ સાહિત્યિક અને સામાજિક એકતાને મજબૂત કરે છે. તે માનવતાનું પ્રતીક છે અને સ્થાનિક સંસ્કૃતિને વૈશ્વિક સ્તરે ઓળખ અપાવવાનું મહત્વનું સાધન છે. આ રીતે, લોકસાહિત્ય માત્ર ભૂતકાળનું શિલ્પ નથી, પરંતુ તે ભવિષ્ય માટેનો મજબૂત પાયો છે. તે પેઢી દર પેઢી જીવંત રહે છે, ક્યારેક પ્રાચીન સ્વરૂપમાં, તો ક્યારેક નવી રીતે વૈશ્વિકતા સાથે ગૂંથાય છે.

ઉપરોક્ત ચર્ચા પરથી લોકગીતોનાં લક્ષણો નીચે મુજબ તારવી શકાય:

- (1)લોકગીતોનું કર્તૃત્વ અજ્ઞાત હોય છે.
- (2)લોકગીત એ પ્રયત્ન વિનાનું સહજ સ્વયંસ્ફૂરિત ગાન છે.
- (3)લોકગીતોમાં પ્રકૃતિનો મહિમા વ્યંજિત થતો હોય છે.
- (૪)લોકગીતો માનવસહજ હૃદયોર્મીઓને વ્યક્ત કરે છે.
- (૫)લોકગીતો પ્રણયભાવની સહજ અભિવ્યક્તિ છે.
- (6)લોકગીત વરણાત્મક ચિત્ર કાવ્ય છે.

(7)લોકગીત એ સંઘોર્મિનું ગાન છે.

(8)લોકગીતોમાં સ્વર, તાલ, લય અને સંગીત સમન્વય હોય છે.

(9)તે કાંઠોપકંઠપ પરંપરા છે.

(10) લોકગીતમાં લોક કલ્યાણની ભવ્યતા ઉજાગર થાય છે.

(11)લોકગીત એ વ્યંજનાત્મક અભિવ્યક્ત છે.

(12)તે સરળ, સચોટ, વાણીમાં ઉપલબ્ધ છે.

(13)લોકગીતોમાં ઐતિહાસિક તત્વ છુપાયેલું હોય છે.

(14) કેટલાક લોકગીતોમાં રાજા, બહારવટીયા અને સંતનાં કથાનકો જોવા

મળે છે.

આ રીતે લોકગીતોનાં સામાન્ય લક્ષણો તારવવામાં આવ્યાં છે.

હવે આપણે લોકસાહિત્યમાં કવિશ્રી દુલા ભાયા કાગના યોગદાનની ચર્ચા કરીશું.

❖ દુલાભાય કાગનું જન્મ અને શિક્ષણ :-

ગીતકાર, લેખક, કલાકાર અને પદ્મશ્રી એવોર્ડ પ્રાપ્ત કરનાર કવિશ્રી દુલા ભાયા કાગ (કાગબાપુ)નો જન્મ તા.25-11-1903 ના રોજ મહુવા પાસેના સોડવદરી (હવે રાજુલા તાલુકા)માં થયો હતો. પોતાના ઢોર ઢાંખર અને 650 વિધા જમીનને સાચવવા માટે તેમણે પોતાનું ભણતર છોડ્યું, તે પહેલા તેમણે ધો.5 શુધીનું પ્રાથમિક શિક્ષણ મેળવ્યું હતું. વિનોબા ભાવેના ભૂદાન યજ્ઞમાં તેમણે પોતાની 650 વિધા જમીન ધરી દીધી હતી. તેમણે ઔપચારિક શિક્ષણ બહુ ઓછું મેળવ્યું, પરંતુ જીવનજ્ઞાન અને ધાર્મિક ગ્રંથોના અભ્યાસથી તેઓ સમૃદ્ધ બન્યા. સંતો અને મહાત્માઓના સંપર્કથી તેમને આધ્યાત્મિક પ્રેરણા મળી.

તેમનું અવસાન 22 ફેબ્રુઆરી, 1977ના રોજ થયું, પરંતુ તેમની વાણી આજે પણ જીવંત છે. દુલાભાયા કાગના સાહિત્યનું કેન્દ્ર ભક્તિ છે. તેઓ ભગવાન પ્રત્યે અડગ શ્રદ્ધા ધરાવતા. તેમના ભજનોમાં ભગવાન અને ભક્ત વચ્ચેનો હૃદયસ્પર્શી સંવાદ જોવા મળે છે. તેમની ભક્તિ માત્ર ધાર્મિક કથન પૂરતી નહોતી; તે જીવનમાં સદાચાર, કરુણા અને સેવા સાથે જોડાયેલી હતી.

❖ ગાંધીવાદી પ્રભાવ

દુલાભાયા કાગ પર મહાત્મા ગાંધી ના વિચારોનો ઊંડો પ્રભાવ હતો.

તેમની રચનાઓમાં સત્ય, અહિંસા, સ્વદેશી અને રાષ્ટ્રપ્રેમના મૂલ્યો સ્પષ્ટપણે જોવા મળે છે.

સ્વાતંત્ર્ય આંદોલનના સમયમાં તેમની કવિતાઓ લોકજાગૃતિનું સાધન બની.

તેમણે પોતાના ભજનો દ્વારા લોકોને નૈતિક જીવન જીવવા અને દેશપ્રેમી બનવા પ્રેરિત કર્યાં.

❖ લોકજીવનના સાચા વાલ્મીકિ:-

સનાતની સંસ્કારના પાક રંગ, સ્વાશ્રય, અને વ્રત-સત્સંગમાં વણાઈ ગયેલા બાળકવી દુલા કાગ મુક્તાનંદ સ્વામીના આશીર્વાદથી લોકજીવનના સાચા વાલ્મીકિ બન્યાં. 'વિચારસાગર' સમા 'પંચદર્શી' અને માર્મિક વાણી સાથે વહેતી કવિ દુલા કાગની શાશ્વત સરવાણી આગળ જતાં અસ્ખલિત ધોધ બની ગઈ.

❖ સંતો પાસેથી પ્રેરણા:-

તેમની પાસે જન્મજાત કસુંબલ ગીતોનો વ્યવહારદર્શી વૈભવ હતો. ભલે તેમનું શિક્ષણ સામાન્ય હતું પરંતુ ગણતરની દ્રષ્ટિએ સમાજના દુઃખો- પીડાને કેવી રીતે ઓછા કરી શકાય તેની ઊંડી સમજ તેમનામાં હતી. મરમી સંતો સમાન સનાતની સંસ્કારનો પાકો રંગ તેમણે પ્રાપ્ત કર્યો હતો. આજે જ્યારે એક તસુ જમીન પણ લોકો જતી કરવા તૈયાર નથી હોવા, ત્યારે ૬૫૦ વીઘાં જેટલી જમીન તેમણે એક જ ક્ષણમાં ભૂદાન યજ્ઞમાં ધરી દીધી તેમનું હૃદય કેવું વિશાળ અને મર્માવું હતું, તે તેમનાં ગીતો તેમજ રચનાઓ દ્વારા જાણી શકાય છે.

'આકાશને ધડનાર ધરને કોણે ધડયા હશે?' એવી ગીત-રચના આપનાર કવિનું માં પ્રારંભથી જ પ્રભુભજનમાં લીન હતું. 'આકાશની માતા તણાં કોઠા કહો કેવડા હશે?' એવો પ્રશ્ન સામાન્ય જનને ન ઉદ્ભવે, પરંતુ આ જન્મ કવિ-કલાકારને આવા પ્રશ્નો ઉત્તર ન મળતાં તેમણે પોતે કબૂલ્યું કે, 'બ્રહ્માંડે ભટકી રહી, અંતે મતિ અટકી રહી.' પોતે 'અવધૂતનાં જોગી' છે. તેમ કહેવામાં તેઓ ગૌરવ અનુભવતા હતા. અને જેમને સત્સંગી થવું હોય તેમના માટે 'નિસરણી બની ઊભા' રેહતા હતા.

'જગતને ધડનાર કેવો હશે?' તે વિષે તેઓ કાયમ વિચાર્યા કરતા હતા. તેથી જ પોતાની જાતને તેઓ ખેત હતા કે, 'ઊડી ઓ પંખી.' તેમણે મુખેથી આવાં અનેક અલખ લોકગીતો પ્રાપ્ત થાય છે.

સંસારની માયા ભૂલી, સ્વાનુભૂતિ મુલક તત્વચર્યા જ સત્વ અને સત્સંગની અભિવ્યક્તિ છે. જગત મિથ્યા છે. ‘વનરાયું સળગી, હવે જૂના માળા મૂકી ઊડી જાઓ’ તેમ તેઓ લોકોને સમજાવતા હતા. તેમનું મન- હૃદય કેવું માથાળું હતું તે તેમની પ્રખ્યાત રચના-

“તારા આંગણિયા પૂછી કોઈ આવે તો

આવકારો મીઠો આપજે રે.....

“હેજી તારે કને સંકટ કોઈ સંભળાવે તો

સંકટ થોડું કાપજે રે.....

(કારણકે) માનવીની પાસે કોઈ માનવી નવ આવે રે....”

આગળ જતાં કવિ કહે છે કે,

“કેમ રે આવ્યાં છો તેમ મત પૂછજો રે..”

લોકહૈયામાં વસેલી આ અને આવી અસંખ્ય રચનાઓ કવિ ડાયરમાં ગાતા હતા. ત્યારે સૌ કોઈ શ્રોતાની આંખો અશ્રુભીની થઈ જતી હતી. તેવું જ તેમનું અન્ય લોકગીત-

“હંસલો ચાલ્યો જવાનો એકલો રે..”

હોય કે,

“આપના મલકનાં માયાળુ માનવી” ગીત હોય શ્રોતાજનોની આખોમાંથી અશ્રુધારા અસ્ખલિત વહેતી હતી. તેમનાં લોકગીતોમાં ઊંડું દર્દ હતું.

મર્મી સંતોની પેઠે તેઓ કહેતા હતા કે,

“અમે પંખીડા રે જીવન દિન ચારનાં..”

રૂઢિગ્રસ્ત જિંદગીમાં લોકોને કઈક નવું આપવું તેવી તેમની વિચારધારા હતી. સાશ્વત મનીષાનું અસાધારણ પ્રતિનિધિત્વ તેઓ કરતા હતા.

‘કાગવાણી’(૧ થી ૮ભાગ) તેમની રચનાઓ અને લોકગીતોનો સમાજને અપાયેલો અમૂલ્ય અક્ષર વારસો છે. ૧૯૬૨માં તેમને ‘પદ્મશ્રી’ ના ઇલ્કાલ દ્વારા નવાજમાં આવ્યા હતા. તેમણે તેમની જિંદગીના આંટી, દિવસો પીપાવાવ અને તુલસીશ્યામમાં અર્પિત કરી દીધા હતા. તેમનું અવસાન

તા.૨૨-૨-૧૯૭૭ ના રોજ પોતાના ગામ મજાદરમાં થયું હતું. કસુંબલ લોકગીતોના કસબી કવિશ્રી દુલા ભાયા કાગની વિદાય થતાં, સમજે એક મરમી ફિલસૂફીના દુલાભાયા કાગ ગુજરાતી સાહિત્યના તેજસ્વી પ્રતિક છે. તેમણે પોતાના જીવન અને સાહિત્ય દ્વારા ભક્તિ, રાષ્ટ્રપ્રેમ અને નૈતિક મૂલ્યો સમાજમાં પ્રસ્થાપિત કર્યાં.

તેમની રચનાઓમાં લોકજીવનની સરળતા અને વૈશ્વિક માનવતાનો સંદેશ એકસાથે જોવા મળે છે. આથી દુલાભાયા કાગનું સ્થાન માત્ર ગુજરાતી લોકસાહિત્યમાં જ નહીં, પરંતુ ભારતીય ભક્તિ પરંપરામાં પણ વિશિષ્ટ છે.

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## **Artificial Intelligence, Data Analysis, and Digital Learning: Catalysts for Social Change and Sustainable Development**

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### **Abstract:**

The rapid evolution of Artificial Intelligence (AI), Data Analytics, and Digital Learning technologies is reshaping education systems, governance models, and socio-economic development across the global. These technologies are not only enhancing learning efficiency and decision-making processes but also serving as powerful instruments for social transformation and sustainability. This paper explores the integration of AI-driven tools, big data analytics, and digital learning platforms in fostering inclusive education, reducing inequalities, improving resource management and enabling sustainable development. The study highlights key applications, benefits, challenges and policy implications of technology-enabled learning ecosystems. The findings suggest that when strategically implemented, AI and data-driven learning systems significantly contribute to achieving Sustainable Development Goals (SDGs), particularly quality education, reduced inequalities and sustainable communities. The paper concludes with recommendations for ethical governance, capacity building and sustainable digital adoption.

**Keywords:** Artificial Intelligence, Data Analytics, Digital learning, Social Change, Sustainability, Smart Education, EdTech, SDGs.

### **Introduction:**

Digital transformation has emerged as one of the most influential forces shaping contemporary society. Artificial Intelligence (AI), Data Analytics and Digital Learning technologies have significantly altered how knowledge is created, delivered and consumed. Educational institutions, governments and organization increasingly rely on intelligent systems to improve to accessibility, personalization and efficiency. The twenty-first century is witnessing an unprecedented digital transformation driven by rapid advancements in Artificial Intelligence (AI) and Digital Learning technologies. These innovations are fundamentally reshaping education systems, governance structures.

The convergence of these technologies offers unprecedented opportunities to bridge educational gaps, empower marginalized communities and promote sustainable development.

Particularly in developing countries, digital learning platforms supported by AI and analytics can democratize education and enhance social mobility. However, the transformative potential of these technologies also presents critical challenges, including concerns related to data privacy, algorithmic bias, digital exclusion and ethical governance.

This Research Paper investigates how AI, Data Analytics and digital learning act as enablers of social change and sustainability by transforming traditional educational ecosystems into intelligent, inclusive and future-ready systems.

### **Literature Review:**

#### 1. Artificial Intelligence in Education

AI technologies such as machine learning, natural language processing and intelligent tutoring systems enable:

- Personalized learning experiences
- Automated assessments
- Smart content recommendations
- Virtual assessments and chatbots

Research shows AI enhances learning outcomes by adapting instruction based on student behaviour and performance.

#### 2. Data Analytics in Education

Data analytics helps institutions:

- Monitor student progress
- Predict dropouts
- Improve curriculum design
- Optimize resource allocation

Learning analytics provides actionable insights that improve instructional effectiveness.

#### 3. Digital Learning Systems

Digital learning platforms include:

- MOOCs
- E-learning portals
- Mobile learning apps
- Virtual Classrooms

These systems increase flexibility, accessibility and affordability of education.

#### 4. Technology and Social Change

Scholars argue that technology-driven education:

- Reduces inequality
- Promotes digital literacy
- Enhances employability
- Encourages lifelong learning

#### 5. Sustainability in Education

Sustainable education focuses on:

- Reduced paper usage
- Remote learning
- Energy-efficient systems
- Environmental awareness

Digital solutions support eco-friendly learning environments.

### **Objectives of the Study:**

The study aims to:

1. Examine the role of AI improving educational outcomes
2. Analyse the impact of data analytics on decision-making
3. Evaluate digital learning as a tool for social transformation
4. Assess the contribution of these technologies toward sustainability
5. Identify challenges and policy implications

### **Methodology:**

This research adopts a quantitative and conceptual approach, supported by:

- Secondary data from journals, reports and policy documents
- Case study analysis
- Comparative evaluation of digital learning initiatives

Sources include UNESCO, World Bank and EdTech research publications.

### **Role of AI in Digital Learning:**

AI enhances education through intelligent automation and personalization.

Key Applications:

- Adaptive learning systems
- AI chatbots for student support
- Automated grading
- Content generation tools

Benefits:

- Faster feedback
- Customized instruction
- Reduced teacher workload
- Better engagement

AI allows learners to progress at their own pace, improving retention and performance.

**Role of Data Analytics:**

Data analytics transforms raw educational data into actionable insights.

Applications:

- Predictive analytics for dropout prevention
- Performance tracking dashboards
- Institutional planning
- Behavioural analytics

Impact:

- Evidence-based decisions
- Improved student success rates
- Efficient resource management

Institutions can proactively address learning gaps.

**Digital Learning and Social Change:**

Digital learning promotes social inclusion and equality.

Contributions:

- Remote education for rural areas
- Affordable online courses
- Skills development

- Women empowerment through flexible learning

Outcomes:

- Increased literacy
- Higher employment opportunities
- Reduced socio-economic barriers

Technology reduces geographical and economic constrains.

### **AI, Analytics and Sustainability:**

Environmental Sustainability:

- Paperless classrooms
- Reduced travel emissions
- Energy-efficient cloud systems

Economic Sustainability:

- Cost-effective delivery
- Scalable infrastructure
- Reduced operational expenses

Social Sustainability:

- Equal access to education
- Inclusive learning environments
- Community empowerment

These technologies align with SDGs 4, 9, 10 and 11.

### **Case Studies:**

#### Case-1: AI-Based Adaptive Learning Platforms

Platforms like Coursera and Khan Academy use AI to personalize learning pathways, increasing completion rates.

#### Case-2: Data Driven School Management

Institutions using analytics dashboard academic performance and reduced dropout rates.

#### Case-3: Digital Learning in Rural Regions

Government-led digital initiatives enabled remote access to education, bridging rural-urban gaps.

### **Challenges:**

Despite benefits, several issues remain:

- Digital divide
- Data privacy concerns
- Algorithmic bias
- High implementation costs
- Lack of digital literacy

Ethical and regulatory frameworks are essential for responsible adoption.

Benefits:

- Develop inclusive digital infrastructure
- Provide teacher training in AI tools
- Ensure data protection policies
- Promote open-source platforms
- Encourage public-private partnerships
- Focus on sustainable technology practices

### **Future Scope:**

Future research may explore:

- AI-powered immersive learning (AR/VR)
- Blockchain in credential verification
- Green computing in education
- Smart campuses

Emerging technologies will further enhance sustainable digital ecosystems.

### **Conclusion:**

Artificial intelligence (AI), data analytics and digital learning are transforming education into a more intelligent, inclusive and sustainable systems. These technologies empower learners,

improve institutional efficiency and promote social equity. When integrated thoughtfully and ethically, they become powerful drivers of sustainable development and social change. Policymakers, educators and technologists must collaborate to create resilient digital education systems that serve future generations.

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**THE ROLE OF ARTIFICIAL INTELLIGENCE IN SHAPING  
MODERN DIGITAL PAYMENT SYSTEMS: MARKETING  
INNOVATION, PERSONALIZATION, AND CUSTOMER ADOPTION**

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**Abstract**

The digital payment ecosystem in India has grown at a very fast pace in the last ten years through both active government mobility and due to unrelenting technological advancement. The volume of digital payment transactions expanded by 2.07 billion in FY201718 to 18.7 billion in FY20 23 24, which shows a structural change in consumer payment behaviour. In parallel with the growth in this field, artificial intelligence (AI) has become a disruptive technology in the fintech industry, as it allows data-driven marketing innovations and highly personalized marketing. This paper analyses how the personalization that AI enables and AI-based marketing innovation impact the adoption of India consumers to digital payment systems.

On the basis of primary survey data gathered among Indian users of digital payments, the research will be able to test two hypotheses: whether AI-based personalization is substantially related to customer adoption (H01/H11) and whether customer adoption depends on the various levels of AI-based marketing innovation (H02/H12). Analysis of data was performed through reliability analysis, Pearson correlation and one way analysis of variance (ANOVA). The findings indicate that there is an enormous and significantly significant positive correlation between the perceived AI-driven personalization and customer adoption, which rejects H01 and supports H11. Moreover, it also was noted that there were large disparities in the adoption of low, medium, and high AI-based marketing innovation groups leading to the rejection of H02 and acceptance of H12.

The results confirm that AI-based personalization and new AI-based marketing techniques are vital towards increasing the identification of digital payment platforms among Indian consumers. The paper has significant managerial and policy implications as it reveals the necessity of fintech companies to strategically invest in AI-driven personalization and prompt

policymakers to enhance AI-permitted security and governance systems as a means of maintaining the long-term growth of digital payments.

**Keywords:** Artificial Intelligence, Digital Payments, Personalization, Marketing Innovation, Customer Adoption, India.

## 1. Introduction

### 1.1 Background

The shift of India to a digitally-enabled payment ecosystem is one of the most important changes in the global financial sector. Pull policy measures, regulatory facilitation, and quick growth of digital infrastructure have all contributed to the accelerated pace in the uptake of cashless transactions. According to official statistics, digital payment transactions have grown by almost 2,070 crore in FY201718 to 18,737 crore in FY202324, or by almost 44 percent per year. The Indian payments market is dominated by mobile-based and real-time payment platforms specifically the Unified Payments Interface (UPI), which make almost 70 percent of all digital interactions in FY202324. The success of UPI has been commonly known as a globally scalable and interoperable payment infrastructure of retail, which has transformed traditional interpretations of payment systems.

In the face of success due to nearly saturation adoption of digital payments in the city India, the importance of competitive differentiation has risen amongst the service providers in the payment industry. Having over 504 million users actively using UPI platforms, fintech companies and banks can no longer afford to stick to the basic transactional services to retain and increase their user base. User experience, quality of engagement and effectiveness in digital marketing have become strategic necessities in this ever-competitive landscape.

It has therefore become a mainstream topic in artificial intelligence (AI) as a disruptive enabler of fintech. Banks are widely using AI-powered technologies to detect fraud, chatbots, credit rating, transaction alerts, and interact with customers. In addition to enhancing efficiency in its operations, the technologies will help firms provide more responsive customer-focused services. The two most notable ways to use AI in the fintech sector are AI-driven personalization and AI-based marketing innovation, which directly affect the use of digital payments platforms by users.

The concept of AI-driven personalization is using machine learning algorithms and behavioural data to shape digital interfaces, offers, and services to the individual preferences of the user. According to previous studies, perceived usefulness, customer satisfaction, and long-term loyalty are improved by personalization. In the digital payments domain, AI-based systems have the ability to process the transactional history to produce customized rewards, spending information, and contextual suggestions to enhance the overall user experience. AI-based marketing innovation, which can be defined as the implementation of AI technologies in creating new, data-driven marketing approaches like targeted advertising, dynamic content delivery, gamified incentives, and personalized promotional campaigns is closely connected to personalization.

Although the use of AI in fintech operations is increasing, the empirical data on the changes in customer adoption of digital payment systems using AI-driven personalization and AI-based marketing innovation is scarce, especially in developing economics, like India. Current research findings on the adoption of digital payments are mostly on the perceived ease of use, security, trust, and social influence as opposed to the relative scarcity of academic interest on advanced AI-based customer engagement mechanisms.

## **1.2 Research Problem**

In order to fill this gap, the current study explores two fundamental questions of the research:

- (1) Does personalization based on AI have a significant impact on the adoption of digital payment systems by consumers?
- (2) Is there a difference in customer adoption with different levels of AI-based marketing innovation?

## **1.3 Research Objectives**

In this regard, the research proposes and empirically verifies two null hypotheses: H01 that will assume the lack of significance between AI-driven individualization and customer adoption, and H02 that will assume the lack of difference in the customer adoption with diverse extents of AI-based marketing innovation. These hypotheses are examined by a Pearson correlation analysis and one-way ANOVA based on the survey data taken on the Indian digital payment users.

## 1.4 Significance of the Study

This research will make its contribution to the literature on fintech and information systems by empirically investigating AI-based marketing innovation and AI-driven personalization as two factors that determine the adoption of digital payments in relation to current models of adoption. The results provide valuable information to the managers of fintech institutions that want to enhance user engagement and those interested in inclusive, secure, and sustainable growth of digital payments.

## 2. Literature Review

### 2.1 Theoretical Framework

#### **The Digital Payments in India have been evolving:**

The situation in digital payments in India has been experiencing a swift and long-term transformation, with the help of governmental efforts like Digital India, 2016 demonetization, and ongoing support of fintech policies. The adoption has been greatly boosted by the development of electronic payment systems such as NEFT and RTGS in the early 2000s as well as by the introduction of the Unified Payments Interface (UPI) in 2016 (Reserve Bank of India, 2024). The national statistics suggests that UPI transactions grew by 92 crore in FY201718 to 13,116 crore in FY202324, indicating that UPI is at the heart of the payment ecosystem in India. The use of mobile wallets and prepaid instruments also increased in the times of the COVID-19 when contactless payment options were becoming necessary (Deloitte India, 2022).

These changes are reflected in academic studies, which signify convenience, ease of use, security, and trust as the main factors of digital payment adoption (Chaturvedi and Singh, 2021). As an illustration, Ali and others (2024) show that convenience, cost-effectiveness, security, social influence, and innovativeness are some of the factors that have a significant effect on the adoption among the Generation Z users. The same can be said about the work based upon the Technology Acceptance Model (TAM) and UTAUT frameworks, which focus on the importance of perceived usefulness and trust as the key factors of adoption (Gartner, 2022). Nevertheless, a large portion of this literature focuses on technological features and demographic variables, which provide a minimal understanding of the role played by the innovative AI-enabled personalization and marketing in influencing the adoption behaviour.

Whereas the use of incentives and security assurance as the adoption facilitators is commonly known, little is understood about the role of AI-based engagement mechanisms.

### **Artificial intelligence in Financial Technology and Digital Payments:**

Artificial intelligence usage in the financial industry is not new. Fintech companies and banks are increasingly using AI and machine learning to detect fraud, score credit, automate KYC, and use chatbots to provide customer services, and it has been shown that the rate of fraud decreases by 2030. The banking industry in India has witnessed accelerated AI adoption with nearly 70 percent of banks also claiming enterprise-level AI strategy and most banks using AI-driven chatbots (KPMG India, 2023). On the international scale, India represents almost 46 percent of real-time payment volumes, which are mainly backed by AI-based applications, including UPI.

Financial services marketing has also undergone a revolution as applied by AI. Generative AI-based tools enable the automatic generation of content, hyper-personalized offers as well as dynamic pricing. According to the industry reviews, AI can be used to optimize personalization in online payments and operational efficiency due to the ability to use transaction-based data to provide customized recommendations and promotional discounts (Kotler and Keller, 2021). Even though over fifty percent of fintech companies allegedly use AI in core business operations and marketing activities, empirical studies exploring the immediate effect of AI-based innovation on consumer adoption behaviour are few, especially on the digital payment part.

### **Customer Behaviour and Customization:**

Personalization can be described as product, service or interface customization in accordance with the preferences and behavioural data of a particular customer. The literature of marketing and financial services has previously indicated that, personalization is likely to improve the perceived value, customer satisfaction and retention. Customized spending notifications or customized financial guidance, which can be achieved through AI in a banking setting, has been demonstrated to enhance customer engagement and intensity of use. Industry reports also point to the fact that AI-based personalization has the potential to greatly increase customer satisfaction, which supports marketing theory that active and applicable content increases user response (Ernst & Young LLP, 2024).

In the digital payment space, the concept of personalization can be the adaptive interface or personalized rewards, or offers that depend on the context. Nevertheless, there is still scarce and inconclusive empirical evidence that relates to digital payments. Other studies in the region do not identify any direct effect of personalized features on purchase decision-making, which could be explained by contextual or methodological reasons. In theory, the extensions of the Technology Acceptance Model imply that personalization increases the perceived usefulness and the ease of use, consequently boosting the intentions to adopt (Vyas and Maheshwari, 2020). This conceptual connection justifies the assumption that AI-based personalization has a positive impact on the adoption of digital payments.

### **Digital Payments Innovation in Marketing:**

The AI also offers the possibilities of marketing innovation through permitting companies to create data-driven, targeted, and interactive promotion approaches. Examples of AI-based marketing innovations in the digital payments industry are customized ads, incentives based on gamification, context-specific offers, and real-time optimization of campaigns (Singh and Malik, 2022). AI-based analytics are becoming more and more relied upon to segment users and tailor marketing messages to them, dynamic pricing and personalized offers are becoming possible due to real-time data processing.

Despite the scarcity of academic sources on AI-based marketing innovation in the area of digital payments, the general marketing literature has it that innovative marketing practices have a crucial impact on technology uptake, especially in digitally intensive markets. The theory of the Diffusion of Innovations states that exposure to differentiate and new marketing communications may speed up the adoption through increasing awareness and perceived value (India Brand Equity Foundation, 2024). Therefore, the users who are subjected to increase AI-enhanced marketing tend to show greater adoption behaviour as compared to users who are subjected to generic marketing strategies.

The literature review indicates that there are two acute gaps that informed the current research. To begin with, despite the established role of traditional predictors like perceived ease of use, security, trust, and social influence as determinants of digital payment adoption, it has not been thoroughly studied how AI-driven personalization specifically predicts digital payment adoption, especially in the case of the emerging economy and India in particular.

Second, even though fintech companies are becoming more dependent on AI-based marketing innovation such as personalized campaigns, data-driven targeting, and interactive marketing approaches, there is limited empirical data to examine the impact of these innovations on customer adoption behaviour (Kumar and Sharma, 2021).

## **2.2 Previous Studies**

The majority of the previous research is based on traditional technology adoption models and the emphasis on functional or infrastructural features thus ignoring the increasing significance of AI-based and user-driven interaction systems.

## **2.3 Research Gap**

Current literature is relatively willing to accept marketing innovation as a concept, yet there is a paucity of systematic empirical studies of AI-initiated marketing behaviours as adoption motivators, particularly in the high-frequency adoption contexts of digital payments.

## **2.4. Objectives:**

Relating to these gaps, the current research contributes to the existing technology adoption models, specifically, the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT), by intentionally introducing AI-driven personalization and AI-driven marketing innovation as key explanatory factors (Reserve Bank of India [RBI], 2023). The study contributes to the existing knowledge on fintech adoption in new digital economies by empirically researching their impact on customer adoption of digital payment systems. To this end, the paper will specify and test H01/H11 and H02/H12 to evaluate the impacts of these AI-related variables on the uptake of digital payments in India.

## **3. Methodology**

### **3.1 Research Design**

It will have a quantitative, cross-sectional survey design in which the researcher is going to test how AI-driven personalization and AI-based marketing innovation affects the adoption of digital payment systems. The given research design is suitable to empirically test the relationship between perceptual constructs and behavioural intentions in a large and heterogeneous sample of users.

The target customer base was Indian customers who are either users or aware of digital payment applications like UPI-based applications and mobile wallets. The structured online questionnaire was utilized as the method of data collection and disseminated in social media and email networks, where the convenience sampling strategy was selected (PricewaterhouseCoopers, 2024). This approach has facilitated effective reach to the wide range of cross-sectional digital payment users in the varying demographic groups.

Valid responses were received with the participants that represent various age brackets, geographic areas, and professions. The demographic data were obtained to characterize the sample group (age and gender). The survey was voluntary, and respondents were guaranteed anonymity and confidentiality to limit bias in responding to the survey and motivate them to report honestly.

### **3.2 Sample and Sampling Technique**

The questionnaire was used to measure three important constructs, which include AI-driven Personalization, AI-based Marketing Innovation, and Customer Adoption of digital payment systems. All the constructs were operationalized with the help of several items that were assessed on a five-point Likert scale, with 1 (strongly disagree) and 5 (strongly agree).

The Personalization based on AI was measured using the items related to the perception of the respondents about the degree to which digital payment applications offer customized offers or services and interface according to the behaviour of using the application (e.g., My payment app provides me with customized offers or services based on my usage behaviour) (McKinsey and Company, 2023). The items used to measure AI-based Marketing Innovation were those that captured the perceptions of innovative, data-oriented, and personalized promotional actions done by the digital payment platforms (e.g., the promotional campaigns of digital payments I see are innovative and customized to my needs). Customer Adoption was assessed with the help of items that reflected both the frequency of use and the intention to use digital payment services (e.g., I often use digital payment services, and I will use them in the future).

All items of measurement were based on the already tested scales in the technology adoption and fintech literature and adjusted to the situation to apply AI-enablers peculiar to digital payment systems (NITI Aayog, 2018). The questionnaire underwent pre-test among around 30

respondents before the main survey in order to be certain that the questionnaire is clear, relevant, and face-valid.

Cronbachs alpha was performed to assess the reliability, and the levels of alpha were satisfactory, and all constructs were above the recommended alpha level of 0.70 (NASSCOM et al., 2023). Validity was also construct measured using exploratory factor analysis, which ensured that measurement items fitted the measures well on their constructs.

**Table 2: Descriptive Statistics and Reliability Analysis**

<b>Construct</b>	<b>Number of Items</b>	<b>Mean</b>	<b>Standard Deviation</b>	<b>Cronbach's Alpha</b>
AI-driven Personalization	Multiple	3.80	0.70	0.82
AI-based Marketing Innovation	Multiple	3.20	0.80	0.79
Customer Adoption	Multiple	3.71	0.65	0.85

All Cronbach's alpha values exceed the recommended threshold of 0.70, indicating satisfactory internal consistency.

### 3.3 Data Collection

Data collection was performed for one month by using the online survey. The respondents identified themselves as the users or the informed consumers of digital payment platforms such as applications of UPI and mobile wallets. After screening for incomplete and invalid answers the final sample comprised of around 250 valid samples (PricewaterhouseCoopers, 2023). This is a sample size that is considered to be sufficient for correlation analysis and analysis of variance (ANOVA) with conventional levels of statistical power (Department of Financial Services, 2024).

The data was coded, cleaned and analysed with the MS Excel 2019. Descriptive statistic, Pearson correlation analysis and also one way analysis of variance were done with in build statistical functions. The statistical significance was tested at  $p < 0.05$  or 5 percent level.

### 3.4 Data Analysis

In order to test the proposed hypotheses two main statistical techniques have been used. First, the relationship between the use of AI-driven Personalization and Customer Adoption was examined using Pearson correlation analysis. Second, one way analysis of variance (ANOVA) was conducted to know whether there is a significant difference of customer adoption in various levels of AI-based Marketing Innovation.

Before moving on to the analysis normality assumption and homogeneity of variance assumption were checked and found satisfactory. For the purpose of the ANOVA, respondents were included in Low, Medium and High group of Marketing Innovation based on their composite scores of innovation. Post-hoc comparisons, based on Tukey's HSD test were conducted where applicable. The results of the statistical tests was then used to accept or reject the null and alternative hypotheses (H01/H11 and H02/H12).

### **Hypotheses Development**

Based on theoretical foundations and industry evidence, the study proposes the following hypotheses:

- (1) **H01:** There is no significant association between AI-driven personalization and customer adoption of digital payment systems.
- (2) **H11:** There is a significant association between AI-driven personalization and customer adoption of digital payment systems.

AI-driven personalization is expected to enhance perceived usefulness and user satisfaction by delivering customized offers, recommendations, and support services, thereby increasing adoption and usage intensity. However, the null hypothesis assumes that personalization may not significantly influence adoption behaviour.

- (1) **H02:** There is no significant difference in customer adoption across different levels of AI-based marketing innovation.
- (2) **H12:** There is a significant difference in customer adoption across different levels of AI-based marketing innovation.

AI-based marketing innovation, through mechanisms such as gamified promotions, targeted campaigns, and interactive engagement, is expected to influence adoption behaviour. The null hypothesis assumes that adoption remains uniform irrespective of marketing innovation levels.

## Data Analysis and Interpretation

Descriptive analysis showed a high level of digital payment usage among the respondents in general. The mean score relating to Personalization (AI driven) was 3.80 (SD = 0.70) - implying positive feelings regarding personalized features. The average score for AI-based Marketing Innovation was 3.20 (SD = 0.80) which suggest that there is moderate exposure towards innovative marketing practices.

### Correlation Analysis (H01/H11)

Pearson correlation analysis revealed there exists a strong and statistically significant positive relationship between the concept of AI driven Personalization and Customer Adoption, ( $r=0.76$ ,  $P < 0.001$ ). This result leads to the conclusion that the higher level of perceived personalization is related to higher adoption and continued use of digital payment systems. Accordingly, the null hypothesis H01 is rejected and H11 is supported. The finding provides support for the case that AI-enabled personalization improves user engagement and adoption behavior.

**Table 3: Correlation Matrix of Key Constructs**

Variables	Mean	SD	1	2	3
1. AI-driven Personalization	3.80	0.70	1.00	—	—
2. AI-based Marketing Innovation	3.20	0.80	—	1.00	—
3. Customer Adoption	3.71	0.65	0.76**	—	1.00

$p < 0.001$

## 4. Results

### 4.1 Descriptive Statistics

To investigate whether customer adoption varies at different levels of marketing innovation based on AI, one way analysis of variance (ANOVA) was performed. Respondents were classified into three groups Low, Medium and High Marketing Innovation according to their composite innovation scores.

The results show statistically significant differences in customer adoption in the three groups. The mean adoption scores increased from the Low Innovation group with a mean score of 3.39

(n = 58) to the Medium Innovation group with a mean score of 3.74 (n = 99) and High Innovation group with a mean score of 4.02 (n = 43) respectively. The ANOVA gave an F-value of 9.87 which was statistically significant at 0.1 percent levels of significance ( $p < 0.001$ ) proved that there is significant variation in customer adoption with respect to levels of AI-based marketing innovation.

Post-hoc comparison using Tukey's Honestly Significant Difference (HSD) test showed that customer adoption in the High Innovation group was significantly higher than in the Low Innovation group ( $p < 0.01$ ). The difference between the Medium and the High Innovation groups was positive but relatively lower. Based on these results, the null hypothesis H02 is rejected and the alternative hypothesis H12 is supported.

#### Panel A: Mean Customer Adoption Scores Across Marketing Innovation Levels

Marketing Innovation Level	Sample Size (n)	Mean Adoption Score
Low Innovation	58	3.39
Medium Innovation	99	3.74
High Innovation	43	4.02
<b>Total</b>	<b>200</b>	—

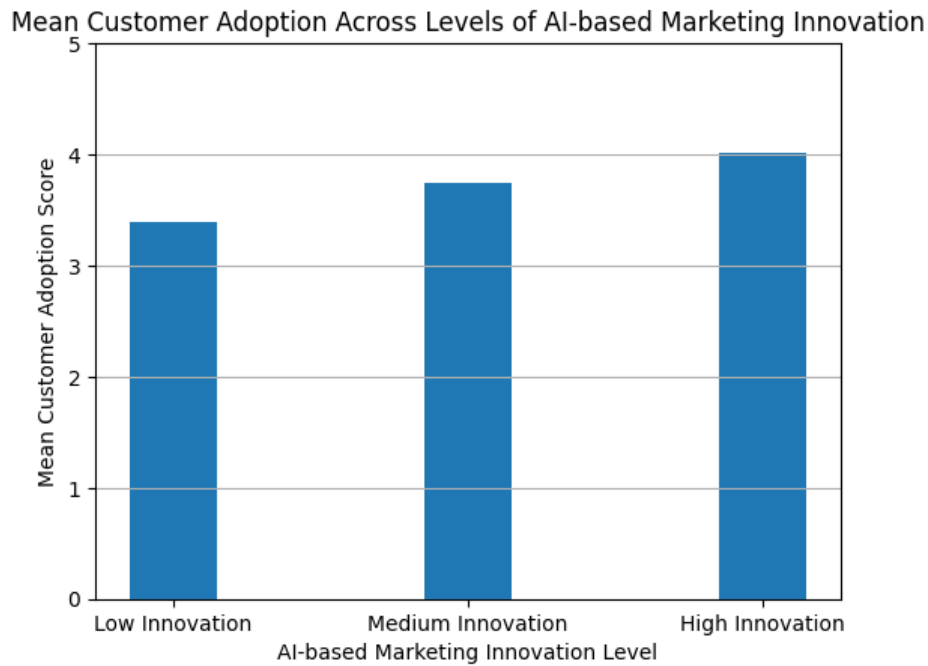
#### 4.2 Inferential Statistics

##### Panel B: One-Way ANOVA Results

Source of Variation	Degrees of Freedom (df)	F-value	Significance (p)
Between Groups	2	9.87	$< 0.001$
Within Groups	197	—	—
Total	199	—	—

##### Post-hoc Test:

- Tukey's HSD test indicates that the **High Innovation group exhibits significantly higher adoption than the Low Innovation group ( $p < 0.01$ )**.



**Figure 1: Mean Customer Adoption Across Levels of AI-based Marketing Innovation**

Figure 1 illustrates the mean customer adoption scores across Low, Medium, and High levels of AI-based marketing innovation. The chart shows a clear upward trend in adoption as the level of marketing innovation increases, visually reinforcing the ANOVA results and highlighting the positive role of AI-enabled marketing strategies in driving digital payment adoption.

### 4.3 Key Findings

The empirical results prove that the AI based personalization and AI based marketing innovation has a significant role to play for deciding the digital payment adoption in India. The positive linkage between AI-driven personalization and customer adoption is so strong that it provides empirical evidence for the case that customized digital experiences help to increase user engagement, loyalty and ongoing usage. This finding is consistent with past studies in the marketing and information systems literature concerning the importance of personalization and its usefulness as a determinant of perceived usefulness and customer satisfaction.

Similarly, enormous variances in adoption in comparison to different degrees of AI based marketing innovation suggest there is a measurable effect of innovative marketing strategies using AI on the behaviour of consumers. Users who are exposed to a higher level of marketing innovation - dynamic marketing promotions, personalized marketing campaigns, and

interactive mechanisms - report significantly higher levels of adoption than users exposed to less innovative approaches. While the study is based on perceptual and cross sectional data, the consistency and strength of the statistical data adds up to compelling evidence of the strategic importance of AI in the digital payments ecosystem.

## **5. Discussion**

### **5.1 Interpretation of Findings**

The empirical analysis had two main findings which contributed in the rightful understanding of the digital payment adoption in India.

First, AI-based personalization was positively and significantly associated with customer purchasing digital payment systems. Users that experience higher levels of personalization such as customized offers, intelligent recommendations and customized user interfaces, are more likely to adopt and continue using digital payment services (Bhardwaj & Gupta, 2020). This finding offers compelling empirical evidence for H11, and is consistent with established theory in the marketing and information systems fields which would suggest that personalization is supportive of perceived usefulness, engagement and overall user satisfaction, which helps to strengthen intended continued usage.

These results have a strong resonance with the trends in the current industry. Fintech companies have often contended that initiatives started by AI can bring about customer acquisition and retention, and the current study is an empirical evidence in corroboration of the same in the Indian digital payments ecosystem. Industry reports focussing on AI and machine learning around personalization, security and engagement coupled with regulatory initiatives by institutions like the Reserve Bank of India sums up to the fact that technologically sophisticated and secure payment systems form a vital part of building consumer trust and driving acceptance (Accenture, 2023).

Although some customer perceptions underpin the results, and thus introduce some level of interpretive elements, the robustness and consistency of the relations noted indicate that the association between AI driven personalization, marketing innovation and marketing adoption is substantive as opposed to spurious. Overall, the findings are an important reminder that AI-powered personalization and marketing innovation is not just a theoretical phenomenon, but is empirically linked with the adoption outcome in India's digital payment ecosystem.

## 5.2 Comparison with Previous Studies

This result is consistent with the wider AI and customer experience literature identifying the role of personalization as a key mechanism of value creation in the digital services. Industry surveys which report on the significant increase in customer satisfaction by AI driven personalization also further validate the relevance of the above finding (National Payments Corporation of India [NPCI], 2024). In contrast, none of the null hypotheses (H01), assuming the irrelevance of AI-driven personalization is supported, underlining the increasing importance of personalized experiences in the digital financial services arena.

Notably, the findings are different from some previous research on the region in India that did not find much of an effect of personalization on purchase behaviour. This discrepancy may be explained by differences in the design of the research, in the composition of the sample, or in the behavioural outcome being studied. While the previous research areas have been isolated to purchase decisions, now the research is looking at more general adoption behaviour for instance continuing an intention to use. In a rapidly digitizing economy like India's, where digital payments is playing an increasingly important role in day-to-day transactions, value-added features that can be made possible by personalization seem to have a greater gravitational pull on sustained adoption.

## 5.3 Theoretical Implications

From a theoretical perspective, the results show that there are important extensions in the existing technology adoption models. While the classical models like TAM and UTAUT identify ease of use, cost effectiveness and trust, the current research identifies that artificial intelligence (AI) based personalization and AI based marketing innovation are a vital part as antecedents of adoption in today's Fin-tech spaces (Research and Markets, 2022). Perceived personalization might, therefore, be introduced as a generalization of perceived usefulness in models on technology acceptance. Furthermore, the results support practitioner observations that generic and one size fits all marketing approaches are becoming less and less effective in data-rich digital environments in which consumers show stark differences between personalized and non-personalized services.

## 5.4 Practical Implications

The implications of this study have a number of significant implications for fintech managers, digital payment providers and industry practitioners.

First, the sizeable relationship between AI-powered personalization and customer adoption suggests investments in AI-powered personalization capabilities as a strategic priority (not an optional enhancement). Fintech companies should use machine learning and advanced analytics to translate personal behaviour and design customized payment experiences such as customized cashback offers, customized spending insights and context-aware payment recommendations. In the face of the established relation between personalization and adoption, such initiatives can provide a critical source of competitive separation in a growing crowded digital payments market.

Second, the findings are a way of pointing out the strategic importance of marketing innovation based on artificial intelligence. The massive difference in adoption rates for the levels of marketing innovation indicates that the traditional and generic approach to marketing has failed to keep users engaged. Marketing teams should rely more on AI-driven analytics, to plan targeted marketing campaigns that appeal to certain sections of the customers. Examples are dynamic discounts based upon spending behaviour, AI-based adaptive advertisements and gamified referral or reward programs. Importantly, these marketing innovations should be accompanied by messaging around security and trust as the focus on AI's role in fraud prevention and risk mitigation can further leads to higher consumer confidence.

Third at the organizational level, the leadership has to create an AI oriented culture with a strong culture of continuous innovation. This means investing in building capabilities of the marketing, product and analytics teams and forming strategic partnership with AI vendors or fintech incubators/technology startups. Managers should also be watching adoption patterns by demographic and geographical segments, and design targeted intervention in areas where adoption lags. Aligning organizational strategy along the lines of AI-enabled personalization and marketing innovation can help firms to tap into sustained growth potential of Indian digital payments market in India.

## **6. Limitations**

Despite its contributions, there are a number of limitations to the study that need to be considered. First, the convenience of using a non-random sample of the participants based on

online means may present a bias and the results do not necessarily represent the general user population. Second, the cross sectional design captures perceptions only as they stand at a single point in time and limits ability to make any definitive inferences about causality. Third, use of self-reported measures can gain common method bias that in turn can inflate relationships.

Additionally, the study is purely focused on AI driven personalization and AI based marketing innovation other contributing factors such as digital literacy, institutional trust or socio-economic conditions were not explicitly included in the study. Finally, there was an aggregate level of measurement of the constructs, in the future, studies that focused on specific AI applications could be undertaken in greater detail. Despite these limitations, the study helps in providing a strong empirical basis to understand the role of AI in the adoption of digital payments.

## **7. Conclusion**

### **7.1 Summary of Findings**

This research is an example of the importance of artificial intelligence in the fast evolving digital payments landscape in India. The results show that the impact of AI-powered personalization is significant to improve customer adoption and users that experience a higher level of personalization have a higher level of usage and stronger will to continue using the digital payment services. Similarly, in AI-based marketing innovation there is a high variation in the level of adoption with innovative AI-enabled marketing strategies being implemented in the promotional process equating to higher user adoption. Together, these results provide support to alternative hypotheses (H11 and H12), and suggest that AI has the potential to promote the use of digital payments at a faster rate.

The conclusions are close to the findings of industry observers, which identified personalization and marketing that takes an AI approach to be important competitive levers in fintech. Rather than being deployed solely to drive efficiency in the backroom, AI technologies are now increasingly being hired as front-line mechanisms that are intended to create a better customer experience and engagement. At a macro level, the findings suggest that in order for India to continue its digital payment momentum, it will not only be dependent on infrastructure expansion, but also on the ability of firms to offer user-centric, personalized and innovative services.

In sum, the integration of AI in the digital payment systems is not a matter of choice, but a strategic need. This research proves that the AI-Powered personalization and marketing innovation is an important catalyst for customer adoption in the cashless transformation in India. As digital payments continue to grow, fintech companies, banks, and policy makers need to use a combination of technological development and user-oriented design and engagement approaches to ensure inclusive, secure, and long-term growth.

## 7.2 Contributions

Despite these limitations, the study helps in providing a strong empirical basis to understand the role of AI in the adoption of digital payments.

## 7.3 Future Research Directions

Future researches can go more in a meaningful way from the present study. Longitudinal designs which track users before and after introduction of certain AI features would allow for more powerful causal inference. The use of objective usage data which is obtained from digital payment platforms could be used to complement self-reported measures and increase accuracy. Demographic segmentation like age, income level, urban-rural may tell us whether there would be different benefits from AI driven personalization for different user categories.

Qualitative methods such as interviews and focus groups may provide more information on user's perception of AI driven features and understand which type of personalization and marketing innovation is appreciated most (Verma & Kumaran, 2021). Emerging AI technologies such as generative AI applications such as voice-enabled payments and AI-powered financial assistants are promising opportunities when it comes to investigating in the future. Comparative cross-country studies may provide further information on the cultural and regulatory factors influencing the dynamics of AI-driven adoption.

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**AI-Enhanced Entrepreneurial Competence and SMEs Performance in Nigeria**

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**Abstract**

Despite increasing AI adoption, Nigerian SMEs lack empirically validated evidence on how AI-enhanced entrepreneurial competence drives performance, limiting strategic capability development and sustained competitive advantage in dynamic markets. This study examined the influence of AI-enhanced entrepreneurial competence on the performance of small and medium-sized enterprises (SMEs) in Nigeria, focusing on registered SMEs in Abuja, Federal Capital Territory. Grounded in Dynamic Capabilities Theory, the study posits that firms achieve superior performance by developing the capacity to sense opportunities, seize them through strategic decision-making, and reconfigure resources in response to technological and environmental changes. In this context, AI-enhanced entrepreneurial competence represents a strategic capability that enables SMEs to integrate artificial intelligence tools into opportunity recognition, innovation, and operational optimization processes. A quantitative approach was adopted using survey and cross-sectional research designs. The population comprised 17,321 registered SMEs, from which a sample size of 390 was determined using the Taro Yamane formula and increased to 430 to account for potential non-responses. A total of 366 valid responses from SME owner-managers were analysed. Data were collected through structured questionnaires administered both physically and online across the six Area Councils of the FCT. Preliminary diagnostic tests, including outlier assessment, normality, multicollinearity, non-response bias, and common method bias tests, confirmed data suitability. The findings revealed that AI-enhanced entrepreneurial competence (Knowledge and Skills) positively and significantly influences SMEs' performance. The study extends Dynamic Capabilities Theory within the digital entrepreneurship domain and provides practical implications for strengthening SME competitiveness in Nigeria's evolving technological landscape. Keywords:

Artificial intelligence, Entrepreneurial competence, Small and Medium Scale Enterprises, SMEs performance, Dynamic Capabilities Theory

**Keywords:** Artificial intelligence, Entrepreneurial competence, AI-Knowledge, AI-Skills, SMEs performance, Dynamic Capabilities Theory

## INTRODUCTION

Artificial intelligence (AI) is redefining the architecture of competitive advantage in contemporary markets, particularly for small and medium-scale enterprises (SMEs) operating in emerging economies. Globally, AI adoption in business is accelerating, with an estimated 78% of firms reporting active use of AI technologies and over 71% exploring integration into core operations (McKinsey & Company, 2025). AI-driven systems enhance decision quality, predictive analytics, customer relationship management, and operational efficiency, thereby strengthening entrepreneurial competence in dynamic environments. Entrepreneurial competence comprising opportunity recognition, strategic decision-making, innovation capability, digital literacy, and risk management has become increasingly technology-embedded. In Nigeria, SMEs constitute about 96% of businesses, contribute approximately 48% to national GDP, and account for nearly 84% of employment (Moniepoint FB, 2026). Despite their economic significance, Nigerian SMEs face structural constraints including limited access to finance, weak technological infrastructure, and low digital capability. Empirical evidence showed that over 70% of Nigerian SMEs have yet to adopt advanced digital tools beyond basic accounting software (Ajayi, 2025). The integration of AI into entrepreneurial competence offers a strategic pathway for overcoming productivity stagnation and enhancing scalability. However, AI-enhanced competence requires more than technological acquisition; it demands cognitive adaptability, data-driven decision orientation, and absorptive capacity (Nguyen et al., 2026). In highly competitive markets characterized by volatility and uncertainty, AI-enabled entrepreneurial competence may determine whether SMEs achieve sustainable performance growth or remain vulnerable to disruption.

Despite increasing discourse on digital transformation, the performance trajectory of Nigerian SMEs remains inconsistent and fragile with over 95% of SMEs in Nigeria fail within the first five years of operation due to managerial inefficiencies, inadequate market intelligence, and limited innovation capability (Mohac Africa, 2026). In addition, between 2023-2025, roughly 7.2 million SMEs closed, erasing 30% of the country's registered businesses (Plu Team, 2025). Entrepreneurial competence has traditionally been conceptualized in terms of skills,

experience, and behavioural attributes; however, the rapid diffusion of AI technologies necessitates a reconceptualization toward AI-enhanced entrepreneurial competence (Tang, 2026). This construct integrates machine learning-assisted forecasting, automated customer analytics, intelligent inventory management, and algorithmic financial planning into the entrepreneurial decision-making process. While AI tools are increasingly available through cloud-based platforms, adoption among Nigerian SMEs remains below 30%, largely due to cost perceptions, skill gaps, and infrastructural deficiencies (Omonzejele & Okogun, 2025). Consequently, many SMEs continue to rely on intuition-driven strategies rather than data-driven models, resulting in suboptimal resource allocation and weak competitive positioning. The absence of structured AI capability development further exacerbates digital inequality between large firms and SMEs (Arroyabe et al., 2024). Although prior studies have examined entrepreneurial competence and firm performance e.g., Rehman et al., 2023; Kamuri, 2023; Mokbel Al Koliby et al., 2024 & Labo et al., 2024, limited empirical attention has been devoted to the specific mechanisms through which AI augmentation influences SMEs' performance within the Nigerian context.

Extant literature provides growing evidence that digital capability positively influences firm performance e.g., Joensuu-Salo & Matalamäki, 2023; Atobishi et al., 2024; Chukwudi, 2024, yet the empirical linkage between AI-enhanced entrepreneurial competence and SMEs performance remains under-theorized in developing economies. Studies in advanced markets report productivity gains of 6%-20% among firms integrating AI into core processes (Gao & Feng, 2023; Ajuzieogu, 2013), while data-driven firms are 23 times more likely to acquire customers and 19 times more likely to be profitable (McKinsey & Company, 2014). However, contextual differences in infrastructure, institutional support, and human capital may moderate these outcomes in Nigeria. Evidence indicates that internet penetration in Nigeria stands at approximately 51%, with broadband access unevenly distributed across regions (The Guardian, 2026). Such disparities affect SMEs' ability to leverage AI platforms effectively. Moreover, significant digital skill gaps remain, as a large proportion of the Nigerian workforce demonstrates only basic digital competencies, thereby contributing to a pronounced digital skills deficit (Okwuchukwu, 2025). These structural constraints underscore the need to empirically examine how AI-enhanced entrepreneurial competence translates into SMEs performance. Without systematic investigation, policy prescriptions promoting AI adoption risk remaining aspirational rather than evidence-based. Therefore, a context-specific analysis is required to clarify the magnitude, direction, and significance of AI-enhanced entrepreneurial competence on SMEs performance in Nigeria's evolving digital economy.

In Nigeria, government initiatives such as the National Digital Economy Policy and Strategy (2020–2030) aim to increase digital contribution to GDP and promote technology-driven entrepreneurship. Nevertheless, implementation gaps and limited SME readiness constrain the realization of these objectives. Regional disparities in electricity supply, broadband infrastructure, and technical training further complicate AI diffusion across SMEs. While fintech adoption has expanded rapidly with Nigeria hosting over 200 fintech startups and attracting more than \$1 billion in venture capital between 2021 and 2023 (Healthcap Africa, 2023) traditional SMEs in manufacturing, retail, and agribusiness lag in AI utilization. The performance implications of this technological divide are substantial, as digitally advanced SMEs demonstrate higher customer retention rates, faster product development cycles, and improved cost management. The present study therefore aims to examine the influence of AI-enhanced entrepreneurial competence on SMEs performance in Nigeria by operationalizing competence dimensions such as AI-driven knowledge and skills. Specifically, the study seeks to determine whether AI-enhanced entrepreneurial knowledge and skills significantly improve SMEs performance and to provide empirical insights that inform managerial strategy and public policy. By doing so, it contributes to the emerging discourse on digital entrepreneurship within Sub-Saharan Africa's largest economy.

## **REVIEW OF RELATED LITERATURE AND THEORETICAL FRAMEWORK**

### **Concept of Performance**

Performance has been conceptualized in several scholarly traditions as an indicator of overall organizational effectiveness and goal attainment. El Fallahi et al. (2023), viewed performance as the extent to which an organization achieves its financial and strategic objectives, emphasizing both economic outcomes and broader operational success. Ahmad et al. (2023), conceptualized performance as a multidimensional construct reflecting growth, profitability, and efficiency indicators that collectively demonstrate venture progress and sustainability. Kakeesh et al. (2005) described it as the realized outcomes of entrepreneurial activities measured through sales growth, profitability, and overall business expansion relative to competitors. Trivedi et al. (2009) posited that performance as encompassing financial results, market outcomes, and shareholder value, representing the aggregate effectiveness of managerial actions and resource deployment. Consequently, performance in scholarly discourse reflects the overall achievement of enterprise objectives through effective utilization of resources, strategic positioning, and operational execution within competitive environments.

### **Concept of AI-Enhanced Entrepreneurial Competence**

AI-enhanced entrepreneurial competence in this study refers to a technology-augmented capability construct grounded in two core dimensions: AI-knowledge and AI-skills. It is conceptualized as the entrepreneur's cognitive understanding of artificial intelligence principles, tools, and strategic applications (AI-knowledge), combined with the practical ability to deploy AI systems in venture operations (AI-skills) to improve organizational outcomes. AI-enhanced entrepreneurial competence is defined as the entrepreneur's capacity to sense, seize, and reconfigure opportunities using AI-driven analytics and intelligent automation, where AI-knowledge supports opportunity recognition and AI-skills facilitate execution (Chotia et al., 2025). It represents a digital entrepreneurial capability integrating awareness of AI technologies such as machine learning and predictive analytics with the technical proficiency to apply these tools in decision-making and value creation processes (Yamani et al., 2025). It can be viewed as an extension of traditional entrepreneurial competence, where AI-knowledge strengthens strategic insight while AI-skills operationalize data-driven innovation and process optimization (Park & Kim, 2025). Finally, within this study, AI-enhanced entrepreneurial competence is defined as the synergistic combination of AI-knowledge (conceptual, analytical, and strategic understanding of AI) and AI-skills (practical, technical, and application-oriented capabilities) that collectively enable entrepreneurs to leverage intelligent technologies.

### **AI-Enhanced Entrepreneurial Knowledge and SMEs Performance**

Recent empirical evidence consistently demonstrates that AI-enhanced entrepreneurial knowledge and knowledge management capabilities significantly improve organizational performance across diverse contexts. Shaban et al. (2025), using a quantitative design grounded in the Resource-Based View, found that AI capability and knowledge management systems exert direct positive effects on organizational performance within SMEs. Similarly, Cui (2025), drawing on the Resource-Based Theory and Knowledge-Based View, reported that AI-driven knowledge sharing, organizational learning, and knowledge management dynamic capabilities each significantly enhanced performance outcomes in Chinese technology firms. In the Iranian public sector, Zahedi (2025), revealed that AI applications strengthened knowledge management processes, particularly knowledge creation, transfer, retention, and application, and that the integration of artificial intelligence with knowledge management positively influenced human resource performance. Expanding the scope, Dash et al. (2025), concluded that integrating AI technologies with knowledge management structures significantly improves business process efficiency and strengthens competitive advantage across organizations. Furthermore, Bruhin et al. (2025), found that generative AI tools enhanced knowledge transfer,

team collaboration, and productivity within software development teams. Collectively, these studies converge in affirming that AI-enabled knowledge capabilities function as strategic assets that enhance organizational effectiveness and overall performance across sectors and institutional contexts.

**H01:** AI-Enhanced Entrepreneurial knowledge does not significantly predict SMEs performance in Nigeria

### **AI-Enhanced Entrepreneurial Skills and SMEs Performance**

Empirical studies consistently affirm that AI-enhanced entrepreneurial skills significantly improve performance outcomes across educational and SME contexts. Gong, Wang, and Dong (2025) demonstrated that AI integration within entrepreneurship education strengthens students' dynamic capabilities specifically their abilities to sense, seize, and reconfigure opportunities which subsequently enhances AI-enabled performance. Their findings highlight that technology-driven, organizational, environmental, and human factors collectively develop practical AI-oriented skills that translate into superior entrepreneurial outcomes. Similarly, Mohd Noor and Zainuddin (2025) found that AI marketing adoption among women entrepreneurs significantly improves digital competencies and overall business performance, indicating that the ability to apply AI tools in marketing analytics, customer targeting, and digital engagement enhances enterprise sustainability. In the SME sector, Soomro et al. (2025) reported that AI capabilities foster creativity and green innovation, which in turn drive long-term performance, emphasizing that practical AI infrastructure integration and proactive entrepreneurial orientation are critical performance enablers. Furthermore, Njeri, Wekesa, and Hassan (2025) established that AI-driven marketing, operations automation, customer engagement systems, and AI-based decision support positively influence SME performance, with digital skills strengthening this relationship. Collectively, these studies converge on the conclusion that AI-enhanced entrepreneurial skills reflected in the practical application of AI technologies for innovation, marketing, operations, and strategic decision-making serve as a significant driver of improved organizational and SME performance outcomes across diverse economic contexts.

**H02:** AI-Enhanced Entrepreneurial Skills does not significantly predict SMEs performance in Nigeria

### **Dynamic Capabilities Theory**

Dynamic Capabilities Theory (DCT) provides a robust theoretical foundation for explaining how firms achieve sustained performance in volatile and technology-driven environments. The

theory was advanced by Teece, Pisano, and Shuen (1997). Teece et al. (1997) argued that competitive advantage does not stem merely from resource possession, as suggested by the Resource-Based View, but from a firm's ability to integrate, build, and reconfigure internal and external competences in response to rapidly changing environments. Central to DCT are the microfoundations of sensing, seizing, and reconfiguring (Kowalski et al., 2025). Sensing refers to identifying technological and market opportunities; seizing involves mobilizing resources to capture value from those opportunities; and reconfiguring denotes transforming organizational structures and capabilities to maintain alignment with environmental shifts (Engelmann, 2024). The theory emphasizes managerial cognition, learning processes, and strategic orchestration as drivers of adaptive capacity. In digital economies characterized by technological discontinuities such as artificial intelligence (AI), dynamic capabilities become critical for firms seeking resilience and performance sustainability.

This study is underpinned by Dynamic Capabilities Theory because AI-enhanced entrepreneurial competence reflects the entrepreneur's capacity to sense digital opportunities through AI-knowledge and to seize and reconfigure resources through AI-skills. AI-knowledge enables SME owners to recognize emerging data-driven market patterns, technological trends, and innovation possibilities, aligning with the sensing dimension. AI-skills operationalize the seizing and reconfiguring processes by facilitating intelligent decision-making, automation, and resource optimization that improve overall SME performance. In the Nigerian SME context, where environmental uncertainty, infrastructural instability, and competitive pressures are prevalent, dynamic capabilities explain why mere access to AI tools is insufficient without the competence to strategically deploy and continuously adapt them. Thus, AI-enhanced entrepreneurial competence represents a dynamic capability that enables SMEs to transform technological inputs into sustained general performance outcomes, consistent with the propositions of Teece et al. (1997)

## **METHODOLOGY**

This study adopted a quantitative research approach employing survey and cross-sectional research designs to examine the influence of AI-enhanced entrepreneurial competence on SMEs' performance in Nigeria. The target population comprised 17,321 registered small and medium-sized enterprises (SMEs) operating within Abuja, Federal Capital Territory (FCT). Using the Taro Yamane formula, a sample size of 390 was determined and subsequently increased to 430 to accommodate potential non-response bias. Data were collected from SME owner-managers through structured questionnaires administered both physically and online

across the six Area Councils of the FCT. A total of 366 valid responses were retrieved and used for analysis. Prior to hypothesis testing, several preliminary diagnostic procedures were conducted to ensure data integrity and robustness. These included outlier assessment, normality testing, multicollinearity diagnostics, non-response bias evaluation, and common method bias testing. The results of these tests confirmed the suitability of the dataset for empirical analysis. The study's methodological design enabled systematic examination of the proposed relationships within a real-world SME context.

### **Measures**

Validated scales from previous studies were adapted and used in the study on 5-point Likert scale of 1 Strongly Disagree to 5 Strongly Agree. SMEs performance was measured using 8-item firm performance scale of Spillan and Parnell (2006). Sample of item is "Profit goals have been achieved" with reported Cronbach's alpha of 0.764. AI-Enhanced entrepreneurial knowledge was measured using 4-item Xia et al. (2025) Ai-knowledge scale. Sample of the adapted item is "I understand how AI technologies can support opportunity recognition" with reported Cronbach's alpha of 0.899. AI-entrepreneurial skill was measured using 9-item entrepreneurial skills of Amaewhule and Ogor (2020) with reported Cronbach's alpha of 0.723. Sample of adapted item is "I have the skill to apply AI-based accounting software to calculate and analyse accounting records".

### **DATA ANALYSIS**

Partial Least Squares Structural Equation Modeling (PLS-SEM), implemented through Smart-PLS, was utilized for data analysis. The assessment covered indicator outer loadings, internal consistency reliability, and both convergent and discriminant validity within the measurement model. In addition, the structural model was evaluated by examining path relationships, effect sizes ( $f^2$ ), predictive relevance ( $Q^2$ ), coefficient of determination ( $R^2$ ), and overall model fit to determine the strength and explanatory power of the hypothesized relationships.

#### **Assessment of Measurement Model**

The measurement model assessment commenced with the evaluation of indicator outer loadings. According to Hair et al. (2022), standardized loadings of 0.70 and above are considered ideal for indicator retention. Nevertheless, in social science research where lower loadings may occur, indicators with loadings between 0.40 and 0.70 may be retained, provided their inclusion does not adversely affect composite reliability or the average variance extracted (AVE). In contrast, Hulland (1999), suggested a minimum acceptable loading of 0.50. Guided by this more conservative threshold, the present study eliminated indicators with loadings

below 0.50. Consequently, only item AI-EES1, AI-EES4 and AI-EES7 was removed due to a loading less than 0.50 (see Figure 1 and Table 1).

Subsequently, internal consistency reliability was examined using Composite Reliability (CR) and Cronbach’s alpha coefficients. . Hair et al. (2017), recommended a benchmark value of 0.70 or higher to establish adequate construct reliability and instrument consistency. As presented in Table 1, all CR and Cronbach’s alpha values exceeded the 0.70 threshold, confirming the reliability of the constructs.

Furthermore, convergent validity was assessed through the Average Variance Extracted (AVE). Fornell and Larcker (1981), asserted that an AVE value of at least 0.50 is required to demonstrate sufficient convergent validity. The AVE values reported in Table 1 all surpassed 0.50, thereby confirming that convergent validity was satisfactorily established.

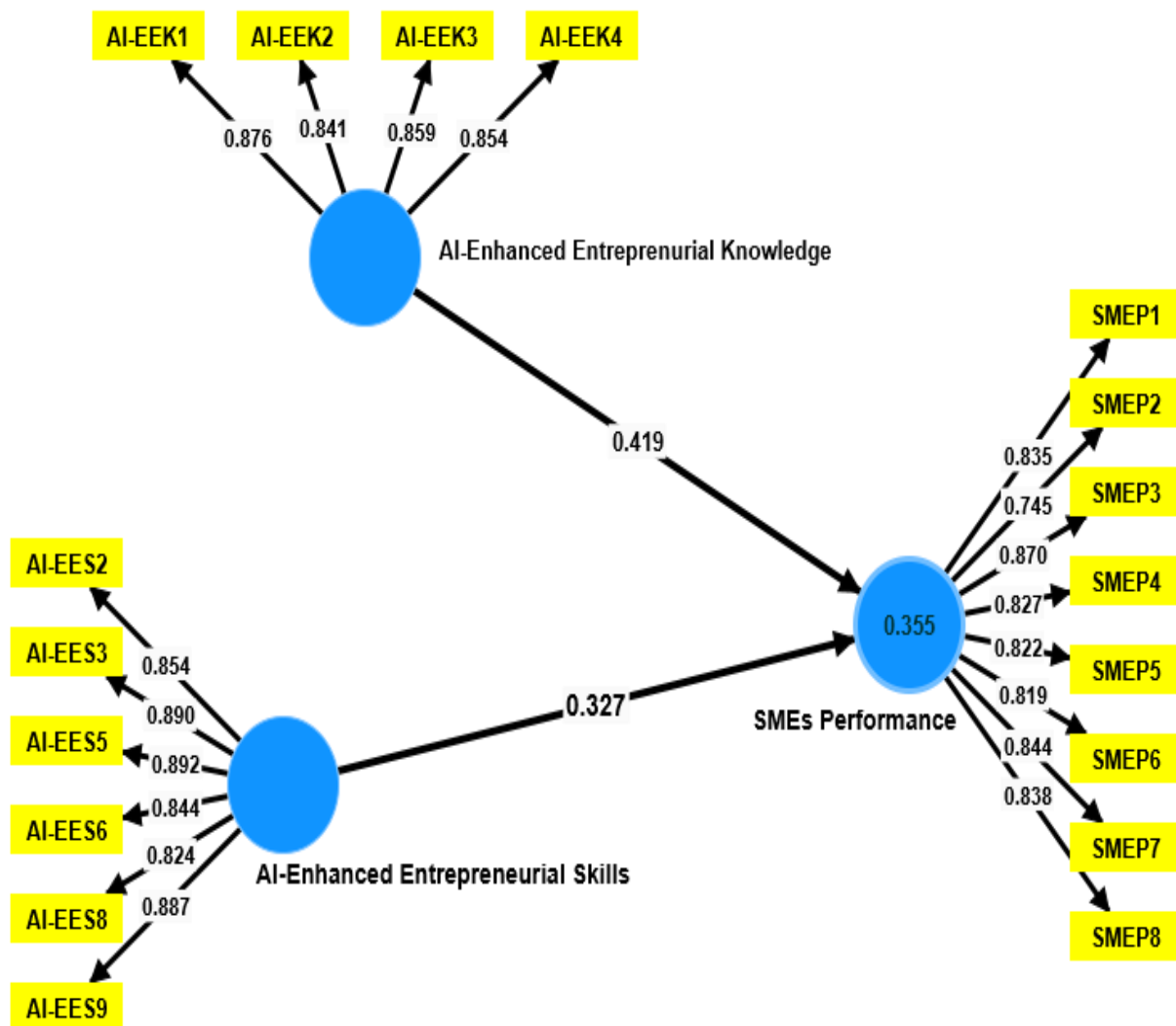


Figure 1: Measurement Model

**Table 1: Outer loadings, Reliability and Convergent Validity**

Constructs	Indicator	Outer Loadings	Cronbach's alpha	Composite reliability	Average variance extracted (AVE)
AI-Enhanced Entrepreneurial Knowledge	AI-EEK 1	0.876	0.880	0.917	0.735
	AI-EEK 2	0.841			
	AI-EEK 3	0.859			
	AI-EEK 4	0.854			
AI-Enhanced Entrepreneurial Skills	AI-EES 2	0.854	0.933	0.947	0.749
	AI-EES 3	0.890			
	AI-EES 5	0.892			
	AI-EES 6	0.844			

	AI- EES	8	0.824		
	AI- EES	9	0.887		
SMEs Performance	SME P1	0.835	0.933	0.945	0.682
	SME P2	0.745			
	SME P3	0.870			
	SME P4	0.827			
	SME P5	0.822			
	SME P6	0.819			
	SME P7	0.844			
	SME P8	0.838			

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Source: Authors' systemization of Smart-PLS output, 2026

Discriminant validity was further assessed using the Heterotrait-Monotrait (HTMT) ratio of correlations. Given that the constructs in this study are conceptually distinct, the more stringent HTMT threshold of 0.85, as suggested by Kline (2011), was adopted rather than the 0.90 criterion proposed by Henseler et al. (2015), for conceptually similar constructs. The results presented in Table 2 indicate that all HTMT values fall below the 0.85 cutoff point. This outcome provides sufficient evidence that discriminant validity has been satisfactorily established among the constructs.

**Table 2: Discriminant validity using HTMT correlations**

Construct	AI-Enhanced Entrepreneurial Skills	AI-Enhanced Entrepreneurial Knowledge	SMEs Performance
AI-Enhanced Entrepreneurial Skills			
AI-Enhanced Entrepreneurial Knowledge	0.291		
SMEs Performance	0.466	0.556	

Source: Authors’ systemization of Smart-PLS output, 2026

The effect size ( $f^2$ ) was evaluated in accordance with the guidelines proposed by Cohen (1988). Within the context of PLS-SEM, effect size represents the magnitude of the contribution that an exogenous construct makes to the  $R^2$  value of an endogenous construct in the structural model (Hair et al., 2022). Thus,  $f^2$  provides a quantitative estimate of the substantive impact of each predictor variable on the corresponding outcome variable.

**Table 3: Assessment of Effect Size ( $f^2$ )**

Constructs	SMEs Performance	Degree
AI-Enhanced Entrepreneurial Skills	0.154	Medium
AI-Enhanced Entrepreneurial Knowledge	0.252	Medium

Source: Authors’ systemization of Smart-PLS output, 2026

Cohen (1988) proposed that  $f^2$  values of 0.02, 0.15, and 0.35 represent small, medium, and large effect sizes, respectively. As shown in Table 3, when SMEs Performance is specified as the endogenous (target) construct, AI-Enhanced Entrepreneurial Skills  $f^2 = 0.154$  demonstrates a medium effect size, as the value slightly exceeds the 0.15 threshold. This indicates that entrepreneurial skills enhanced through AI adoption make a meaningful and practically relevant contribution to explaining variations in SMEs performance. Additionally, AI-Enhanced Entrepreneurial Knowledge  $f^2 = 0.252$  also exhibits a medium effect size, but with a stronger magnitude compared to entrepreneurial skills. This suggests that AI-enhanced knowledge contributes more substantially to the explained variance in SMEs performance.

Comparatively, AI-Enhanced Entrepreneurial Knowledge exerts a greater substantive impact on SMEs performance than AI-Enhanced Entrepreneurial Skills. However, neither construct reaches the 0.35 benchmark required to be classified as having a large effect. Overall, the findings imply that both AI-driven skills and knowledge are important predictors of SMEs performance, with AI-enhanced knowledge playing a relatively more influential role in strengthening firm outcomes.

**Table: 4 Model Fit**

	Saturated model	Estimated model
SRMR	0.039	0.039
d_ ULS	0.261	0.261
d_ G	0.117	0.117
Chi-square	276.293	276.293
NFI	0.947	0.947

Source: Authors' systemization of Smart-PLS output, 2026

Table 4 presents the model fit indices for both the saturated and estimated models obtained from Smart-PLS. The values are identical across both models, indicating consistency between the measurement and structural specifications. The Standardized Root Mean Square Residual (SRMR) value is 0.039 for both models. Since SRMR values below 0.08 are generally considered indicative of good model fit as recommended by Hu and Bentler (1999), this result suggests that the model demonstrates an excellent fit to the data. The discrepancy measures, d\_ ULS (0.261) and d\_ G (0.117), are relatively low. In PLS-SEM, smaller values of these indices indicate better model fit when compared against bootstrap-based confidence intervals. The reported values therefore suggest acceptable model adequacy. The Chi-square value is 276.293 for both models. Although Chi-square is sensitive to sample size and is not the primary fit criterion in PLS-SEM, it is reported for completeness. Finally, the Normed Fit Index (NFI) is 0.947, which exceeds the commonly recommended threshold of 0.90 (Hair et al. 2022). This indicates a high level of model fit. Ultimately, the SRMR and NFI values, together with the low discrepancy indices, provide sufficient evidence that the model exhibits a good overall fit and is appropriate for interpreting the structural relationships.

#### **Assessment of Structural Model**

The structural Model was used to test the hypothesized relationship between ai-enhanced entrepreneurial knowledge and skills and SMEs performance. Bootstrapping 5000 was used.

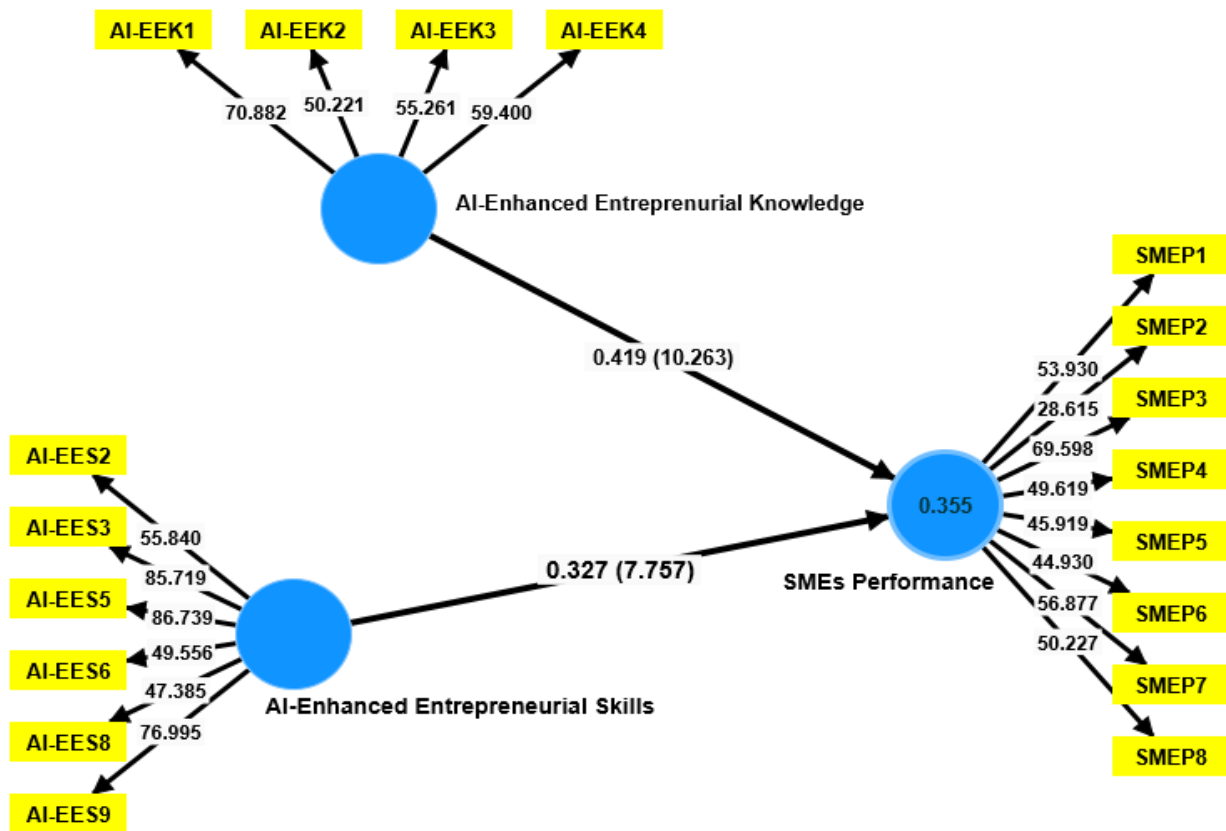


Figure 2: Structural Model

Table 5: Hypothesized Relationship

Hypot	Relationships	Beta	STD	T	P	Decision
theses		a	EV	statistics	values	
<i>H01</i>	AI-Enhanced Entrepreneurial Knowledge -> SMEs Performance	0.419	0.04	10.263	0.000	Rejected
<i>H02</i>	AI-Enhanced Entrepreneurial Skills -> SMEs Performance	0.327	0.04	7.757	0.000	Rejected
		<b>R<sup>2</sup>= 0.355</b>		<b>Q<sup>2</sup>=0.237</b>		

Source: Authors' systemization of Smart-PLS output, 2026

The results presented in Table 5 show that AI-Enhanced Entrepreneurial Knowledge has a positive and statistically significant direct effect on SMEs Performance ( $\beta = 0.419$ ,  $t = 10.263$ ,

$p = 0.000$ ). Since the  $p$ -value is below the 0.05 significance level and the  $t$ -statistic substantially exceeds the critical value of 1.96,  $H_0$  is thereby rejected as it is stated that AI-Enhanced Entrepreneurial knowledge does not significantly predict SMEs performance in Nigeria. The magnitude of the beta coefficient indicates a moderately strong positive relationship, suggesting that SMEs that effectively leverage AI-driven entrepreneurial knowledge are more likely to experience improved performance outcomes. Similarly, AI-Enhanced Entrepreneurial Skills demonstrate a positive and statistically significant influence on SMEs Performance ( $\beta = 0.327$ ,  $t = 7.757$ ,  $p = 0.000$ ). Given that the  $p$ -value is less than 0.05 and the  $t$ -statistic exceeds 1.96,  $H_2$  is also rejected based on the assertion that AI-Enhanced Entrepreneurial Skills does not significantly predict SMEs performance in Nigeria. This finding implies that SMEs that integrate AI-enhanced practical skills into their operations tend to achieve better productivity and competitive performance. Comparatively, AI-Enhanced Entrepreneurial Knowledge ( $\beta = 0.419$ ) exerts a stronger direct effect on SMEs Performance than AI-Enhanced Entrepreneurial Skills ( $\beta = 0.327$ ).

The  $R^2$  value of 0.355 indicates that the model explains 35.5% of the variance in SMEs Performance, representing a moderate level of explanatory power based on Hair, Hult, Ringle and Sarstedt (2014), classification of  $R^2$  values of 0.75, 0.50, and 0.25 as substantial, moderate and weak respectively in PLS-SEM). Furthermore, the Stone-Geisser's  $Q^2$  value of 0.237 is greater than zero, confirming predictive relevance. According to Cohen (1988)  $Q^2$  values classification of 0.02, 0.15, and 0.35 representing small, medium, and large predictive relevance, respectively., This  $Q^2$  value of 0.237 reflects a medium level of predictive relevance, indicating that the model possesses adequate forecasting capability.

## **Discussions**

The finding indicated that AI-enhanced entrepreneurial knowledge has a positive and significant influence on SMEs performance in Nigeria. This suggests that entrepreneurs who possess strong conceptual and strategic understanding of artificial intelligence such as knowledge of machine learning applications, predictive analytics, data governance, and intelligent automation are better positioned to interpret market signals and make evidence-based decisions. AI-knowledge strengthens opportunity recognition, improves forecasting accuracy, and reduces environmental uncertainty (Abdulmuhsin et al., 2025), thereby enhancing overall firm effectiveness. In the Nigerian SME environment, where market volatility, infrastructural instability, and intense competition are prevalent, data-informed cognition becomes a strategic asset. Entrepreneurs with higher AI-knowledge demonstrate

superior capacity to align technology investments with business strategy, optimize pricing models, anticipate customer demand, and identify emerging niches. The positive coefficient obtained in the study confirms that AI-knowledge enhances managerial quality and strategic responsiveness, which collectively translate into improved general SME performance. This aligns with the dynamic capabilities logic that sensing technological opportunities is foundational to sustained competitive advantage.

Similarly, the result showed that AI-enhanced entrepreneurial skills exert a positive and statistically significant effect on SMEs performance in Nigeria. While AI-knowledge reflects cognitive awareness, AI-skills represent the practical ability to deploy AI tools for operational and strategic execution (Bobitan et al., 2024). Entrepreneurs who can implement AI-driven inventory systems, automate financial tracking, utilize customer analytics dashboards, and integrate intelligent decision-support systems demonstrate improved efficiency and resource utilization (Dachepalli, 2025). In a context where many SMEs struggle with cost control and process inefficiencies, AI-skills enable automation of repetitive tasks, reduction of human error, and acceleration of response time to market changes. The empirical evidence suggests that beyond awareness, the technical and application-oriented proficiency to use AI tools directly enhances overall organizational outcomes. This reinforces the dynamic capabilities perspective that seizing and reconfiguring capabilities are essential for converting technological knowledge into tangible performance gains. Therefore, both AI-enhanced entrepreneurial knowledge and AI-enhanced entrepreneurial skills function as complementary drivers of improved general SMEs performance in Nigeria.

### **Implications**

The findings generate important practical implications for SME owners, managers, policymakers, and enterprise development institutions in Nigeria. Practically, the positive influence of AI-enhanced entrepreneurial knowledge and AI-enhanced entrepreneurial skills on general SMEs performance suggests that digital transformation strategies must go beyond mere technology acquisition to capability development. SME operators should invest in structured AI literacy programs, executive digital training, and hands-on technical workshops to strengthen both conceptual understanding and application proficiency. Business development service providers and government agencies such as SMEDAN should integrate AI-focused modules into entrepreneurship support schemes, incubation programs, and capacity-building initiatives. Financial institutions and development partners may also consider linking digital capability development to funding access, ensuring that SMEs are

technologically prepared to utilize advanced tools efficiently. At the organizational level, SMEs should adopt incremental AI implementation models beginning with affordable cloud-based analytics and automation tools to reduce operational inefficiencies and enhance overall firm effectiveness. The evidence indicates that AI competence is not a luxury but a strategic necessity for improving productivity, adaptability, and competitiveness in Nigeria's volatile business environment.

Theoretically, this study contributes to the advancement of Dynamic Capabilities Theory by empirically operationalizing AI-enhanced entrepreneurial competence as a firm-level dynamic capability within an emerging economy context. By decomposing the construct into AI-knowledge (sensing capability) and AI-skills (seizing and reconfiguring capability), the study extends the microfoundational understanding of how digital competencies translate into improved overall SMEs performance. It moves beyond traditional entrepreneurial competence models by integrating artificial intelligence as a core strategic resource, thereby enriching digital entrepreneurship literature. Furthermore, the study provides empirical validation from Nigeria, addressing the geographical imbalance in prior research predominantly concentrated in developed economies. By measuring SMEs performance as a unified aggregate construct rather than fragmented dimensions, the research also offers a parsimonious analytical framework that enhances comparability and theoretical clarity. Consequently, the study bridges digital capability scholarship and SME performance research, reinforcing the relevance of technology-embedded entrepreneurial competence in contemporary strategic management discourse.

## **CONCLUSION AND RECOMMENDATIONS**

The study concludes that AI-enhanced entrepreneurial competence significantly improves general SMEs performance in Nigeria. Specifically, both AI-enhanced entrepreneurial knowledge and AI-enhanced entrepreneurial skills were found to exert positive and statistically significant effects on overall firm effectiveness. This implies that SMEs that possess strong cognitive understanding of artificial intelligence concepts and the practical ability to deploy AI tools demonstrate superior organizational outcomes compared to those that rely solely on traditional managerial approaches. The findings reinforce the proposition of Dynamic Capabilities Theory that firms operating in volatile and technology-driven environments must develop the capacity to sense opportunities, seize them strategically, and reconfigure resources continuously. In the Nigerian context characterized by infrastructural instability, competitive pressure, and market uncertainty AI-enhanced competence functions as a strategic capability

that strengthens adaptability, decision quality, and operational efficiency. Therefore, AI is not merely a technological add-on but a performance-enabling mechanism when embedded within entrepreneurial competence structures. The study thus provides empirical evidence that integrating AI-knowledge and AI-skills into entrepreneurial practice is essential for improving the overall performance trajectory of SMEs in Nigeria's evolving digital economy.

Based on the findings, the following recommendations are proposed:

- i. SME owners and managers should prioritize continuous capacity development in AI-knowledge and AI-skills through structured digital training, certification programs, and strategic partnerships with technology providers to enhance overall business performance.
- ii. Government agencies and enterprise development institutions should design and implement targeted AI adoption support schemes, including subsidized training, digital infrastructure enhancement, and accessible AI toolkits, to accelerate competence-driven performance improvement among Nigerian SMEs.

### **Limitations and Suggestions for Further Study**

This study is subject to several limitations that should be acknowledged. First, the use of a survey and cross-sectional research design restricts the ability to establish causal inferences among the study variables. While the design was appropriate for examining relationships at a single point in time, it does not capture longitudinal dynamics or changes in AI-enhanced entrepreneurial competence and SMEs' performance over time. Future studies may adopt longitudinal or experimental designs to provide stronger causal explanations and track capability development across different growth stages of SMEs. Second, the geographical scope of the study was limited to registered SMEs operating within Abuja, Federal Capital Territory. This limits the generalizability of the findings to other regions of Nigeria with different infrastructural, economic, and institutional conditions. Additionally, the study focused exclusively on formally registered SMEs, thereby excluding informal sector enterprises, which constitute a substantial proportion of Nigeria's SME landscape. Including informal businesses in future research could provide a more comprehensive understanding of AI competence adoption across the broader entrepreneurial ecosystem.

Furthermore, the study examined only the direct relationship between AI-enhanced entrepreneurial competence and SMEs' performance, without incorporating potential mediating or moderating variables. Factors such as innovation capabilities, institutional

support, organizational resilience, digital infrastructure, and environmental dynamism may significantly influence or condition the strength of this relationship. The exclusion of these intervening mechanisms limits deeper theoretical explanation of how and under what conditions AI-enhanced competence translates into superior performance outcomes. Future research should extend the current model by integrating relevant mediators and moderators to provide a more nuanced and comprehensive analytical framework. Such extensions would enhance theoretical refinement and offer richer managerial insights into capability-driven performance improvement among SMEs.

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## **US Tariff Effects on the Indian Stock Market: An Analytical Study**

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### **Abstract**

This research paper examines the impact of United States tariff announcements on the Indian stock market, focusing on market-wide indices, sector-specific movements, and volatility responses. Using a hybrid approach that combines an event-study methodology with volatility analysis, the paper investigates short-run abnormal returns and conditional volatility changes following major US tariff events. The study evaluates indices such as the Nifty 50, Sensex, and trade-sensitive sectors including Metals, IT, Auto, and Pharma. Event windows surrounding tariff announcements are analyzed to compute Abnormal Returns (AR), Cumulative Abnormal Returns (CAR), and volatility shifts using GARCH-type models. Findings indicate that tariff shocks trigger meaningful short-term reactions in Indian stocks, driven by global supply chain expectations, export sensitivity, exchange-rate adjustments, and investor risk sentiment. Sectors with direct export exposure exhibit stronger negative responses compared to domestically oriented industries. The results provide insights into cross-border policy transmission, emerging-market vulnerabilities, and implications for investors, portfolio managers, and policymakers.

**Keywords:** US tariffs, Indian stock market, event study, volatility, GARCH, Nifty 50, global trade policy

### **1. Introduction**

The interconnected nature of global financial markets implies that policy measures in one major economy often influence economic and market conditions in others. Among such measures, **trade policy actions**—especially tariff impositions by the United States—have historically been associated with international financial volatility. India, being a heavily trade-linked emerging market economy, is sensitive to fluctuations in global conditions, including changes in tariff structures by the US government.

The 21st century has seen multiple waves of tariff interventions by the US, especially during periods of geopolitical tension, trade rebalancing, and protectionist policy phases. These tariff actions not only affect bilateral trade flows but also trigger broader market expectations around global demand, supply chains, cost structures, and competitiveness. For India, whose economic

sectors such as Information Technology, Pharmaceuticals, Automotive Components, and Metals maintain significant exposure to US markets, tariff shocks can translate into stock market fluctuations.

This study aims to evaluate how US tariff announcements affect the Indian stock market in the short run. Focusing on event windows surrounding tariff events, the research uses market-model-adjusted abnormal returns to assess immediate reactions and volatility models to capture conditional impacts. The results offer updated insights into globally transmitted policy shocks and their implications for emerging-market equities.

## 2. Literature Review

Previous empirical work establishes that international trade policy has a measurable effect on global financial markets. Studies on event-driven impacts of tariff announcements highlight that markets tend to react instantly to such shocks, especially when the affected industries are globally integrated. Emerging markets, due to their dependence on export channels and foreign capital flows, experience amplified volatility following US policy actions.

Research focusing on India indicates that sectors with substantial US exposure—such as IT services and pharmaceuticals—demonstrate sensitivity to US tariffs through stock price adjustments and changes in trading volumes. Metals and Auto sectors, which depend on imported components or global commodity cycles, experience indirect influences through cost structures and demand expectations.

GARCH-based volatility studies further show that tariff announcements elevate risk premiums in global equity markets. Increased uncertainty results in volatility spikes, capital flow adjustments, and heightened sensitivity to global news cycles. Against this backdrop, this paper extends existing research by combining event-study analysis with volatility modeling to quantify India-specific effects.

## 3. Research Objectives

This paper is structured around the following core objectives:

1. **To examine whether US tariff announcements produce abnormal returns in the Indian stock market.**
2. **To evaluate sector-wise sensitivity to tariff events**, focusing on export-oriented and globally linked industries.
3. **To assess volatility changes before and after tariff announcements** using GARCH-class models.

4. **To interpret the economic and financial transmission mechanisms** linking US tariff actions to Indian equity markets.
5. **To draw implications for investors, policymakers, and market analysts.**

## 4. Data and Methodology

### 4.1 Data Sources

The study uses secondary data from publicly available financial resources, including:

- Daily closing prices of **Nifty 50**, **Sensex**, and relevant sectoral indices (Metals, IT, Pharma, Auto).
- Daily data for **INR/USD exchange rate** and **India VIX** for volatility tracking.
- Event dates obtained from official US government notices and major news outlets reporting tariff decisions.

### 4.2 Event Selection

Four major tariff announcement events involving US trade policy decisions were selected, focusing on episodes that had global impact. Each event includes:

- The announcement date (Day 0)
- An estimation window (**-120 to -21 days**)
- Event windows: **0, ±1, ±3, ±5, ±10 days**

### 4.3 Methodology Framework

#### 4.3.1 Event Study Method

The event-study model calculates:

- **Expected Return (ER)** using market model regression
- **Abnormal Return (AR)** = Actual Return – Expected Return
- **Average Abnormal Return (AAR)** for index-level aggregation
- **Cumulative Abnormal Return (CAR)** across multi-day windows
- **Cumulative Average Abnormal Return (CAAR)** for market-wide effects

This allows measurement of immediate market reaction to tariff shocks.

#### 4.3.2 Volatility Modeling

To assess shifts in volatility, the study employs:

- **GARCH(1,1)** for baseline volatility dynamics
- **EGARCH** to capture asymmetric effects

These models help quantify risk premium changes and market uncertainty following tariff events.

## 5. Analysis and Findings

### 5.1 Market-Wide Response

Across the selected events, the Indian stock market displayed statistically significant abnormal returns within the (0, +3) and (0, +5) event windows. Negative CAR values were most noticeable in periods when tariffs targeted global supply chains, particularly during heightened trade tensions.

Nifty 50 and Sensex experienced mild negative shocks on Day 0, followed by stabilization within days. This pattern is consistent with global risk-off sentiment triggered by policy uncertainty.

### 5.2 Sector-Wise Impact

#### Metals Sector

The Metals sector exhibited the **highest sensitivity**, with CARs showing significant negative deviations across (0, +5) and (0, +10) windows. Since metals are directly linked to global commodity flows, tariffs indirectly influenced demand expectations and commodity prices.

#### IT Sector

The IT sector showed moderate negative reactions, primarily due to concerns around outsourcing, US client budgets, and global demand uncertainty. However, the impact was less severe compared to Metals.

#### Pharma Sector

Pharmaceutical stocks displayed resilience, with mixed results. Many Indian pharma firms have diversified markets and strong domestic demand, thereby reducing sensitivity.

#### Auto Sector

Auto stocks reacted negatively, largely due to concerns over input costs (imported components) and global supply chain disruptions.

### 5.3 Volatility Shifts (GARCH Analysis)

GARCH estimates showed:

- Increased volatility immediately after tariff announcements

- Persistence of conditional variance, indicating prolonged uncertainty
- Stronger asymmetric effects (captured via EGARCH), suggesting negative shocks magnified volatility

#### 5.4 Exchange Rate Influence

The INR depreciated slightly following tariff announcements, influencing stock returns through:

- Changes in export competitiveness
- Cost implications for import-dependent sectors

#### 5.5 Summary of Results

- Market reactions were **short-lived but significant**.
- Export-linked sectors experienced sharper negative effects.
- Volatility remained elevated for days after the events.
- Results confirm globally transmitted spillover effects.

### 6. Discussion

The findings highlight how US tariffs influence Indian equity markets through global linkages rather than direct bilateral trade volumes. Tariffs introduce uncertainty about global demand, corporate earnings, and cost structures. Export-oriented industries face heightened risks, prompting stronger reactions.

The volatility effects underscore the role of global macroeconomic shocks in shaping emerging-market risk perceptions. For investors, tariff news serves as a trigger for portfolio adjustments and hedging strategies. For policymakers, the results emphasize the need to strengthen economic resilience through diversified trade relationships.

### 7. Conclusion

This study demonstrates that US tariff announcements have measurable impacts on the Indian stock market through abnormal returns and volatility adjustments. The hybrid methodology combining event study and GARCH modeling offers comprehensive insight into short-run and dynamic market effects. The results reaffirm the importance of monitoring international policy developments for market forecasting and investment decision-making.

Future studies may use firm-level data for deeper insights, incorporate machine-learning methods for prediction, or extend analysis to other emerging markets.

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**Residential Solar Adoption in India and Germany: A Comparative Analysis of Consumer Behavioral Drivers and Policy Maturity**

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**Abstract**

The shift to sustainable energy has become a global priority, with many countries treating it almost like a race. However, the journey to adopting residential solar power looks very different in developed and emerging economies. This study aims to take a closer look at how consumers in India and Germany decide whether to install solar panels, highlighting insights that matter not just locally but also for the broader push toward global sustainability. In Germany, a mature market characterized by "grid parity", adoption is increasingly driven by emotional factors such as pride and happiness, as well as spillover effects from other green technologies, such as electric vehicles and heat pumps. Now, in the case of India, the market is in a growth stage. Here, the main drivers of a person adopting solar products are perceived government subsidies, awareness of functional benefits, and social influence. The findings highlight that, while policy incentives are crucial in both contexts, their effectiveness depends on the level of cultural and economic maturity. This paper provides some recommendations for policymakers to tailor communication strategies - focusing on emotional fulfilment in developed markets and on financial viability and energy security in emerging markets - to support meaningful progress toward sustainability goals.

**Keywords:** Comparative Analysis, Consumer Buying Behavior, Green Marketing, Solar Energy Adoption, Sustainability.

**1. Introduction**

**1.1 Background**

Since the Industrial Revolution, the world has been on a constant path of development towards greater advancement. Moreover, the primary fuels we use to achieve all of this are our fossil fuels. Using non-renewable energy would not be so bad, but the rate of our consumption is escalating. This creates two significant problems: first, the way we consume our fuels is

hazardous to future generations. Moreover, the second is all the carbon that gets released into the atmosphere from those fuels. This carbon is the main reason for global warming.

Decarbonizing the global energy system has become a central objective in climate mitigation strategies, as the energy sector accounts for the largest share of anthropogenic greenhouse gas emissions. Deep decarbonization pathways require a rapid transition from fossil-fuel-based electricity generation toward renewable energy systems, alongside structural transformation in consumption patterns and governance frameworks (Luderer et al., 2018).

Within this broader transition, residential solar photovoltaics (PV) represent a key decentralized potential technology with significant mitigation potential. Understanding this transition requires an integrated perspective that extends in both ecological reasoning and sociological importance along with its technological advancement and its implication on policy shift described as “Climate dialectic”; a dynamic and reciprocal process in which the climate and society influence the policy development (Goodman, 2016). Germany and India are in two distinct phases of this transition. Where Germany has reached at a stage of mature market where solar has reached grid parity, meaning it competes with conventional electricity in terms of localized cost of production without heavy subsidies by government institution (Karakaya et al., 2015). India, however, is navigating the challenges of a nascent market where potential is high, but adoption is hindered by structural and financial barriers (Kumar & Nayak, 2024).

## **1.2 Research Problem**

Despite falling technology costs, the intention-behavior gap remains a significant hurdle. In India, consumers express interest but hesitate due to perceived risks and complexity (Roy & Mohapatra, 2022). In Germany, the challenge has shifted from encouraging initial adoption to managing usage patterns and grid stability (Wittenberg & Matthies, 2016). There is a critical need to understand how policy maturity has strengthened the development of the regulatory environment which shifted the psychological drivers of the consumer in adoption of Solar PVs.

## **1.3 Research Objectives**

1. To identify and compare the core behavioral drivers of residential solar adoption in India and Germany.
2. To analyze how market maturity influences the shift from economic to psychological motivators.
3. To explore the role of "spillover effects" and personality traits in mature solar markets.

4. To provide policy recommendations tailored to the specific maturity level of each market.

## **1.4 Significance of the Study**

This research is significant for both scholars and practitioners. It challenges the "one-size-fits-all" marketing approach by demonstrating that as a market matures, the consumer profile evolves from a risk sensitive, performance-oriented consumer to an environmentally conscious consumer. Understanding this evolution and evaluating driving factors is key to designing effective subsidies and communication strategies.

## **2. Theoretical Framework**

This study utilizes a multi-theoretical approach to capture the complexity of consumer behavior across different cultures.

### **2.1 Diffusion of Innovation (DOI) Theory**

According to Rogers' DOI theory, the adoption of solar technology depends on perceived attributes: relative advantage, compatibility, complexity, observability, and trialability. Research in India suggests that relative advantage and observability are primary drivers (Kumar & Kaushik, 2022). In Germany, as the technology becomes standard, these attributes shift toward how solar fits into a wider ecosystem of green living (Wittenberg & Matthies, 2016).

### **2.2 Extended Theory of Planned Behavior (TPB)**

While TPB - focusing on attitude, subjective norms, and perceived behavioral control—is a cornerstone for understanding the Indian market, it must be extended with "Perceived Government Subsidy Policy" (PGSP) as a critical moderator (Kumar & Nayak, 2024). In the German context, the framework is often extended by the "Big Five" personality traits, where risk propensity and environmental concern directly influence the decision-making process (Poier, 2021).

## **3. Market Context and Policy Landscapes**

### **3.1 Germany: The Mature Market**

Germany's *Energiewende* has led to a mature market with over 1.5 million residential installations. The focus has shifted from mere adoption to "self-consumption" and load shifting (Wittenberg & Matthies, 2016). German consumers often exhibit "spillover effects," where the

adoption of a heat pump or an electric vehicle (EV) increases the likelihood of installing solar PV (Loder, 2025).

### **3.2 India: The Nascent Market**

India's journey is driven by ambitious national targets but faces "nascent stage" challenges. For Indian households, primary barriers include high initial investment and a lack of reliable information (Roy & Mohapatra, 2022). Perceived government support is a psychological necessity that validates the technology's reliability (Kumar & Nayak, 2024).

## **4. Research Methodology**

This study is based entirely on secondary data, utilizing information and statistics previously published by credible sources. No primary data collection, surveys, or fieldwork were conducted.

The approach involved a comprehensive review and synthesis of selected sources to extract key information. Consistency across multiple sources was taken as an indicator of reliability.

A key limitation of this methodology is its reliance on secondary data, which constrains the ability to independently verify findings or conduct new empirical research. Despite this, care was taken to select sources that are authoritative and widely recognized for their credibility.

## **5. Analysis and Discussion**

### **5.1 Behavioral Drivers: Economic vs. Emotional**

In the nascent Indian market, the driver is primarily functional consideration. Households prioritize experience and habit significantly shape decision making, which are heavily influenced by social influence communicated by the opinions of their community and peers (Sahu et al., 2021). There are also a perceived technological risk remains a material barrier. Concerns regarding system underperformance, maintenance uncertainty or backup failure contribute to trust deficits. (Roy & Mohapatra, 2022).

In contrast, the German market is entering a post-subsidy psychological phase. Adoption is driven by emotional factors among serial adopters" defined as households that are already invested in sustainable technologies such as Electric Vehicles (EVs), Heat Pumps etc. (Loder, 2025). Furthermore, personality traits like "Extraversion" have been found to play a direct role in adoption for couple-led households, suggesting that social interaction and social interaction and identity signaling remains a driver even in mature markets, though for different reasons than in India (Poier, 2021).

## 5.2 The Role of Policy Maturity

Policy maturity determines the "perceived complexity" of the technology. In India, relatively low policy maturity has been associated with higher perceived complexity among consumers. Here consumers struggle with the administrative and procedural hurdles of subsidies, approvals and grid connection which delays the installations and commissioning of adoption (Sahu et al., 2021). In such context these barriers can increase the perceived risks in the households and consumers, seeding more hesitation even when the economic incentive is favorable.

In Germany, high policy maturity has normalized residential solar adoption. The institutionalization of economic incentives, along with streamlined administrative processes and approval mechanisms, has embedded PV into the mainstream energy system. However, advanced policy maturity also introduces second-order behavioral dynamics, notably rebound effects, whereby households increase electricity consumption due to the perception that the environmental cost of self-generated energy is negligible (Wittenberg & Matthies, 2016).

## 6. Findings and Practical Implications

### 6.1 Findings

1. **Maturity Shift:** In India, adoption decisions remain strongly anchored in financial viability, subsidy accessibility, and risk reduction, reflecting a performance-oriented consumer profile. In contrast, Germany exhibits a transition toward psychologically driven adoption, where environmental identity, emotional satisfaction, and lifestyle alignment increasingly complement economic considerations.
2. **Moderating Factors:** Subsidies operate differently depending on regulatory maturity and institutional trust. In India, perceived government incentives act as a decisive moderator bridging intention and actual installation, making policy visibility crucial. In Germany, however, subsidies have become institutionalized and function as a background stabilizer rather than a primary behavioral trigger.
3. **Spillover Effect:** In mature markets such as Germany, residential solar adoption increasingly occurs within a broader ecosystem of low-carbon technologies, including electric vehicles and heat pumps. This bundling dynamic reflects positive behavioral spillover, where prior sustainable investments reinforce subsequent decisions. In India, by contrast, solar remains an independent high-involvement purchase with limited ecosystem reinforcement.

## 6.2 Practical Implications

- For India: Policymakers should prioritize reducing procedural complexity and strengthening subsidy accessibility to minimize perceived risk and administrative friction. Communication strategies should emphasize financial savings, energy security, and community validation to align with functionally driven consumers. Improving transparency and simplifying regulatory processes will be central to accelerating adoption in the emerging market context.
- For Germany: In mature markets, policy efforts should shift from financial activation toward behavioral optimization and identity reinforcement. Messaging that appeals to environmental pride and technological leadership can leverage intrinsic motivation, particularly among serial adopters. Simultaneously, integrating solar with broader home decarbonization packages and addressing rebound risks through smart consumption policies will sustain long-term system efficiency.

## 7. Barriers and Challenges

### 7.1 Technical and Structural Obstacles

In India, the primary barriers are structural: high upfront costs, lack of awareness, and perceived complexity (Sahu et al., 2021). Interpretive structural modelling (ISM) reveals that these factors are deeply interconnected, with "awareness" acting as a foundational variable.

### 7.2 Usage Patterns and Rebound Effects

In Germany, a unique challenge is the "rebound effect." While solar households are environmentally conscious, their actual electricity consumption is often not lower than non-solar households because they feel "licensed" to use more energy since it is self-generated (Wittenberg & Matthies, 2016).

## 8. Discussion and Policy Recommendations

The "climate dialectic" reveals that energy policy must evolve with market maturity.

- **For India:** Policies should focus on reducing the "perceived complexity" and strengthening the visibility of subsidies to build trust (Kumar & Nayak, 2024).
- **For Germany:** Strategies should leverage emotional drivers and spillover effects. Marketing solar as a "bundle" with EVs or heat pumps can tap into the "serial adopter" psychology (Loder, 2025).

## 9. Limitations and Future Research Directions

A limitation of this study is the cultural variance within the countries; India's regional diversity (e.g., Rajasthan vs. Kerala) may produce different behavioral results. Future research should utilize longitudinal data to track how Indian consumers' motivations change as they gain more "experience and habit" with the technology.

Also, using secondary data means this research relies on data collected by others, and those data may be outdated.

## 10. Conclusion

This brief comparative study of residential solar PV adoption in India and Germany illustrates two distinct phases in the lifecycle of a sustainable energy transition. India is currently building the foundational trust and institutional stability required for mass adoption, whereas Germany is refining the integration of solar into a broader, holistic green lifestyle.

The findings confirm that policy maturity not only accelerates diffusion but also reshapes consumer psychology and post-adoption behavior. Emerging markets require complexity reduction and financial assurance, while mature markets must focus on behavioral optimization and managing rebound effects. For global sustainability, the concept of the "climate dialectic" suggests that policy frameworks must remain as dynamic and adaptive as the consumers they aim to influence.

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**ROLE OF TRAINING AND MOTIVATION ON EMPLOYEE  
SATISFACTION: A REVIEW WITH REFERENCE TO HIGHER  
EDUCATION INSTITUTIONS OF SAURASHTRA REGION**

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**Abstract**

Higher education institutions (HEIs) are increasingly recognized as knowledge-intensive organizations in which the quality and commitment of human resources critically determine academic outcomes, stakeholder satisfaction, and long-term institutional sustainability. In India, reforms such as the National Education Policy (NEP) 2020 have foregrounded faculty development, continuous professional learning, and supportive work environments as key levers for improving institutional performance and global competitiveness (Ministry of Skill Development and Entrepreneurship, 2024; National Education Policy, 2020). Within this context, training and motivation are central determinants of employee satisfaction, particularly among faculty and administrative staff who experience growing demands related to teaching, research, accreditation, and student support. This paper presents a structured review of theoretical and empirical literature on the role of training and motivation in shaping employee satisfaction in HEIs, with a specific contextual focus on institutions in the Saurashtra region of Gujarat. The review synthesizes major motivational and job satisfaction theories and examines contemporary evidence on how training and development initiatives influence satisfaction, loyalty, and retention among academic staff (Mampuru & Bakae, 2024). Special attention is given to studies from Indian higher education and related service sectors to build a contextually grounded understanding. The paper identifies gaps relating to limited region-specific studies, insufficient integration of intrinsic and extrinsic motivational factors, and the scarcity of comprehensive models linking training, motivation, and satisfaction in semi-urban HEIs. Based on the synthesis, the paper outlines implications for institutional leaders and policymakers and suggests directions for future empirical work in the Saurashtra higher education context.

**Keywords:** Employee Motivation; Higher Education Institutions; Job Satisfaction; Training and Development

## **1. Introduction**

### **1.1 Background**

Higher education institutions operate in a dynamic environment characterized by massification of enrolments, technological disruption, global competition, and increasing accountability to regulators, students, and society. In India, quality assurance frameworks, accreditation requirements, and NEP 2020 reforms have intensified expectations regarding teaching effectiveness, research productivity, innovation, and community engagement (Ministry of Skill Development and Entrepreneurship, 2024; National Education Policy, 2020). These developments place human resources—particularly faculty and key administrative staff—at the centre of institutional performance, making their satisfaction and engagement critical strategic concerns for HEI management.

Employee satisfaction in HEIs has been linked to improved instructional quality, research output, student satisfaction, and institutional reputation, as well as reduced turnover and absenteeism (Gautam et al., 2020; Mampuru & Bakae, 2024). Studies on faculty satisfaction in Indian universities show that intrinsic factors such as meaningful work, sense of responsibility, and recognition, alongside extrinsic conditions such as job security, salary, and social status, significantly influence overall job satisfaction levels (Gautam et al., 2020). As HEIs in semi-urban and regional locations attempt to attract and retain qualified staff, the design of effective training and development systems and the cultivation of motivating work environments become increasingly important.

### **1.2 Research Problem**

Despite a growing body of literature on job satisfaction and human resource management in higher education, training and motivation are often examined in isolation rather than as interconnected drivers of employee satisfaction. Empirical studies confirm positive associations between participation in training and development programmes and employee satisfaction, loyalty, and retention among university academics (Mampuru & Bakae, 2024; Owusu & Agyapong, 2024). Similarly, motivation—both intrinsic and extrinsic—has been shown to significantly influence job satisfaction and performance in educational and service settings (Shi et al., 2023; Sudiarditha & Mayasari, 2022; Supardi, 2023). However, relatively

little research systematically integrates these constructs within a unified framework, particularly in the Indian HEI context and even less in specific regions such as Saurashtra. HEIs in Saurashtra, comprising a mix of public universities, self-financing colleges, and private universities, face distinct contextual challenges related to resource constraints, talent attraction, and career advancement opportunities, which may shape how training and motivation affect employee satisfaction.

### **1.3 Research Objectives**

In view of the above, this review paper pursues the following objectives:

1. To examine major theoretical perspectives that link training, motivation, and employee satisfaction in organisational contexts, with emphasis on higher education.
2. To review empirical studies on the impact of training and development on motivation and job satisfaction among employees, particularly academic staff in HEIs.
3. To identify gaps in existing literature, with specific attention to Indian and regional (Saurashtra-like) higher education settings.
4. To derive theoretical and practical implications for HEIs in the Saurashtra region regarding the design of training systems and motivational strategies aimed at enhancing employee satisfaction.

### **1.4 Significance of the Study**

Theoretically, the paper contributes by integrating classic and contemporary motivational theories (Herzberg, 1966; Maslow, 1954) with evidence on training and job satisfaction, and by highlighting the mediating and reciprocal relationships among these constructs in academic organizations (Shi et al., 2023; Sudiarditha & Mayasari, 2022). Practically, it offers HEI leaders in the Saurashtra region insights into how structured training and development, when aligned with employees' intrinsic and extrinsic needs, can enhance satisfaction, commitment, and retention (Mampuru & Bakae, 2024; Sattar et al., 2023). The review also aids policymakers and regulators in understanding the importance of context-sensitive faculty development and HRD policies for regional institutions.

## **2. Literature Review**

### **2.1 Theoretical Framework**

Job satisfaction has been defined as a positive emotional state resulting from the appraisal of one's job and job experiences, whereas motivation refers to the psychological processes that energize, direct, and sustain behaviour toward work-related goals (Herzberg, 1966; Maslow, 1954). Herzberg's two-factor theory distinguishes between hygiene factors (such as pay, working conditions, and policies) whose absence causes dissatisfaction, and motivators (such as achievement, recognition, and growth) that lead to positive satisfaction when present (Herzberg, 1966; Yuguero et al., 2020). Studies on faculty satisfaction in Indian universities often use Herzberg's framework to distinguish between intrinsic motivators (e.g., work itself, sense of responsibility, recognition) and extrinsic hygiene factors (e.g., salary, job security, social status) (Gautam et al., 2020). In this perspective, training and development opportunities function primarily as motivators by fostering growth, competence, and advancement prospects, while supportive HR policies form part of the hygiene context.

Maslow's hierarchy of needs suggests that individuals are motivated to satisfy a progression of needs from physiological and safety through belongingness and esteem to self-actualization (Maslow, 1954). In HEIs, basic needs are reflected in secure employment, equitable pay, and safe working conditions, while higher-level needs involve collegial relationships, professional respect, academic freedom, and opportunities for self-development through research and innovation. Training programmes, particularly faculty development initiatives, directly address esteem and self-actualization needs by enhancing professional competence and academic identity.

Social exchange theory and psychological contract perspectives further illuminate how employees reciprocate perceived organizational investments, such as training and supportive supervision, with increased commitment and satisfaction (Shi et al., 2023; Sudiarditha & Mayasari, 2022). When HEIs signal long-term investment in staff through continuous professional development, mentoring, and career pathing, employees are more likely to develop positive attitudes and a sense of obligation toward the institution. Conversely, failure to honour implicit expectations regarding development and recognition may erode satisfaction and trust.

Recent work on work-related basic needs satisfaction and self-determination theory emphasizes that autonomy, competence, and relatedness are fundamental psychological needs whose satisfaction leads to higher motivation, engagement, and job satisfaction (Shi et al., 2023; Sudiarditha & Mayasari, 2022). Training and development programmes that build

competence, encourage collaborative learning, and provide some autonomy in choosing learning pathways can therefore foster intrinsic motivation and satisfaction. Motivation itself has been identified as a mediator between organizational support (including training) and job satisfaction in various professional groups (Shi et al., 2023; Supardi, 2023).

Taken together, these frameworks suggest that training can influence employee satisfaction both directly—through enhancement of skills, career prospects, and self-efficacy—and indirectly, through its impact on intrinsic and extrinsic motivation, perceived organizational support, and fulfilment of psychological needs (Herzberg, 1966; Maslow, 1954; Shi et al., 2023; Sudiarditha & Mayasari, 2022).

## **2.2 Previous Studies on Training, Motivation, and Satisfaction**

A substantial body of empirical research supports the positive relationship between training and development programmes and job satisfaction among employees in different sectors. Recent studies report that training and development are significant predictors of job satisfaction, loyalty, and retention among academic staff at universities, using quantitative designs and structured questionnaires (Mampuru & Bakae, 2024). Regression analyses in these studies indicate that when employees perceive training to be relevant, well-designed, and adequately resourced, they exhibit higher satisfaction and stronger intentions to remain with the institution (Mampuru & Bakae, 2024; Sattar et al., 2023).

Review-based and empirical papers focused on general employee populations also highlight strong positive correlations between participation in training programmes and self-reported job satisfaction (Owusu & Agyapong, 2024; Sattar et al., 2023). One study found a very high correlation coefficient between engagement in training and job satisfaction, interpreting the result through human capital theory, which posits that investments in employees' skills generate returns in performance and satisfaction (Owusu & Agyapong, 2024). Another body of work emphasizes that training environments that promote continuous learning, feedback, and career development contribute to positive attitudes, organizational commitment, and reduced turnover intentions (Sattar et al., 2023; Supardi, 2023).

Motivation is consistently shown to be positively related to job satisfaction across occupational groups (Shi et al., 2023; Sudiarditha & Mayasari, 2022). Several studies indicate that both intrinsic motivators (such as achievement, interest in work, and professional growth) and extrinsic factors (such as job security, salary, and promotion) significantly explain variance in

satisfaction levels (Gautam et al., 2020; Yuguero et al., 2020). Research examining motivation as a mediator demonstrates that high motivation can increase job satisfaction by encouraging greater engagement, higher achievement, and a stronger sense of fulfillment, creating a reinforcing cycle where satisfaction further sustains motivation (Shi et al., 2023; Sudiarditha & Mayasari, 2022; Supardi, 2023).

In higher education contexts, studies on faculty job satisfaction in Indian and international universities reveal nuanced patterns regarding intrinsic and extrinsic factors. Research on Indian agricultural and traditional universities, grounded in Herzberg's theory, shows that faculty tend to be more satisfied with intrinsic factors such as sense of responsibility, work itself, ability utilisation, and recognition than with extrinsic conditions like salary and job security, although both sets of factors matter (Gautam et al., 2020). These findings suggest that academic staff often derive satisfaction from their professional roles and responsibilities, but may experience dissatisfaction when extrinsic conditions are perceived as inadequate or inequitable.

### **2.3 Training and Development in Higher Education**

Within HEIs, training and development encompass a diverse array of activities, including induction and orientation programmes, faculty development programmes (FDPs), workshops on innovative pedagogy and educational technology, leadership and administrative training, and research capacity-building initiatives (Mampuru & Bakae, 2024). Studies focusing on universities report that structured training interventions tailored to academic roles can enhance teaching effectiveness, assessment practices, and curriculum design, thereby indirectly contributing to student outcomes and institutional quality (Mampuru & Bakae, 2024).

Evidence suggests that when academic staff perceive training programmes as aligned with their professional needs and institutional priorities, they report higher satisfaction with both the training and their broader work environment (Mampuru & Bakae, 2024; Sattar et al., 2023). Conversely, ad hoc or mandatory programmes perceived as irrelevant or perfunctory may not produce meaningful improvements in motivation or satisfaction. Factors such as management support for training, availability of resources, and recognition of training participation in promotion or appraisal systems shape the overall impact of training on employee attitudes (Shi et al., 2023; Supardi, 2023).

Research on the mediating role of motivation indicates that management support and training opportunities can enhance employees' intrinsic and extrinsic motivation, which in turn influences job satisfaction and engagement (Shi et al., 2023; Sudiarditha & Mayasari, 2022; Supardi, 2023). Studies with health and education professionals show that when employees experience strong management support and opportunities for development, they report higher levels of work-related basic needs satisfaction, motivation, and job satisfaction (Shi et al., 2023; Sudiarditha & Mayasari, 2022). These findings are relevant for HEIs, where managerial support and participative leadership are crucial for leveraging training as a motivational tool.

## **2.4 Research Gap**

Despite the growing literature on training, motivation, and job satisfaction, several gaps remain. First, many studies focus either on training and satisfaction or on motivation and satisfaction, but relatively few integrate all three constructs into a coherent model, particularly in higher education settings (Mampuru & Bakae, 2024; Shi et al., 2023; Sudiarditha & Mayasari, 2022). Second, much of the empirical work is situated in corporate or health sectors, with fewer rigorous studies on HEIs, especially in non-metropolitan and regional contexts (Owusu & Agyapong, 2024; Shi et al., 2023). Third, within Indian higher education, existing studies on faculty satisfaction often emphasise broad intrinsic and extrinsic factors without systematically examining the specific role of structured training and development initiatives as determinants of satisfaction (Gautam et al., 2020).

Specific to the Saurashtra region, there is a near absence of published empirical research that focuses on the interaction of training, motivation, and employee satisfaction across universities and colleges. Available national-level studies tend to aggregate institutions from different states and contexts, making it difficult to derive region-specific insights for Saurashtra's mix of public and private HEIs. This gap underscores the need for contextually grounded research that explores how training systems, motivational climates, and satisfaction levels interact in Saurashtra's higher education ecosystem, taking into account local labour markets, institutional governance structures, and resource constraints.

## **3. Methodology**

This paper adopts a narrative review approach, drawing on peer-reviewed journal articles, conference papers, and relevant reports related to training, motivation, and job satisfaction in higher education and allied service sectors. Electronic databases and academic portals were searched using combinations of keywords such as "training and development", "employee

motivation", "job satisfaction", "higher education institutions", and "India", with preference given to studies published in the last decade. Specific attention was paid to research focusing on HEIs, faculty or academic staff, and Indian or comparable contexts in terms of development and institutional structures (Gautam et al., 2020; Mampuru & Bakae, 2024; Owusu & Agyapong, 2024; Sattar et al., 2023; Shi et al., 2023).

Both conceptual and empirical studies were included to capture theoretical perspectives and evidence-based findings. Quantitative survey-based research, qualitative case studies, and mixed-methods designs were considered to ensure a broad yet focused synthesis. While systematic review protocols were not fully implemented, efforts were made to ensure transparency in selection by prioritizing peer-reviewed sources that clearly articulated methodology and reported empirical findings of relevance to training, motivation, and satisfaction. Given the scarcity of region-specific research for Saurashtra, the review extrapolates from national and international literature to infer implications for HEIs in the region, thereby highlighting the need for future primary studies.

## **4. Results of the Review**

### **4.1 Training and Job Satisfaction**

Across reviewed studies, a consistent positive association emerges between training and development programmes and employee job satisfaction. Research in higher education demonstrates that training not only enhances academic staff members' skills and knowledge but also signals institutional support and investment in their careers, which contributes to higher satisfaction and loyalty (Mampuru & Bakae, 2024; Owusu & Agyapong, 2024; Sattar et al., 2023). For example, a study of university academics reported that training and development initiatives significantly predicted job satisfaction, loyalty, and retention, with regression models showing training as a strong positive predictor even after controlling for demographic variables (Mampuru & Bakae, 2024). Similar findings are reported in general employee populations, where training participation correlates strongly with satisfaction indicators, reinforcing the idea that staff who engage more actively in training are more satisfied with their jobs (Owusu & Agyapong, 2024; Sattar et al., 2023; Supardi, 2023).

### **4.2 Motivation–Satisfaction Relationship**

Evidence also confirms that motivation is a robust predictor of job satisfaction (Shi et al., 2023; Sudiarditha & Mayasari, 2022). Studies that differentiate intrinsic and extrinsic motivation

typically find that intrinsic motivators, such as meaningful work, sense of achievement, autonomy, and opportunities for growth, are strongly associated with satisfaction, particularly in professional and academic roles (Gautam et al., 2020; Yuguero et al., 2020). At the same time, extrinsic motivators like salary, job security, and promotion opportunities remain important, especially in contexts where baseline needs and job stability are not fully met (Gautam et al., 2020; Yuguero et al., 2020). Research indicates that higher levels of work motivation not only increase job satisfaction but also enhance engagement and performance, creating a mutually reinforcing cycle where satisfied employees exhibit higher motivation and vice versa (Shi et al., 2023; Sudiarditha & Mayasari, 2022; Supardi, 2023).

### **4.3 Training as a Driver of Motivation**

Several studies provide evidence that training influences motivation, which in turn affects job satisfaction. When employees perceive training as relevant, well-structured, and supportive of their career aspirations, they report enhanced intrinsic motivation and a stronger sense of competence (Owusu & Agyapong, 2024; Sattar et al., 2023; Supardi, 2023). Studies on the mediating role of motivation show that organizational support, including training, can enhance work-related basic needs satisfaction, which then leads to higher motivation and job satisfaction (Shi et al., 2023; Sudiarditha & Mayasari, 2022). In this view, training not only builds human capital but also operates as a motivational resource that fulfils psychological needs for competence and growth. Conversely, poorly designed or poorly supported training may have limited or even negative effects if employees view it as tokenistic or burdensome.

### **4.4 Insights from Indian Higher Education**

Indian studies on faculty satisfaction reinforce the importance of intrinsic and extrinsic factors but tend to pay limited attention to explicit training systems (Gautam et al., 2020). Research on faculty in agricultural and traditional universities found that respondents were generally more satisfied with intrinsic factors such as sense of responsibility, work itself, ability utilisation, and recognition compared to extrinsic conditions like salary and job security (Gautam et al., 2020). These findings suggest that academic roles are inherently meaningful, but dissatisfaction may arise from perceived inadequacies in extrinsic rewards and institutional support. While some studies refer to faculty development programmes and professional learning opportunities, systematic analysis of how these initiatives affect motivation and satisfaction remains relatively sparse.

For HEIs in regions like Saurashtra, these patterns imply that staff may be intrinsically committed to teaching and academic work but may also face constraints related to remuneration, infrastructure, workload, and career progression. In such settings, strategically designed training and development initiatives that are explicitly linked to recognition, promotion criteria, and supportive leadership may serve as important levers for enhancing both motivation and satisfaction.

## **5. Discussion**

### **5.1 Interpretation of Findings**

The reviewed literature collectively indicates that training, motivation, and job satisfaction are interlinked constructs that significantly shape employee attitudes and behaviour in higher education institutions. Training and development programmes emerge as key organizational practices that can directly improve job satisfaction by enhancing skills, clarifying roles, and signalling institutional investment in staff (Mampuru & Bakae, 2024; Owusu & Agyapong, 2024; Sattar et al., 2023). Motivation, comprising both intrinsic and extrinsic factors, is shown to be a strong determinant of satisfaction, with intrinsic motivators often playing a particularly prominent role in academic contexts (Gautam et al., 2020; Shi et al., 2023; Sudiarditha & Mayasari, 2022). Furthermore, evidence points to the mediating role of motivation in the relationship between organizational support (including training) and job satisfaction, suggesting that training influences satisfaction partly by enhancing motivational states (Shi et al., 2023; Sudiarditha & Mayasari, 2022; Supardi, 2023).

### **5.2 Comparison with Previous Studies**

The findings of this review are consistent with earlier work grounded in Herzberg's two-factor theory, which posits that growth-oriented factors such as advancement, recognition, and personal development serve as motivators that enhance satisfaction, whereas hygiene factors must be managed to prevent dissatisfaction (Herzberg, 1966; Yuguero et al., 2020; Gautam et al., 2020). Training in HEIs can be understood as both a motivator (by providing development and recognition) and, when institutionalized, as part of the broader hygiene environment that signals professional standards and support. The reviewed evidence also aligns with social exchange perspectives, which argue that perceived organizational investment in employees leads to reciprocation in the form of commitment and satisfaction (Shi et al., 2023; Sudiarditha & Mayasari, 2022).

At the same time, the review highlights limitations in the existing literature, particularly the limited number of studies that explicitly model the full pathway from training through motivation to job satisfaction in HEIs. While some studies in health and service sectors have examined motivation as a mediator between management support and satisfaction or engagement, there remains scope for similar integrative models in higher education contexts (Shi et al., 2023; Sudiarditha & Mayasari, 2022; Supardi, 2023).

### **5.3 Theoretical Implications**

Theoretically, the review suggests that future models of employee satisfaction in HEIs should incorporate training and development not merely as contextual variables but as central components of motivational processes. Integrating Herzberg's two-factor theory with self-determination and social exchange perspectives offers a more comprehensive understanding of how training interventions can fulfil psychological needs, build perceived organizational support, and enhance both intrinsic and extrinsic motivation (Herzberg, 1966; Maslow, 1954; Shi et al., 2023; Sudiarditha & Mayasari, 2022; Yuguero et al., 2020). Such integrative frameworks are particularly relevant for academic settings, where autonomy, competence, and relatedness are vital but must be balanced with institutional requirements and resource realities.

### **5.4 Practical Implications for HEIs in Saurashtra**

For HEIs in the Saurashtra region, several practical implications emerge:

- Institutions should design structured training and development portfolios that address the diverse needs of teaching and non-teaching staff, including pedagogy, digital tools, research methods, and leadership skills, and should clearly communicate the relevance of these programmes to staff careers (Mampuru & Bakae, 2024; Sattar et al., 2023).
- Management should link participation in accredited training and development programmes with performance appraisal, recognition, and promotion pathways to strengthen both extrinsic and intrinsic motivation (Supardi, 2023).
- Training initiatives need to be supported by a positive learning climate, adequate resources, and supportive leadership, ensuring that employees perceive training as a genuine investment rather than a compliance requirement (Shi et al., 2023; Supardi, 2023).
- Given the likely resource constraints of some institutions in Saurashtra, collaboration among HEIs, participation in government-sponsored faculty development schemes, and

the use of blended and online training modalities may help expand access while controlling costs (Ministry of Skill Development and Entrepreneurship, 2024; National Education Policy, 2020).

By adopting these strategies, HEIs in Saurashtra can enhance the motivational and satisfaction levels of their employees, which in turn can contribute to student outcomes, institutional reputation, and regional development.

## **6. Limitations**

This review has several limitations that should be acknowledged. First, it is based on a narrative rather than systematic review protocol, which may introduce selection bias, even though efforts were made to prioritize peer-reviewed and methodologically sound studies. Second, the review relies heavily on studies conducted outside the Saurashtra region and, in some cases, outside India, which may limit direct generalizability due to contextual differences in institutional structures, labour markets, and cultural expectations (Mampuru & Bakae, 2024; Owusu & Agyapong, 2024; Shi et al., 2023; Sudiarditha & Mayasari, 2022). Third, the review draws primarily on quantitative survey-based research, with relatively less representation of qualitative or mixed-methods studies that could provide deeper insights into employees' lived experiences of training and motivation in HEIs. Finally, given the evolving nature of higher education and policy reforms, some findings may need periodic updating to reflect new initiatives and changing organizational practices.

## **7. Conclusion**

### **7.1 Summary of Findings**

This paper reviewed theoretical and empirical literature on the role of training and motivation in employee satisfaction, with reference to higher education institutions and implications for the Saurashtra region. The review indicates that training and development programmes are positively associated with job satisfaction, loyalty, and retention among academic staff (Mampuru & Bakae, 2024), while motivation—both intrinsic and extrinsic—emerges as a key predictor of satisfaction (Gautam et al., 2020; Shi et al., 2023; Sudiarditha & Mayasari, 2022). Evidence suggests that motivation can mediate the relationship between organizational support, including training, and job satisfaction, underscoring the importance of viewing these constructs as interconnected rather than isolated (Shi et al., 2023; Sudiarditha & Mayasari, 2022; Supardi, 2023).

## 7.2 Contributions

Theoretically, the review integrates Herzberg's two-factor theory, Maslow's hierarchy of needs, social exchange perspectives, and self-determination principles to provide a more holistic understanding of how training and motivation jointly shape employee satisfaction in HEIs (Herzberg, 1966; Maslow, 1954; Shi et al., 2023; Sudiarditha & Mayasari, 2022; Yuguero et al., 2020). Practically, it highlights specific strategies that HEIs in the Saurashtra region can adopt to design training systems and motivational policies that address both intrinsic and extrinsic needs of employees. By emphasizing the significance of contextual factors and the scarcity of region-specific research, the paper also foregrounds the importance of localized HRD strategies for semi-urban higher education systems.

## 7.3 Future Research Directions

Future empirical studies in the Saurashtra region could employ cross-sectional and longitudinal survey designs to quantify the relationships among training participation, motivational scales, and job satisfaction for faculty and administrative staff across different types of institutions. Mixed-methods research combining quantitative measures with qualitative interviews or focus groups would provide richer insights into how employees perceive training relevance, motivational drivers, and institutional support. Comparative studies between Saurashtra and other regions or between public and private HEIs could further clarify how governance structures and resource levels moderate these relationships. Developing and testing integrative models in which training influences satisfaction through motivational and organizational support mechanisms would advance both theory and practice in higher education human resource management.

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**IMPACT OF INFLUENCER MARKETING ON CONSUMER BEHAVIOUR: A STUDY OF FASHION APPAREL PURCHASING AMONG YOUNGSTERS IN SAURASHTRA REGION**

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**Abstract**

This paper explores how fashion influencers affect apparel buying behaviour of youngsters in the Saurashtra region of Gujarat, India. Primary data were collected from 113 respondents aged 16–30 years through an online questionnaire. The study focuses on influencer characteristics (attractiveness, expertise, trustworthiness, content quality) and consumer responses (attitude toward the influencer and purchase intention). Overall, 68.1% of respondents reported being influenced by fashion influencers, either by purchasing or seriously considering a purchase. Instagram (73.5%) and YouTube (53.1%) emerged as the main platforms for following fashion influencers. Strong correlations were observed between influencer expertise and attitude ( $r = 0.881$ ), and between attitude and purchase intention ( $r = 0.879$ ). Female respondents showed higher purchase rates than males, and higher monthly fashion spending was associated with more influencer-driven purchases. The findings highlight the importance of influencer credibility and content quality for fashion brands targeting young consumers in regional Indian markets.

**Keywords:** Consumer behaviour, Fashion apparel, Influencer marketing, Purchase intention, Saurashtra region

**Introduction**

The digital revolution has fundamentally transformed the landscape of marketing communication, with social media platforms emerging as powerful channels for brand promotion and consumer engagement. Influencer marketing, defined as the practice of leveraging individuals with significant social media followings to endorse products and services, has become a dominant force in the fashion industry. Recent industry reports estimate

the global influencer marketing industry at about USD 32.55 billion in 2025, with the fashion segment expected to grow sharply over the next decade (Spherical Insights, 2025; Grand View Research, 2024).

Unlike traditional celebrity endorsements, influencer marketing operates on principles of perceived authenticity, relatability, and niche expertise. Fashion influencers leverage platforms such as Instagram, YouTube, and TikTok to showcase styling ideas, product reviews, and lifestyle content, thereby shaping consumer preferences and purchase decisions. Survey evidence suggests that a large majority of consumers make at least one influencer-inspired fashion purchase each year (Best Colorful Socks, 2025)

The Saurashtra region of Gujarat, India, represents an interesting context for studying influencer marketing dynamics. Characterized by a young, digitally-savvy population with increasing disposable income and fashion consciousness, the region has witnessed rapid adoption of social media platforms. However, limited empirical research has examined how influencer marketing specifically impacts fashion apparel purchasing behaviour among youngsters in this regional context. Understanding these dynamics is crucial for fashion brands seeking to penetrate tier-2 and tier-3 Indian markets through digital marketing strategies.

### **Theoretical Framework**

This study is grounded in the Source Credibility Model, which proposes that message effectiveness depends largely on the communicator's expertise and trustworthiness (Hovland & Weiss, 1951). According to this model, the effectiveness of persuasive communication depends significantly on the credibility of the source, which comprises two primary dimensions: trustworthiness (the perceived honesty and integrity of the source) and expertise (the perceived knowledge and competence of the source). In the context of influencer marketing, source credibility extends to include attractiveness (physical appeal and lifestyle aspirations) and content quality (creativity, informativeness, and production value).

The theoretical model posits that influencer characteristics influence consumer attitudes toward both the influencer and the endorsed brands, which subsequently affect purchase intentions and actual purchase behaviour. Recent research also shows that credibility, relatability and message consistency drive consumer trust and engagement in influencer settings (World Journal of Advanced Research and Reviews, 2024; Journal of Management and Social Research, 2025)

### **Research Objectives**

This study aims to:

1. Examine the demographic profile and social media usage patterns of young fashion consumers in the Saurashtra region
2. Assess the influence of fashion influencers on consumer purchase behaviour
3. Analyze the relationships between influencer characteristics (attractiveness, expertise, trustworthiness, content quality) and consumer responses (attitude, purchase intention)
4. Identify platform preferences and influencer-following patterns among target consumers
5. Provide actionable insights for fashion brands implementing influencer marketing strategies in regional Indian markets

## **Literature Review**

### **Influencer Marketing in the Fashion Industry**

Several studies describe fashion as one of the most active categories in influencer marketing, with brands shifting budgets from traditional media towards creator partnerships (Influencer.com, 2024; Statista, 2024).

Work on parasocial interaction indicates that one-sided emotional bonds with influencers can strengthen persuasion and purchase likelihood (Jin & Ryu, 2020; Sokolova & Kefi, 2020)

Studies on young female consumers show that they often regard Instagram influencers as credible sources in fashion decisions (Djafarova & Rushworth, 2017). Younger age groups also tend to place more trust in social media creators than older consumers (Lou & Yuan, 2019)

Research by Jin and Ryu (2020) demonstrated that influencer credibility significantly impacts consumer attitude toward endorsed fashion products, with trustworthiness and expertise serving as key credibility dimensions.

### **Regional Context: Influencer Marketing in India**

Industry overviews suggest that the Indian influencer market is expanding quickly, driven by rising internet access and e-commerce (Exchange4Media, 2024; Statista, 2024). Yet most academic work still focuses on metro cities, leaving smaller regional markets under-studied (World Journal of Advanced Research and Reviews, 2024)

## Research Methodology

### Research Design

This study employs a quantitative research design using a structured questionnaire to collect primary data from young fashion consumers in the Saurashtra region.

### Sample and Data Collection

This is a quantitative, descriptive–correlational study based on a structured questionnaire. Data were collected online using Google Forms in February 2026 from youngsters aged 16–30 years residing in the Saurashtra region and active on social media. Convenience sampling yielded 113 usable responses.

The sample included respondents from Junagadh (54.0%), Rajkot (19.5%), and other towns in Saurashtra (26.5%). The age distribution comprised 16-18 years (37.2%), 19-22 years (46.9%), 23-26 years (11.5%), and 27-30 years (4.4%). Gender distribution was nearly balanced with 50.4% female and 49.6% male respondents. The majority were undergraduate students (63.7%), followed by postgraduate students (18.6%) and working professionals (5.3%).

## Results

### Demographic Profile and Social Media Usage

Table 1 presents the demographic characteristics of respondents. The sample predominantly comprised young adults aged 19-22 years (46.9%), followed by those aged 16-18 years (37.2%). Gender distribution was balanced with 57 females (50.4%) and 56 males (49.6%). Junagadh was the primary location (54.0%), reflecting its status as a major educational and commercial hub in Saurashtra. Most respondents were undergraduate students (63.7%), indicating the sample captures early-stage fashion consumers forming brand preferences.

Table 1: Demographic Characteristics of Respondents (N = 113)

Demographic Variable	Frequency	Percentage
<i>Age Group</i>		
16–18 years	42	37.2%
19–22 years	53	46.9%

23–26 years	13	11.5%
27–30 years	5	4.4%
Gender		
Female	57	50.4%
Male	56	49.6%
City		
Junagadh	61	54.0%
Rajkot	22	19.5%
Other	30	26.5%
Education/Occupation		
Undergraduate Student	72	63.7%
Postgraduate Student	21	18.6%
Working Professional	6	5.3%
Other	14	12.4%

Social media engagement was exceptionally high, with 96.5% reporting active usage of at least one hour daily. This confirms the digital-native nature of the sample. Regarding exposure to fashion influencer content, 50.4% reported seeing promotions "Sometimes," 26.5% "Often," 12.4% "Very often," and 10.6% "Rarely." This distribution indicates widespread but variable exposure to influencer marketing content.

Platform preferences revealed Instagram as the dominant channel (73.5%), followed by YouTube (53.1%), with many respondents using multiple platforms. Facebook (15.0%), Snapchat (12.4%), and other platforms showed lower usage for fashion influencer content.

### **Purchase Behaviour Patterns**

37.2% of respondents reported having purchased fashion apparel due to influencer promotion, while an additional 31.0% had seriously considered such purchases. Combined, 68.1% of the

sample was influenced by fashion influencers to some degree, demonstrating substantial marketing impact.

Table 2: Purchase Behaviour Influenced by Fashion Influencers (N = 113)

Purchase Behaviour Category	Frequency	Percentage
Yes, I have bought	42	37.2%
I have not bought, but I considered	35	31.0%
No	36	31.9%
Total Influenced	77	68.1%

Analysis of influencer-following patterns revealed that 57.5% of respondents followed 0-2 fashion influencers, 23.9% followed 3-5 influencers, 11.5% followed 6-10 influencers, and 4.4% followed more than 10 influencers. This distribution suggests that while most consumers have limited direct followings, they still encounter influencer content through algorithmic recommendations and viral sharing.

Monthly fashion spending patterns showed that 42.5% spent less than ₹1,000, 33.6% spent ₹1,000-₹2,999, 12.4% spent ₹3,000-₹4,999, and 8.0% spent ₹5,000 or above. Cross-tabulation with purchase behaviour revealed a strong positive relationship: among high spenders (₹5,000+), 66.7% had made influencer-driven purchases, compared to only 18.8% among low spenders (<₹1,000).

### **Influencer Characteristics: Descriptive Analysis**

Table 3 presents descriptive statistics for influencer characteristic constructs. All mean scores ranged between 2.61 and 3.17 on the 5-point scale, indicating moderate levels of perceived influencer characteristics. Expertise received the highest mean score (M = 3.04, SD = 1.38), suggesting respondents view fashion influencers as possessing reasonable knowledge and competence. Attractiveness (M = 2.94, SD = 1.31) and Content Quality (M = 2.94, SD = 1.35) showed similar moderate ratings. Trustworthiness received the lowest mean score (M = 2.82, SD = 1.31), potentially reflecting consumer doubt about commercial motivations behind influencer endorsements.

Table 3: Descriptive Statistics for Influencer Characteristics (N = 113)

Construct	Mean	SD	Min	Max
Attractiveness	2.94	1.31	1.00	5.00
Expertise	3.04	1.38	1.00	5.00
Trustworthiness	2.82	1.31	1.00	5.00
Content Quality	2.94	1.35	1.00	5.00

### Consumer Response Variables

Consumer response constructs showed similar moderate levels (Table 4). Attitude toward Influencer averaged 2.76 (SD = 1.24), indicating somewhat favorable but not strongly positive perceptions. Purchase Intention showed the lowest mean score (M = 2.61, SD = 1.22), consistent with the funnel effect where positive attitudes do not always translate fully into purchase intentions. Perceived Value averaged 2.78 (SD = 1.23), while Perceived Risk averaged 2.68 (SD = 1.32), suggesting balanced cost-benefit evaluations.

Table 4: Descriptive Statistics for Consumer Response Variables (N = 113)

Construct	Mean	SD	Min	Max
Attitude toward Influencer	2.76	1.24	1.00	5.00
Purchase Intention	2.61	1.22	1.00	5.00
Perceived Value	2.78	1.23	1.00	5.00
Perceived Risk	2.68	1.32	1.00	5.00

The relatively moderate scores across all constructs suggest considerable heterogeneity in consumer perceptions and responses to influencer marketing. This variability underscores the importance of examining relationships between constructs rather than relying solely on absolute levels.

### Correlation Analysis

Table 5 presents the correlation matrix for key constructs. All correlations were positive and statistically significant ( $p < 0.001$ ), supporting the theoretical model's predicted relationships. Several notably strong correlations emerged:

Table 5: Correlation Matrix for Key Constructs (N = 113)

Construct	1	2	3	4	5	6
1. Attractiveness	1.000					
2. Expertise	0.872**	1.000				
3. Trustworthiness	0.817**	0.898**	1.000			
4. Content Quality	0.811**	0.842**	0.791**	1.000		
5. Attitude	0.839**	0.881**	0.862**	0.874**	1.000	
6. Purchase Intention	0.803**	0.816**	0.792**	0.823**	0.879**	1.000

All four influencer characteristics showed strong correlations with both attitude (ranging from 0.811 to 0.881) and purchase intention (ranging from 0.792 to 0.823), indicating that each characteristic independently contributes to marketing effectiveness.

### Group Comparisons by Purchase Behaviour

Table 6: Mean Construct Scores by Purchase Behaviour Groups

Purchase Behaviour	Attr	Exp	Trust	Cont	Att	PI
Yes, I have bought	3.45	3.63	3.31	3.49	3.28	3.14
Considered but not bought	3.46	3.52	3.20	3.30	3.02	2.78
No	1.85	1.88	1.88	1.95	1.88	1.83

Note. Attr = Attractiveness, Exp = Expertise, Trust = Trustworthiness, Cont = Content Quality, Att = Attitude, PI = Purchase Intention

Respondents who made purchases scored consistently higher across all constructs compared to those who only considered purchases, who in turn scored substantially higher than non-influenced consumers. The "No" group showed remarkably uniform low scores (1.83-1.95), indicating wholesale rejection or non-exposure to influencer content. The "Yes" group's elevated scores (3.14-3.63) demonstrate strong positive perceptions across all dimensions.

### Demographic Differences in Purchase Behaviour

Gender differences emerged in purchase behaviour patterns. Among female respondents, 42.1% had made influencer-driven purchases, compared to 32.1% of males. Conversely, 41.1% of males reported no influencer impact versus 22.8% of females.

Age patterns revealed developmental trends in influencer responsiveness. The youngest group (16-18 years) showed the lowest purchase rate (14.3%), possibly reflecting limited financial autonomy despite high social media engagement. Purchase rates increased substantially for the 19-22 age group (49.1%) and peaked among 23-26-year-olds (61.5%), who possess both fashion consciousness and purchasing power.

Among respondents spending ₹5,000+ monthly on fashion, 66.7% had made influencer-driven purchases and only 11.1% reported no influence. This contrasts sharply with the <₹1,000 spending group, where only 18.8% had purchased and 47.9% reported no influence.

## **Discussion**

### **Interpretation of Findings**

The finding that 68.1% of respondents were influenced by fashion influencers—either through actual purchases (37.2%) or serious consideration (31.0%)—demonstrates substantial marketing effectiveness in this regional context. This influence rate aligns with broader industry statistics showing 86% of consumers make influencer-inspired purchases annually[3], while accounting for regional variations in market maturity.

The strong correlations between influencer characteristics and consumer responses validate the Source Credibility Model in the digital influencer context. The extremely high correlation between trustworthiness and expertise ( $r = 0.898$ ) suggests these dimensions are highly integrated in consumer perceptions, with perceived knowledge enhancing trustworthiness and vice versa.

The finding that expertise most strongly predicts positive attitudes ( $r = 0.881$ ) underscores the importance of demonstrable fashion knowledge and styling competence.

The strong attitude-purchase intention relationship ( $r = 0.879$ ) confirms that while multiple factors influence purchases, positive attitudes toward influencers serve as critical mediators.

### **Social Media Platform Aspects and its Strategic Implications**

The dominance of Instagram (73.5%) and YouTube (53.1%) as primary platforms for following fashion influencers has important strategic implications. Instagram's visual-first format, shopping integrations, and influencer-friendly features (Stories, Reels, Shopping tags) make it ideally suited for fashion content. YouTube's strength lies in longer-form content,

enabling detailed product reviews, styling tutorials, and haul videos that build deeper expertise perceptions.

Fashion brands should adopt platform-specific content strategies. Instagram content should emphasise high-quality visuals, aspirational lifestyle imagery, and quick styling tips optimised for short attention spans. YouTube content should leverage longer formats for in-depth product demonstrations, comparison reviews, and styling tutorials that establish influencer expertise. The relatively lower adoption of TikTok in this sample (1.8%) compared to Western markets suggests a future growth opportunity as the platform expands its fashion influencer ecosystem in India.

The finding that 57.5% of respondents follow only 0-2 fashion influencers directly, yet 68.1% are influenced, indicates that indirect exposure through algorithmic recommendations, viral content, and peer sharing plays a substantial role. Brands should therefore focus not only on direct follower counts but also on content virality potential and shareability. Collaborating with influencers who create highly engaging, shareable content may yield greater reach than those with large but less engaged audiences.

### **Demographic Targeting Recommendations**

The pronounced gender difference in purchase behaviour (42.1% female vs. 32.1% male purchase rates) suggests gender-targeted influencer strategies may enhance effectiveness. Fashion brands targeting female consumers should prioritise influencer partnerships, as this segment demonstrates higher receptivity. However, the substantial male influence (32.1% purchase rate) indicates untapped potential. Brands should develop male-focused influencer content emphasising different value propositions—perhaps functionality, versatility, and value rather than an aspirational lifestyle alone.

The age-purchase behaviour relationship suggests optimal targeting of the 19-26 age bracket, which combines high fashion interest with purchasing power. However, the low conversion among 16-18-year-olds (14.3% purchase rate despite 52.4% considering) represents a future market opportunity. Brands could engage this segment through affordable entry-level products, student discounts promoted through influencers, or aspirational content that builds brand preference for later purchase stages.

The strong spending-behaviour correlation indicates influencer marketing is most immediately effective among mid-to-high fashion spenders. However, this creates a strategic choice: brands

can either focus on high-spending consumers for immediate ROI, or invest in building influence among lower spenders who represent future growth potential as incomes increase. A balanced approach might involve premium influencers targeting established spenders while micro-influencers engage aspirational consumers.

### **Limitations and Future Research Directions**

Several limitations should be acknowledged. First, the convenience sampling method and relatively modest sample size (N = 113) limit generalizability beyond the Saurashtra region. Future research should employ probability sampling across broader geographic areas to enhance external validity.

### **Conclusion**

With 68.1% of respondents influenced by fashion influencers to purchase or seriously consider purchases, the data confirms influencer marketing as a powerful force in regional fashion markets.

The research validates the Source Credibility Model in the digital influencer context, demonstrating that expertise, trustworthiness, attractiveness, and content quality collectively shape consumer attitudes, which in turn drive purchase intentions. The extremely strong correlations between these constructs ( $r > 0.80$  in multiple cases) indicate integrated, mutually-reinforcing effects rather than independent influences.

Platform analysis reveals Instagram and YouTube as dominant channels, suggesting fashion brands should prioritise these platforms for influencer collaborations. Gender, age, and spending patterns significantly moderate influencer effectiveness, providing actionable segmentation criteria. Female consumers, those aged 19-26, and higher fashion spenders demonstrate the greatest responsiveness, representing priority segments for influencer campaigns.

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**DETERMINANTS OF RETIREMENT FINANCIAL PLANNING IN  
 URBAN SAURASHTRA HIGHER EDUCATION**

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**Abstract**

This paper reviews the determinants of financial planning for retirement among salaried employees in higher education institutions in urban Saurashtra, Gujarat. It synthesises existing literature on retirement planning, behavioural finance, and financial literacy to address the unique challenges faced by this cohort. The review examines the impact of behavioural biases, the importance of early savings initiatives, and the role of financial literacy in shaping investment decisions. A theoretical model is proposed, integrating these determinants to provide a framework for understanding and improving retirement outcomes. The model highlights the interplay between demographic factors, financial literacy, and behavioural influences. The implications for higher education employees in urban Saurashtra are discussed, focusing on institutional interventions, behavioural finance tools, and tailored financial strategies. The paper concludes by emphasising the need for financial literacy programs and policy changes to promote resilient retirement plans. Future research should focus on empirical validation of the proposed framework and the development of innovative tools to address sector-specific challenges. This review contributes to the broader discussion on financial well-being and economic stability among academic professionals.

**Key words:** Financial Literacy, Retirement Planning, Salaried employees

**1. Introduction:**

Retirement planning has emerged as a central issue for individuals approaching later life stages. In the context of urban Saurashtra, Gujarat, this topic is of particular importance for salaried employees working in higher education institutions. Although higher education employees often enjoy stable incomes, they face unique challenges in preparing financially for retirement—ranging from behavioral biases to the impact of insufficient financial literacy. This paper examines the determinants of financial planning for retirement among this specific cohort, synthesizing insights from existing literature that has studied broader populations in

Gujarat. In doing so, the research draws upon multiple sources, including the work on connecting financial theory with human behavior in retirement planning [2], studies on the saving behaviors of young employees [6], and research assessing the role of financial literacy among working women in Gujarat [10].

The discussion presented herein is crucial because even though employees in higher education are not traditionally characterized by the same financial vulnerabilities as other sectors, the transition from active employment to retirement involves several common determinants. These include a pronounced fear of return uncertainty, behavioral biases leading to suboptimal portfolio choices, and the interplay between financial literacy and investment decisions. It is imperative, therefore, to understand the drivers that dictate retirement planning. This paper not only reviews the literature but also outlines a theoretical model tailored for higher education employees in urban Saurashtra. Emphasis is placed on practical implications that can guide policy modifications, financial advisory practices, and the formulation of corporate retirement plans that are sensitive to both behavioral and financial determinants.

### **3. Literature Review**

#### **3.1. Overview of Retirement Financial Planning**

Retirement financial planning is a multidimensional process that involves assessment of risk, expected return management, and strategic savings initiatives. The literature broadly defines retirement planning as the systematic process of accumulating, managing, and decumulating assets to ensure financial stability over the post-retirement period. As highlighted in the work on “Secure Retirement: Connecting Financial Theory and Human Behaviour,” investors are often caught between the theoretical promise of higher returns and the practical anxieties associated with market volatility and longevity risk [2]. The document emphasises that even when the expected risk-return trade-off seems favourable on paper, the actual outcomes may deviate significantly due to unpredictable market conditions and behavioural responses exhibited by the average investor [2].

The complexity inherent in retirement planning is further compounded by several factors—ranging from macroeconomic influences such as changing interest rate environments to individual-specific issues like savings behavior and risk tolerance levels. Especially in regions such as urban Saurashtra, where social and cultural factors may affect financial decisions, understanding these determinants becomes crucial. Previous studies have underlined the necessity of blending financial theory with behavioral insights to design adaptive retirement strategies that can respond to both short-term market dynamics and long-term economic shifts [2].

### **3.2. Behavioral and Risk Management Approaches in Retirement**

One of the primary challenges discussed in the literature is the management of behavioral biases that impede optimal financial decisions. The “Secure Retirement” study discusses how fear of unforeseen market downturns and a tendency to react emotionally to short-term market movements often result in suboptimal asset allocation decisions [2]. For instance, investors may inadvertently reduce their equity exposure during bear markets and increase it after market recoveries, thereby compounding the negative impact on cumulative wealth. Such behaviour, identified as a significant contributor to underperformance relative to static benchmark portfolios, underscores the importance of understanding behavioural finance mechanisms in retirement planning.

Behavioural theories indicate that investors are predisposed to what is known as the “disposition effect,” where the tendency to hold onto losing investments while prematurely selling winning assets leads to inefficiencies in portfolio management. In this context, the literature suggests that a well-designed retirement plan must incorporate strategies for risk management throughout the accumulation and decumulation phases [2]. Moreover, the integration of annuity products, despite prevailing low-interest environments, can contribute to a portfolio structure that better sustains income during retirement. Such findings point toward a need for retirement planning models that are not merely static but dynamically adjust to both market conditions and the investor’s behavioural responses.

A key insight from the “Secure Retirement” study is that returns are not the sole determinant of wealth accumulation; rather, the sequence of returns and the timing of contributions and withdrawals also feature prominently in the final financial outcome [2]. The dynamic nature of risk—differing significantly between the accumulation phase (characterised by regular savings contributions) and the decumulation phase (where the focus shifts to withdrawal strategies)—necessitates models that actively manage transitional risk, especially in the later stages of the career. These behavioural insights have a direct bearing on formulating retirement strategies that are resilient to market fluctuations and cognitive biases.

### **3.3. Early Savings Initiatives and Age-Related Factors**

The importance of age and early savings is well documented in the study “Does Young Indians Save for Retirement?” by Patel and Acharya [4]. This research emphasises that retirement planning is not a short-term process but rather requires a long-term strategic approach that ideally begins as soon as an individual starts earning a livelihood [4]. According to Patel and Acharya, early awareness is critical as it influences the accumulation of a retirement corpus over an extended period, thereby mitigating the adverse effects of compounding volatility.

However, while young employees (often those belonging to the millennial or Generation Z cohorts) are increasingly aware of the need for early savings, there exists a notable gap when it comes to translating this awareness into concrete savings behaviour.

The study highlights that although young baby boomers exhibit an understanding of the need to start saving early, proactive saving initiatives among younger employees remain relatively negligible [4]. The reasons attributed to this include a lack of tailored financial advice and a perceived disconnect between the benefits of early savings and immediate financial needs. In higher education institutions, where employees might enjoy a steady income yet face unique career trajectory constraints, early and continuous financial planning becomes essential. This issue is particularly pertinent in the urban Saurashtra region where rapid socio-economic changes necessitate agile planning strategies.

The influence of age on retirement planning is not solely limited to the timing of savings but also extends to risk tolerance and investment choices. Younger employees are generally predisposed to adopt portfolios with a higher allocation towards riskier assets, whereas older employees often lean towards low-risk instruments. This age-related variance in risk preferences implies that retirement planning models need to incorporate age as a key variable—a consideration that is vital in mapping out a long-term financial strategy for higher education employees in urban Saurashtra. Furthermore, early interventions that promote financial literacy can alter risk perceptions and encourage more informed, balanced decision-making processes over time.

### **3.4. Financial Literacy and Investment Decisions**

Financial literacy has emerged as one of the most significant determinants of retirement planning success. The research article “Assessing the Financial Well-Being of Working Women in Gujarat” provides compelling evidence that higher levels of financial literacy correlate with improved investment decisions and increased savings for retirement [6]. Although this study primarily focuses on working women, its findings have broader implications across different demographic groups, including salaried employees in higher education.

According to the study, financial literacy is directly associated with how individuals approach investment decisions, manage portfolio risks, and allocate their resources across different asset classes [6]. The empirical analysis demonstrated that higher financial literacy not only enhances the quality of investment decisions but also fosters the adoption of diversified saving strategies that are crucial during both the accumulation and decumulation phases of retirement planning<sup>6</sup>. In particular, the study notes that women with advanced financial knowledge tend

to adopt more proactive saving behaviours and diversify their investments across fixed deposits, insurance products, mutual funds, and other financial instruments [6].

A detailed ANOVA analysis within the study further confirms that variations in financial literacy levels result in statistically significant differences in financial well-being. This finding is critical for retirement planning because a well-informed investor is more likely to maintain a balanced portfolio that can withstand market volatility. Additionally, regression analysis within the study highlighted that even modest improvements in financial literacy can lead to appreciable enhancements in overall financial well-being. These results underscore the necessity of targeted financial education programs—especially those that are tailored to the specific circumstances of employees in higher education institutions.

Given the diverse challenges that higher education employees face—ranging from institutional budget limitations to the pressures of academic tenure—the role of financial literacy becomes a cornerstone in preparing for a secure retirement. Customised workshops, peer mentoring programs, and institutional financial counselling can serve as critical interventions that boost financial literacy and, consequently, improve retirement outcomes. This area warrants further research with a specific focus on the higher education sector in urban Saurashtra, where existing studies provide a solid foundation for understanding the broader dynamics but do not yet fully address sector-specific peculiarities.

### **Visualization: Comparative Table of Determinants Influencing Retirement Planning**

Below is a table summarizing key determinants of retirement financial planning as derived from the literature, including their source and impact on overall planning outcomes.

Table 1: Comparative Overview of Key Determinants Affecting Retirement Financial Planning

<b>Determinant</b>	<b>Source Reference</b>	<b>Impact Level</b>	<b>Notes</b>
Behavioural Biases & Risk Aversion	Secure Retirement Study [2]	High	Leads to inefficient portfolio adjustments
Early Savings Initiation	Does Young Indian Save for Retirement [4]	Medium to High	Awareness exists, but proactive savings are often lacking
Financial Literacy	Assessing the Financial Well-Being Study [6]	High	Positively correlates with diversified investments and savings

Age and Risk Tolerance	Does Young Indian Save for Retirement [4]	Medium	Younger vs. older preferences necessitate tailored strategies
Investment Diversification	Secure Retirement Study	High	Strategic asset allocation mitigates market volatility
Cultural and Gender Expectations	Assessing the Financial Well-Being Study [6]	Medium	Tailored financial programs are necessary to overcome limitations

This table clearly illustrates how each determinant contributes to building a resilient retirement plan. For higher education employees, integrating these insights into institutional planning can provide a robust framework that accommodates individual behavioral tendencies and financial capabilities.

#### 4. Theoretical Framework and Model Proposition

The theoretical framework for retirement financial planning among salaried employees in higher education institutions of urban Saurashtra integrates multiple determinants derived from previous studies. Building on the behavioral and financial literacy insights, the proposed model identifies three interrelated components:

##### 1. Behavioral Influences and Risk Management:

As noted in the “Secure Retirement” study, behavioural responses—such as the disposition effect, risk aversion during market downturns, and emotional decision-making—play a critical role in determining retirement outcomes. These behavioural influences are compounded by the risk environment, where unexpected market volatility can lead to significant deviations from planned savings routes [2]. In higher education, the pressures of research, teaching, and administrative responsibilities may exacerbate these behaviours, making it imperative that institutional retirement plans incorporate risk management features that are responsive to behavioural biases.

##### 2. Financial Literacy and Investment Decision Capability:

Empirical evidence from the study on working women in Gujarat demonstrates that financial literacy is a significant predictor of effective investment decision-making [6]. In our model, enhanced financial literacy acts as a moderator between income levels and financial outcomes. Specifically, improved literacy leads to greater diversification across asset classes, which in turn reduces the volatility of cumulative wealth. Given the structured

income but variable investment acumen of higher education employees, tailored financial literacy programs could substantially alter investment behaviours and improve retirement readiness.

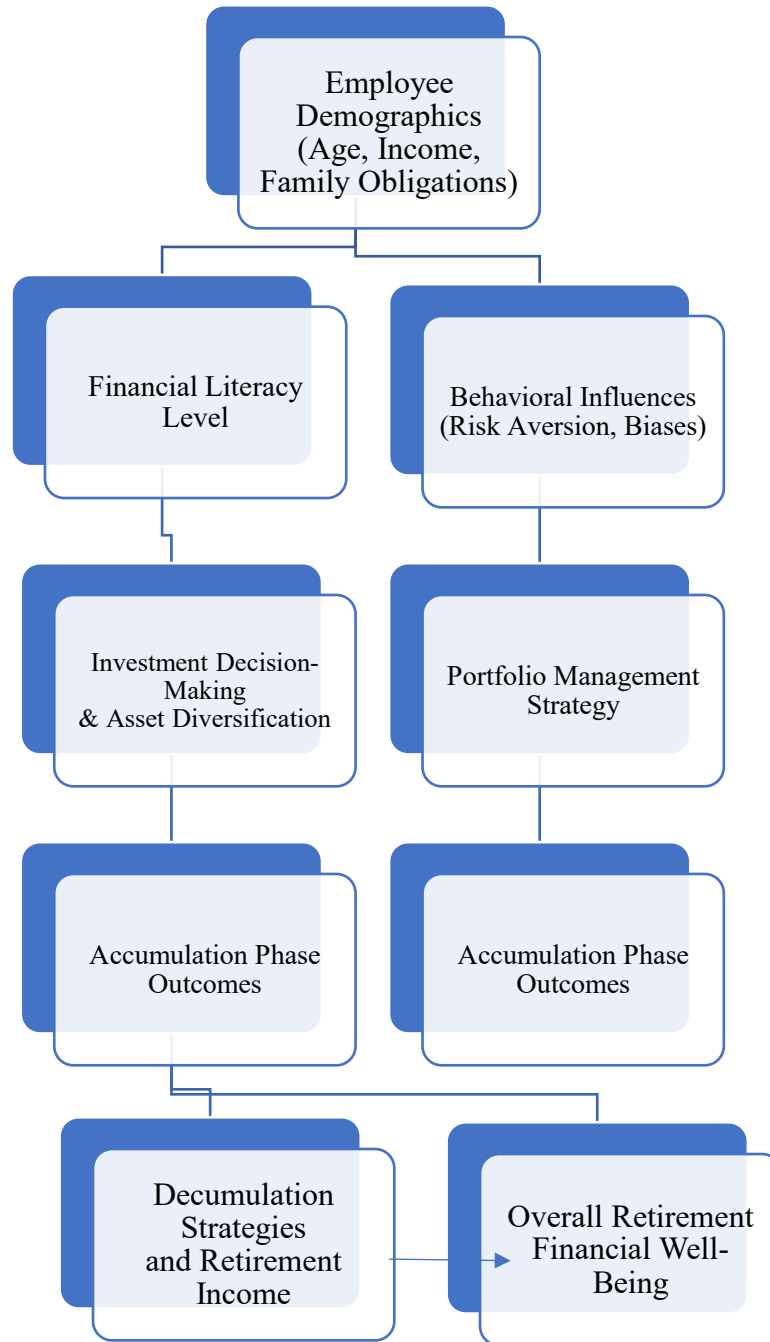
### 3. Demographic and Socioeconomic Variables:

Age, gender, and socio-cultural factors further refine the model. Younger employees, for instance, might exhibit higher risk tolerance and a propensity for aggressive investment strategies, while older employees may prioritise preservation of capital. Studies have shown that even when awareness about early saving is present, the actual commitment to early and consistent saving practices can be lacking [4]. For higher education employees in urban Saurashtra, additional factors such as career stage, marital status, and family financial obligations must be integrated into the planning process.

The proposed model can be visually represented in a flowchart that outlines the interplay among these three components:

#### **Flowchart: Theoretical Model of Retirement Financial Planning Determinants**

#### **Figure 1: Flowchart Representing the Theoretical Model Integrating Demographics, Financial Literacy, and Behavioural Influences in Retirement Planning**



This diagram highlights the sequential relationships among demographic factors, financial literacy, and behavioural influences leading to effective portfolio management. The model suggests that interventions designed to improve financial literacy not only directly affect investment decisions but also mediate the effects of behavioral biases, ultimately contributing to better retirement outcomes.

The developed framework is applicable for higher education employees in urban Saurashtra, where institutional policies can be aligned with these determinants. For example, targeted financial workshops and advisory programs may mitigate behavioral biases and enhance

literacy, thereby enabling employees to optimize their retirement portfolios. This integrative model forms the basis for subsequent empirical validation and intervention design.

## **5. Implications for Higher Education Employees in Urban Saurashtra**

Higher education employees in urban Saurashtra present a unique case in retirement planning. Although they typically enjoy a stable salary and often have access to government-backed pension schemes, the challenges of behavioral biases, inadequate financial literacy, and the complex interplay of socioeconomic factors affect their long-term financial stability. The implications of the reviewed literature and the proposed theoretical framework for this group are multifaceted.

### **5.1. Institutional Interventions for Enhanced Financial Literacy**

One of the major findings from the literature is the pivotal role of financial literacy in shaping investment decisions and safeguarding financial well-being [6]. Higher education institutions can serve as platforms for delivering targeted financial education programs. Workshops, seminars, and peer mentoring initiatives can demystify the complex notions of risk management and asset allocation. By incorporating modules that explain both theoretical aspects of financial planning and practical investment strategies, such programs can help employees make informed decisions that align with their career stages and personal circumstances.

For instance, institutions might collaborate with financial experts to develop a curriculum that covers topics such as understanding market volatility, recognizing behavioral biases, and effectively using retirement savings instruments. The success of such initiatives would not only improve individual retirement outcomes but could also enhance the overall financial culture within the academic community. In settings where employees are expected to balance academic responsibilities with long-term financial planning, these interventions could be particularly beneficial.

### **5.2. Behavioral Finance Tools and Risk Management Strategies**

The literature clearly indicates that behavioral factors—such as excessive risk aversion during downturns and undue optimism during market booms—contribute significantly to retirement planning challenges<sup>2</sup>. For higher education employees, who may be less familiar with the intricacies of market dynamics, reliance on behavioral finance tools could help bridge the gap between knowledge and action. Institutions should consider offering personalized financial counseling that involves behavioral assessments. Such counseling can assist employees in recognizing their predispositions and adjusting their portfolio strategies accordingly.

Additionally, the integration of risk management techniques that account for both the accumulation and decumulation phases is essential. Financial advisors and institutional planners should adopt dynamic planning models that adjust asset allocation based on the investor’s age, career stage, and evolving market conditions. The insights from the “Secure Retirement” research underscore the importance of maintaining a balanced portfolio that adapts to fluctuations in market conditions while compensating for the investor’s tendency toward suboptimal decision-making.

### **5.3. Demographic Considerations and Tailored Financial Strategies**

The role of demographic factors in shaping retirement planning outcomes cannot be overstated. As evidenced by the study on retirement savings among Indian employees, age not only influences the timing of savings but also affects risk tolerance and investment preferences<sup>4</sup>. In higher education institutions, employee demographics can vary widely—from young faculty members at the beginning of their careers to senior professors nearing retirement. This diversity necessitates a segmented approach to financial planning.

For younger employees, interventions might emphasise the benefits of early investment and the power of compound interest. For mid-career professionals, strategies may focus more on optimising the balance between growth and preservation. For those closer to retirement, planning should target decumulation strategies that ensure sustained income and minimal drawdown risks. The heterogeneous nature of the workforce in higher education thus calls for customisation of financial planning tools and advisory services. This tailored approach will ensure that each demographic group can effectively navigate its unique challenges while capitalising on available investment opportunities.

### **5.4. Policy Implications and Recommendations**

The findings and theoretical model discussed in this paper have several policy implications for higher education institutions in urban Saurashtra. First, institutions should integrate financial wellness programs into their employee benefit schemes, ensuring that retirement planning is not an afterthought but a core component of employee welfare. Second, policymakers need to promote collaboration between universities, financial institutions, and government agencies to create an ecosystem that supports long-term financial planning. Government-backed initiatives, such as those seen in broader studies in Gujarat, can be adapted to the higher education sector to provide additional layers of financial security.

Furthermore, the incorporation of technology—such as online financial planning tools and simulation platforms—can offer personalized insights and real-time adjustments to retirement strategies. Such tools have the potential to complement traditional advisory services, thereby

making financial planning more accessible and engaging for academic employees. Lastly, continuous monitoring and evaluation of these initiatives will be crucial in understanding their impact and iteratively improving the strategies to suit evolving market and demographic conditions.

## **6. Conclusion**

Retirement financial planning is an inherently complex endeavor that demands the integration of multi-dimensional factors such as behavioral influences, financial literacy, and demographic variables. For salaried employees in higher education institutions in urban Saurashtra, Gujarat, the challenges and opportunities associated with retirement planning are nuanced by stable income streams, institutional benefits, and the unique socio-cultural milieu of the region.

Key insights from the reviewed literature include:

- Behavioral biases, such as risk aversion and suboptimal asset allocation, significantly impact investment outcomes<sup>2</sup>.
- Early savings initiatives are critical, yet despite awareness, there remains a gap in proactive saving behavior among young employees<sup>4</sup>.
- Financial literacy plays a central role in enhancing investment decision-making and overall financial well-being, with empirical studies showing that even small improvements in literacy yield significant financial benefits<sup>6</sup>.
- A robust theoretical framework that integrates demographic, behavioral, and financial literacy components is essential for developing targeted and effective retirement planning strategies.

Based on these findings, higher education institutions should prioritize financial literacy programs, integrate behavioral finance tools into retirement planning, and tailor strategies to meet the diverse needs of their workforce. Such interventions not only promise to improve individual retirement outcomes but also contribute to broader economic stability and employee satisfaction.

In summary, a concerted effort to blend financial theory with practical, behaviorally informed interventions can pave the way for more resilient retirement plans for higher education employees in urban Saurashtra. Future research should focus on empirical validation of the proposed framework and the development of innovative tools that address the sector-specific challenges of retirement planning.

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## SALT-LOVING ARCHAEA POWERING BIOTECH INNOVATIONS AND SUSTAINABILITY

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### Abstract

Halophilic microorganisms, mainly halophilic archaea, flourish in hypersaline environments where very few other types of life forms can survive. Halophilic archaea are like a treasure trove for biotechnology. They are adapted to conditions in which other microbes cannot survive. They have adaptations such as special membrane lipids, salt-tolerant enzymes, and compatible solutes. Some key uses include biocatalysis. Here, halophilic enzymes such as ectoine synthases and haloarchaeal proteases perform well in high-salt processes. This reduces the risk of contamination in food processing and detergents. In biofuels, these archaea turn biomass into biohydrogen and exopolysaccharides. This offers sustainable alternatives amid water scarcity. Bioremediation is another area in which these halophilic microorganisms offer a significant contribution. Their halozymes (halophilic enzymes) also contribute in pharmaceutical and cosmetic industry. They can stay stable under extreme conditions.

Recent studies state that halophilic microorganisms have a significant potential for bioremediation, producing industrially important enzymes and making bioplastics. Many halophiles are still not well understood. We need to isolate, identify, and study them at a molecular level. Halophilic archaea are leading to an era of innovation driven by extremophiles. They are turning environmental challenges into biotechnological successes.

**Keywords:** Archaea, Halophilic archaea, Biotechnological applications, halozymes, Bioplastic synthesis

### 1. Introduction

#### 1.1 Background and Significance of Halophilic Archaea

The *Archaea* is a domain of the three groups of microorganisms (*Bacteria*, *Archaea* and *Eukarya*) and is different from the domains *Bacteria* and *Eukarya*. The *Archaea* domain has its history, molecular characteristics, and ways of adapting to its environment (Woese et al., 1990). Halophilic archaea are a type of *Archaea* that can thrive in high salt concentrations. They can be found in places like salt lakes, salt mines, and deep-sea brine pools, where the salt concentration is very high (Oren, 2008). They can even live in food products and industrial brine systems (Ventosa et al., 2012).

The study of halophilic archaea (halophiles) has changed the way we think about life and what it can do (Müller et al., 2011). These microorganisms have developed ways to survive in environments that would be deadly to other living things (Rothschild & Mancinelli, 2001). They have molecules that help them keep their cells intact, their proteins stable and their metabolism working. Some well-studied halophilic archaea include *Halobacterium*, *Haloferax*, *Halorubrum*, *Haloarcula*, *Natronomonas* and *Salinibacter*. *Halobacterium salinarum* and *Haloferax* species are often used as examples to study the biotechnological aspects of these microorganisms (DasSarma & DasSarma, 2017). By studying the genome of these archaea scientists have found unique genetic features, such as special DNA replication machinery and novel DNA repair mechanisms (Baliga et al., 2004; González et al., 2008).

The *Archaea* domain and the halophilic archaea are very interesting to scientists because they can teach us a lot about life and how it can adapt to environments. The halophilic archaea are a type of *Archaea* that can live in salty environments and they have special molecules and adaptations that help them survive. The *Archaea* domain is a group of living things that can help us learn more about life and its many possibilities.

### **1.2 Physiological and Molecular Adaptations**

Halophilic archaea can survive in salty environments because of special changes in their bodies and molecules. These organisms maintain high intracellular potassium concentrations while actively excluding sodium ions, creating an osmotic balance with their external environment (Oren, 1999). This balance is made possible by pumps, helpers, and systems that move ions, which could be useful for biotechnology. The proteins of archaea are special and work well in high-salt environments (Bauer & Drüeke, 2011). This acidic surface keeps the protein working even in very salty conditions that would normally break it. This property makes their enzymes called extremozymes valuable for industrial uses that need extreme conditions (Eichler, 2001). The membrane lipids of archaea are another special adaptation. Unlike bacterial membranes, archaeal membranes have special ether-linked chains that make them stable in extreme temperatures, pH, and organic solvents (Koga & Morii, 2007).

### **1.3 Significance in Modern Biotechnology**

The biotechnology industry needs enzymes and processes that work in conditions that halophilic archaea can provide. The development of technologies has increased interest in halophilic archaea as environmentally friendly biocatalysts. The learning of halophilic archaea also helps with development by allowing the usage of salty waste streams, making biodegradable products, and cleaning up contaminated sites (Margesin & Schinner, 2001). As industries move towards bio-based processes, halophilic archaea will be important for the

bioeconomy. As industries worldwide seek to reduce their environmental footprint and transition toward bio-based processes, the unique capabilities of halophilic archaea position them as important contributors to the bioeconomy of the future. (León et al., 2018)

## **1.4 Scope and Objectives**

This review aims to look at what we currently know about using halophilic archaea in biotechnology. The main goals are to summarize findings on the potential uses of halophilic archaea in different areas, to carefully assess the current problems and challenges in using these organisms for industrial purposes, and to find potential research areas that could help turn halophilic archaea research into commercial uses.

This review article cover areas of application, including: Industrial enzymes, biofuel production, bioremediation, pharmaceutical development, biosurfactant and biopolymer synthesis, food and agricultural applications, and environmental technologies. Each section looks at the state of research, key achievements, remaining challenges, and prospects. This review aims to be a valuable source for new researchers as well as established scientists looking to expand their work and industry professionals evaluating the applications of halophilic archaea. Halophilic archaea have potential uses, and understanding their applications can help advance research and commercialization.

## **2. Halozymes: Industrial Enzymes from the Salt-Loving World**

### **2.1 Introduction to Halophilic Enzymes**

The term extremozymes refers to enzymes that come from organisms and these extremozymes can still work in environmental conditions that are not suitable for regular enzymes. This includes high or low temperatures, high salt levels, and high pressure (Gerday & Glansdorff, 2007). Halozymes are a kind of these enzymes. They work well in various environments and are also very stable. The special thing about enzymes is how they are structured. They have several amino acid residues on their surface, which makes the surface of the protein hydrated, which prevents the proteins from sticking and helps them stay dissolved in high salt concentration solutions (Fukuchi et al., 2003). Halophilic enzymes can work in conditions that are too tough for regular enzymes (Eichler, 2001).

### **2.2 Amylases and Carbohydrate-Active Enzymes**

Halophilic amylases are very good at breaking down starch. These enzymes are also useful in the starch processing industry. The amylase from *Halobacterium* species and *Haloferax mediterranei* works well in salty conditions and high temperatures (Pérez-Pomares et al., 2003; Egas et al., 2000). This makes it possible to liquefy starch in conditions that would stop

amylases from working (Sanchez-Mora et al., 2016). Halophilic amylases are also useful in the food industry. In the baking industry these enzymes can help make dough.

### **2.3 Proteases and Lipases**

Protease are used in breaking down proteins. The proteases from *Halobacterium*, *Haloferax* and *Halorubrum* species work well in high salt concentration and high pH levels. Halophilic lipases are also very useful as they help break down fats, hence can be used in laundry and detergents (Gupta & Khare, 2007; Kumar et al., 2005).

### **2.4 DNA Polymerases and applications in molecular biology**

The DNA polymerase from *Halobacterium* species is valuable for molecular biology applications. It can help amplify and manipulate DNA. This makes it very useful, for research and diagnostic applications (Ishino et al., 1994; Ruan et al., 2017).

## **3. Bioremediation of Saline and Hypersaline Contaminated Sites**

### **3.1 The Challenge of Saline Waste Treatment**

The remediation of saline and hypersaline contaminated environments represents one of the most challenging problems in biotechnology. Conventional bioremediation approaches are based on microorganisms that are sensitive to high salt concentrations, limiting their effectiveness in the treatment of saline wastewater and hypersaline industrial effluents (León et al., 2018). The discharge of saline wastewater from biotechnological industries including salt production, seafood processing, leather tanning, and petroleum poses significant environmental risks, while the treatment of salt-contaminated agricultural lands affected by seawater invasion requires specialized approaches.

Halophilic microorganisms offer advantages for the bioremediation of saline environments. These organisms can function at salt concentrations that eliminate most common bioremediation agents, enabling in-situ treatment of hypersaline waste streams without the need to dilute them or salt removal (Ravindran et al., 2016). The metabolic diversity of halophilic archaea and bacteria encompasses the degradation of hydrocarbons, heavy metals, pesticides, and other contaminants, providing a toolkit for addressing various pollution scenarios.

### **3.2 Hydrocarbon Degradation in Saline Environments**

The capacity of halophilic archaea to break down hydrocarbon compounds is very interesting for the bioremediation of petroleum-contaminated salty environments. For instance, marine oil spills and the discharge of petroleum-containing wastewaters create contamination scenarios where traditional hydrocarbon-degrading bacteria may be inhibited by salinity. This creates

opportunities for halotolerant specialists, such as halophilic archaea, to play a vital role in bioremediation (Al-Mailem et al., 2010).

Species of *Halobacterium*, *Haloferax* and *Halorubrum* have demonstrated capabilities for hydrocarbon degradation under laboratory conditions. Some strains of these microorganisms are capable of utilizing aromatic hydrocarbons as the sole carbon sources. The hydrocarbon-degrading activity of these microorganisms is often enhanced under conditions of nitrogen or phosphorus limitation. This suggests potential for nutrient-amended bioremediation strategies, where the addition of nutrients such as nitrogen or phosphorus can enhance the bioremediation process (Al-Mailem et al., 2014). Field studies have explored the application of consortia for the treatment of salty petroleum wastewaters and contaminated soils (Al-Mailem et al., 2017).

### **3.3 Heavy Metal Bioremediation**

The removal and recovery of metals from salty waste streams is another area where halophilic archaea show considerable promise. The high intracellular ion concentrations and specialized metal-binding proteins of these microorganisms provide mechanisms for metal tolerance (DasSarma et al., 2010). These mechanisms can be exploited for bioremediation purposes, such as the removal of metals from salty waste streams. Some halophilic archaea accumulate metals, including cadmium, lead, mercury, and arsenic. Others transform metal species to toxic or more readily removable forms. For example, the presence of surface layer proteins and acidic polysaccharides enhances the adsorption of cationic metal species. The high negative surface charge conferred by proteins also enhances the adsorption of cationic metal species. The stability of biomass in harsh conditions facilitates its use in continuous adsorption systems, which can be used to remove heavy metals from salty waste streams (Oren, 2010).

## **4. Pharmaceutical and Biomedical Applications**

### **4.1 Antimicrobial Compounds**

The exploration for antimicrobial agents has led to considerable research on various secondary metabolites produced by halophilic archaea. These organisms produce different bioactive compounds that can fight against pathogenic bacteria, fungi and viruses. This makes them a good starting point for developing pharmaceuticals (Besse et al., 2019). Halophilic archaea live in unique environments that have helped them develop new biosynthetic pathways. These pathways produce potentially bioactive metabolites.

The antimicrobial peptides produced by archaea are very interesting. They have ways of working and are stable in extreme conditions. The halocins produced by *Halobacterium* and *Haloferax* species are a type of peptide. They can fight against halophilic species (Price & Shand, 2000).

## **4.2 Anticancer and Therapeutic Agents**

Researchers are looking into archaeal metabolites to check if they can help fight cancer. So far the outcomes are promising. Extracts from archaea have been shown to kill cancer cells. Some of these extracts can even tell the difference between cancer cells and normal cells (Besse et al., 2019).

## **4.3 Antiviral Applications**

Halophilic archaeal compounds might also be capable of fighting against viruses. Some of these compounds are like the ones that viruses use to attach to cells (Ghosh et al., 2014). This means they might be capable of blocking the virus from entering the cell. Halophilic archaea also produce proteins that can fight against viruses. These proteins might work by killing the virus stopping it from attaching to cells or helping the immune system fight back (Ghosh et al., 2014). The fact that halophilic proteins are stable in conditions is a big advantage. It could help us make medicines that last longer and work better.

## **4.4 Drug Delivery and Biomedical Materials**

The special properties of halophilic archaeal lipids and proteins make them useful for delivering drugs and making materials (Sprott et al., 1997). The lipids from archaea can form liposomes that can carry drugs. These liposomes are more stable than the ones we use now. This means they could stay in the body longer and release the drug constantly at a slower rate.

# **5. Biosurfactants and Biopolymers**

## **5.1 Biosurfactant Production**

Biosurfactants are represented as surface-active compounds produced by microorganisms. They have some benefits compared to synthetic surfactants. For example, in terms of biodegradability, reduced toxicity, and effectiveness under extreme conditions. The biosurfactants made by halophilic archaea have caught a lot of attention lately. People are interested in using them for their applications in bioremediation, enhanced oil recovery, and food and cosmetic formulations (Das et al., 2016). These special biosurfactants have some properties. They can work well in high salt concentration and temperature. Biosurfactants are an alternative to regular surfactants.

## **5.2 Applications in Enhanced Oil Recovery**

The application of biosurfactants in enhanced oil recovery (EOR) represents a promising application area that influences the unique properties of halophilic archaeal products. Biosurfactant solutions can be injected into oil reservoirs - This can reduce the tension between oil and water, it can also help move the trapped oil and enhance oil displacement efficiency

(Das et al., 2016). Halophilic biosurfactants are stable under reservoir conditions. These conditions include salinity, high temperature and high pressure. They have advantages over biosurfactants. Halophilic biosurfactants work well with reservoir water. This is an advantage in areas where water is limited. Using microorganisms to produce biosurfactants *in-situ* is a worthy approach. It can reduce costs and make oil recovery operations simpler (Das et al., 2016). Injecting nutrients can help stimulate microorganisms. These microorganisms can produce biosurfactants directly in the reservoir. This eliminates the need for surface production of biosurfactants and also eliminates the need to inject external biosurfactant solutions.

### **5.3 Polyhydroxyalkanoates**

Polyhydroxyalkanoates (PHAs) represent a class of biodegradable polyesters produced by microorganisms as carbon and energy storage compounds. The PHA production capacities of halophiles have been extensively characterized, with *Haloferax mediterranei* emerging as a particularly promising production organism (Lillo & Rodriguez-Valera, 1990; Quillaguamán et al., 2010). The PHAs produced by this particular organism, primarily polyhydroxybutyrate (PHB) and polyhydroxyvalerate (PHV) copolymers, exhibit properties suitable for biodegradable plastic production.

The advantages of *Haloferax mediterranei* for PHA production include rapid growth rates, high PHA accumulation capabilities, and the ability to utilize diverse carbon substrates, including glucose, starch, and agricultural waste streams (Lillo & Rodriguez-Valera, 1990; Quillaguamán et al., 2010). The non-sterile cultivation of this organism is facilitated by its requirement for high salt concentrations that inhibit most bacterial and fungal contaminants. The PHA accumulation occurs during the stationary phase under nitrogen or phosphorus limitation, with accumulation levels reaching 60-70 % of cell dry weight.

The properties of halophilic archaeal PHAs have been characterized for various applications. The PHB produced by *Haloferax mediterranei* exhibits mechanical and thermal properties comparable to conventional PHAs from bacterial sources, with glass transition and melting temperatures in ranges suitable for processing (Huang et al., 2016).

## **6. Food and Agricultural Applications**

### **6.1 Food Additives and Flavor Compounds**

The application of halophilic archaea in food production includes the generation of flavor compounds, food additives, and specialty ingredients (Roh et al., 2010). The halophilic archaeal production of volatile compounds, including alcohols, esters, and sulfur-containing compounds, has been characterized for flavoring applications.

Halophiles also make special enzymes that can be used in food production. These enzymes can be used to make cheese and meat taste better (Gupta & Khare, 2007). They work well even when in low temperature and high salt concentration. The special enzymes made by halophilic archaea can also be used in baking and making beer.

## **6.2 Food Preservation and Safety**

Halophiles make compounds that can help keep food safe. These compounds have the potential to be used in food preservation. The antimicrobial compounds from halophiles like halocins and other peptides can be used as preservatives. This means they can help extend the shelf life of food products and reduce the amount of microbes. The fact that these compounds are stable when food is being processed makes them more useful for applications.

Halophiles are also being studied for their use, in making fermented foods. When foods are fermented with salt it creates an environment where halophiles can grow easily. This can help make the food taste better and increases its shelf life (Roh et al., 2010).

## **6.3 Agricultural Applications**

Halophiles are really useful for farming because they can help plants grow and can be used as biocontrol agents. Some halophiles can even break down phosphate and make hormones that plants need to grow. This means they could be used as fertilizers (Ventosa et al., 2012). Halophiles are good at dealing with salt, which is a big problem in some areas where the soil is too salty. This makes them very useful for farming in these areas. People have been looking into using archaea to fight off plant diseases. These microorganisms can make compounds that kill bacteria and fungi that hurt crops (Besse et al., 2019). Using archaea to protect crops in salty areas is a new and exciting idea. Halophiles can also be used in animal food. Their enzymes can help animals digest their food better and get nutrients out of it. These enzymes are special because they can work well in the animal's stomach and intestines even when the pH levels are over the place. This could make animal food more efficient (Gupta & Khare, 2007). So using archaea in animal feed is a new area that could be really helpful for the animal farming industry. Halophiles are very useful, for farming and animal feed because they can help plants grow and animals digest their food.

## **7. Cosmetics and Personal Care Products**

### **7.1 Bioactive Compounds for Cosmetic Applications**

The cosmetic and personal care industry is really interested in halophilic archaea because they can provide unique compounds that are good for skincare, haircare, and anti-aging. The compounds made by archaea have properties of antioxidants, moisturize and reduce inflammation, which is why they are being studied for use in cosmetics (Besse et al., 2019).

The pigments made by halophilic archaea like bacterioruberin are very good at anti-oxidation which can help protect skin from damage caused by the sun and pollution (Roh et al., 2010). Due to its stability, halophilic archaeal pigments can be used in cosmetic products. Halophilic archaea also make exopolysaccharides that can help moisturize and protect skin. These exopolysaccharides can form a layer on the skin that keeps the skin hydrated.

## **7.2 Enzyme Applications in Cosmetics**

The enzymes from archaea are really useful for making cosmetic products and personal care items. These enzymes can help get rid of dead skin cells without being too harsh. They do this without using scrubbing or strong chemicals that can damage the skin. This is because the enzymes from archaea are gentle and work well at the skins natural pH level.

The enzymes that fix DNA and the photolyases from archaea are being studied to see if they can help protect and fix the DNA in skin cells. When skin is exposed to the sun rays it can get damaged and this can cause the skin to age too quickly or even get skin cancer. If we add the enzymes from archaea to sunscreens and products used after being in the sun they might help protect and fix the DNA in the skin (Nicolaus et al., 2010).

Halophilic enzymes that break down fats are also useful for skincare products that help control oil and prevent acne. These enzymes are stable and can be used in different types of skincare products.

## **8. Agricultural and Environmental Applications**

### **8.1 Soil Remediation and Plant Growth Promotion**

Halophilic archaea are useful for agricultural soil remediation and plant growth promotion. The ability of these organisms to thrive in saline soils and their interactions with plants suggest potential applications for agriculture in salt affected regions (Ventosa et al., 2012). Halophilic archaea can make the soil better by producing extracellular polymeric substances that enhance soil structure and water retention (Ventosa et al., 2012). Halophilic archaeal strains are also studied to be capable of siderophore production (Dave et al., 2006)

### **8.2 Aquaculture Applications**

Halophilic archaea are really useful in aquaculture systems. Researchers are interested in using them to keep the water clean and prevent disease (Rathoure et al., 2019). Halophilic archaea can be used in biofilter systems to remove contaminants like ammonia from the water.

### **8.3 Salt-Tolerant Crops and Halophyte Applications**

The study of archaea helps us make crops that can grow in salty water and use plants that like salt for farming in salty areas. By learning how archaea deal with salt we can use this information to make crops better (DasSarma & DasSarma, 2017). With the help of genetic

engineering, we can take genes from archaea and insert them into regular crops to help them deal with high salt concentration.

## **9. Future Perspectives**

The future of archaeal biotechnology relies on ongoing research in improving strains, optimizing processes and turning them into commercial products. To move forward we need genetic engineering tools for halophilic archaea. This will help us create strains that are perfect for specific biotechnological as well as industrial applications (DasSarma & DasSarma, 2017). Using systems biology with fermentation methods can speed up progress toward making halophilic archaeal products a reality. Establishing rules for products made from halophilic archaea is crucial for their commercial success.

Industry, schools and regulatory bodies must work together to set guidelines for safety checks and approvals. When investors know what to expect they are more likely to invest in archaeal biotechnology.

### **9.1 Sustainability Contributions**

Halophilic archaea are really good for the environment because they help in ways. They make things that can replace products made from petroleum, they make use of water that would otherwise be wasted and they help reduce the amount of fresh water needed in biological processes. The plastics made by archaea are biodegradable which means they do not harm the environment like regular plastics do because they break down easily (Huang et al., 2016). Using seawater or fresh water in the processes that involve halophiles also helps with the problem of water scarcity.

Halophiles are also useful in bioenergy production. They can be used to make biohydrogen, biogas, and biofuels, which are all energy sources (Kumar et al., 2016). These organisms can use different types of carbon sources, including waste, to make energy products. Halophilic archaea are really important for sustainability because they help in many ways, including the production of biodegradable alternatives and the reduction of freshwater requirements.

### **9.2 Conclusion**

Halophilic archaea are an interesting group of microorganisms that can survive in extreme conditions. They have a lot of uses in industries because of the way they are able to adapt to their environment. For example, they have proteins that work well in high salt concentrations and their cell membranes are very stable. They also have ways of making energy, which is useful for developing new technologies.

The special enzymes that halophilic archaea produce can work in high salt concentration, high temperature, or acidic conditions, which is not possible for regular enzymes. This makes them very useful for processes that need to happen in tough environments (Eichler, 2001). They can help reduce the amount of energy needed. They do not require sterile conditions to work.

Halophilic archaea are also very good at bioremediation. They can help treat wastewater that has high salt concentration, clean up oil spills in the ocean, and even remove heavy metals from industrial waste. If we can develop ways to use halophilic archaea to clean up the environment, it will be very beneficial for protecting the planet and conserving resources (León et al., 2018). In conclusion halophilic archaea are a treasure trove waiting to be utilized in biotechnology and sustainable development. These tiny organisms have features that can solve industrial problems in ways that usual methods cannot. By keeping an eye on halophilic archaea and working on related technologies, we can spark innovation in many areas (DasSarma et al., 2010). At the time we can shift toward more eco-friendly industrial and environmental practices.

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**Architects of the Void: Assessing Microbial Survival Mechanisms and Pathogenic Evolution in Low-Earth Orbit and Beyond**

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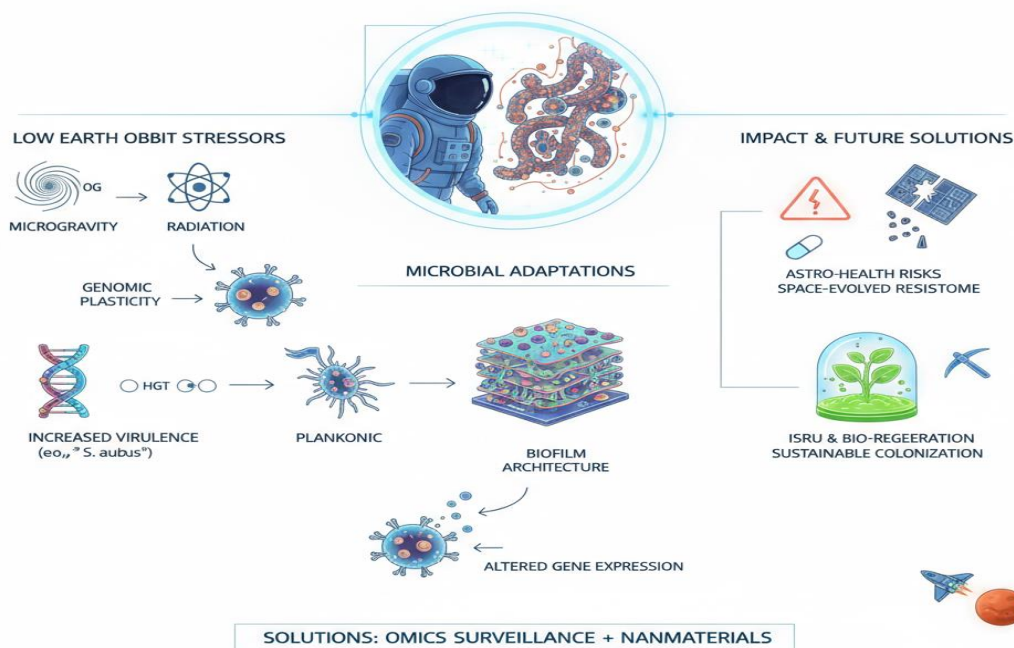
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**Abstract**

The success of long-duration space exploration and future planetary colonization is intrinsically linked to our understanding of the microbial stowaways that accompany human missions. In the confined, resource-limited environments of Low-Earth Orbit (LEO), microorganisms are subjected to unique selective pressures, including microgravity, cosmic ionizing radiation, and altered fluid dynamics. This review synthesizes recent findings from International Space Station (ISS) experiments—such as the 2026 reports on the T7 phage-host evolutionary arms race—to evaluate how these stressors reshape microbial physiology and pathogenicity. Highlight that microgravity induces a transition from planktonic to sessile lifestyles, leading to the formation of "architectural" biofilms with enhanced resistance to traditional disinfectants and antibiotics. At the molecular level, the lack of buoyancy-driven convection alters the extracellular microenvironment, triggering stress-response pathways that promote genomic plasticity and accelerated horizontal gene transfer. These adaptations often manifest as increased virulence in opportunistic pathogens like *Staphylococcus aureus* and *Pseudomonas aeruginosa*, posing significant risks to immunocompromised crews. Furthermore, we examine the "Dual-Use" nature of space-adapted microbes, exploring their potential in bio-regenerative life support systems and in-situ resource utilization (ISRU) against the backdrop of stringent planetary protection protocols. This article concludes that current Earth-based sterilization standards may be insufficient for the "Space-Evolved" resistome. We propose that integrating real-time "Omics" surveillance with the development of biofilm-resistant nanomaterials is essential to safeguard both astronaut health and spacecraft structural integrity. By understanding the mechanisms that allow microbes to act as "architects" of their own survival in the void, we can better engineer the microbial ecosystems necessary for humanity's expansion into the solar system.

Keywords: Microgravity-induced Virulence, Extraterrestrial Biofilms, Genomic Plasticity, Astrobiology, Planetary Protection

## Graphical Abstract



## 1. Introduction

The rapid expansion of human space exploration has intensified interest in understanding how microorganisms adapt, survive, and evolve under extraterrestrial conditions. In confined spacecraft and orbital habitats such as the International Space Station, microbial communities are exposed to a unique combination of stressors including microgravity, elevated radiation, limited nutrient flux, and closed-loop life support systems. These factors collectively impose selective pressures that can alter microbial physiology, stress tolerance, virulence, and resistance profiles, raising important concerns for astronaut health, spacecraft integrity, and long-term planetary colonization (Beheshti *et al.*, 2018; Chęcinska Sielaff *et al.*, 2019). Unlike terrestrial environments where gravity-driven convection and sedimentation influence microbial dispersion and nutrient availability, microgravity fundamentally changes fluid dynamics and cell–surface interactions, often promoting enhanced biofilm formation and altered gene expression patterns (Huang *et al.*, 2018; Taylor, 2019).

Studies conducted by space agencies such as NASA and international collaborators have revealed that spaceflight conditions can induce significant physiological and genomic changes in microorganisms. For example, opportunistic pathogens including *Staphylococcus aureus* and *Pseudomonas aeruginosa* demonstrate increased biofilm formation, altered antibiotic susceptibility, and enhanced stress resistance following exposure to microgravity and space

radiation (Kim *et al.*, 2017; Zea *et al.*, 2018). These adaptations are often mediated through global regulatory networks, stress-response genes, and horizontal gene transfer mechanisms that facilitate rapid microbial evolution in confined habitats (Mastroleo *et al.*, 2019; Schwendner *et al.*, 2020). Such findings suggest that microorganisms not only survive but actively remodel their genetic and phenotypic architecture in response to extraterrestrial environmental pressures.

Microgravity-induced changes in microbial behavior are particularly significant for long-duration missions, where persistent exposure may accelerate evolutionary trajectories and promote the emergence of highly resilient strains. The absence of normal sedimentation forces leads to reduced shear stress and enhanced cell aggregation, fostering the development of structurally complex biofilms with increased resistance to disinfectants and antimicrobial agents (Khalil *et al.*, 2020; Mora *et al.*, 2019). These “architectural biofilms” represent a critical challenge for spacecraft hygiene management, as they can colonize air filtration systems, water recycling units, and structural surfaces, potentially compromising both equipment functionality and crew safety (Checinska Sielaff *et al.*, 2019; Urbaniak *et al.*, 2020).

Beyond their risks, space-adapted microorganisms also present opportunities for biotechnological innovation and bio-regenerative life support systems. Engineered microbial consortia could be harnessed for waste recycling, oxygen regeneration, in situ resource utilization, and food production during deep-space missions (Berliner *et al.*, 2021; Verseux *et al.*, 2021). However, the dual-use nature of these microbes necessitates careful monitoring to prevent unintended pathogenic evolution and contamination of extraterrestrial environments, aligning with stringent planetary protection guidelines (Rummel & Conley, 2018; Yamaguchi *et al.*, 2019).

Despite growing research, critical gaps remain in understanding the integrated mechanisms that govern microbial survival and pathogenic evolution in low-Earth orbit and beyond. Specifically, the interplay between microgravity-induced physiological stress, genomic plasticity, and ecological competition within closed habitats is not yet fully elucidated. Addressing these gaps is essential to predict microbial risks, design robust sterilization strategies, and develop resilient life support ecosystems for future missions to the Moon, Mars, and deep-space habitats. Therefore, this review aims to synthesize recent advances (2016–2026) in space microbiology, focusing on microbial survival mechanisms, adaptive genomic responses, biofilm architecture, and pathogenic evolution under microgravity and radiation

stress. By integrating findings from spaceflight experiments and ground-based analog studies, this work provides a comprehensive framework for understanding how microorganisms act as “architects of their own survival” in the extreme environment of space and how these adaptations impact both astronaut health and the sustainability of long-duration space exploration.

### **1.1 Microbial Adaptation and Survival Dynamics in Spaceflight Environments**

Human space exploration has transitioned from short-duration missions to prolonged habitation in orbital platforms and prospective deep-space environments, intensifying the need to understand microbial behavior under extraterrestrial conditions. Spacecraft and orbital stations represent closed ecological systems where microorganisms are continuously introduced through crew activities, life-support systems, and transported materials. In microgravity, the absence of buoyancy-driven convection and sedimentation alters nutrient diffusion, fluid dynamics, and cell-to-surface interactions, thereby significantly modifying microbial growth kinetics, stress tolerance, and community structure (Huang *et al.*, 2018; Taylor, 2019). These environmental shifts promote unique adaptive responses, including enhanced biofilm formation, metabolic reprogramming, and increased resistance to environmental stressors such as radiation and oxidative damage (Mastroleo *et al.*, 2019; Khalil *et al.*, 2020).

Observations from long-term missions aboard the International Space Station have demonstrated that microbial populations are not only persistent but also dynamically evolving under spaceflight conditions. Studies report alterations in gene expression, mutation rates, and horizontal gene transfer events that collectively enhance microbial adaptability and survival (Beheshti *et al.*, 2018; Schwendner *et al.*, 2020). Opportunistic pathogens, including *Staphylococcus aureus* and *Pseudomonas aeruginosa*, have exhibited increased virulence traits and robust biofilm architectures in simulated and real microgravity environments, posing potential risks to immunocompromised crew members (Kim *et al.*, 2017; Mora *et al.*, 2019).

Furthermore, the integration of microbial systems into bio-regenerative life support technologies has expanded their functional importance in space missions. Engineered microbes are being explored for waste recycling, oxygen regeneration, and in situ resource utilization to support sustainable extraterrestrial habitats (Berliner *et al.*, 2021; Verseux *et al.*, 2021). However, the dual role of microorganisms—as both beneficial biotechnological tools and potential pathogenic threats—necessitates comprehensive investigation into their survival

strategies and evolutionary trajectories in low-Earth orbit and beyond. Thus, the broader context of this research lies at the intersection of space microbiology, astrobiology, planetary protection, and astronaut health management, emphasizing the need for systematic evaluation of microbial adaptive mechanisms under extreme extraterrestrial conditions.

## **1.2 Challenges of Predicting Microbial Evolution and Pathogenic Risks under Microgravity Conditions**

Despite significant advances in space microbiology, a critical challenge persists in predicting how microorganisms adapt and evolve under prolonged exposure to microgravity, ionizing radiation, and confined ecological systems. Current sterilization and microbial control protocols used in spacecraft are largely derived from terrestrial standards, which may be insufficient to address the emergence of “space-evolved” microbial phenotypes exhibiting increased biofilm formation, antimicrobial resistance, and altered virulence (Checinska Sielaff *et al.*, 2019; Urbaniak *et al.*, 2020). These adaptive changes could compromise crew health, contaminate life-support systems, and threaten mission sustainability during long-duration spaceflight and future planetary colonization.

Moreover, the complex interplay between microgravity-induced physiological stress, genomic plasticity, and ecological competition within closed habitats remains poorly understood. There is limited integrative knowledge on how these factors collectively drive pathogenic evolution and functional shifts in microbial communities over time. This gap hinders the development of predictive risk models and targeted mitigation strategies for microbial proliferation in extraterrestrial environments. Therefore, the central research problem addressed in this review is to critically assess the mechanisms underlying microbial survival, adaptation, and pathogenic evolution in low-Earth orbit and spaceflight analog conditions, and to evaluate their implications for astronaut health, spacecraft integrity, and future deep-space exploration.

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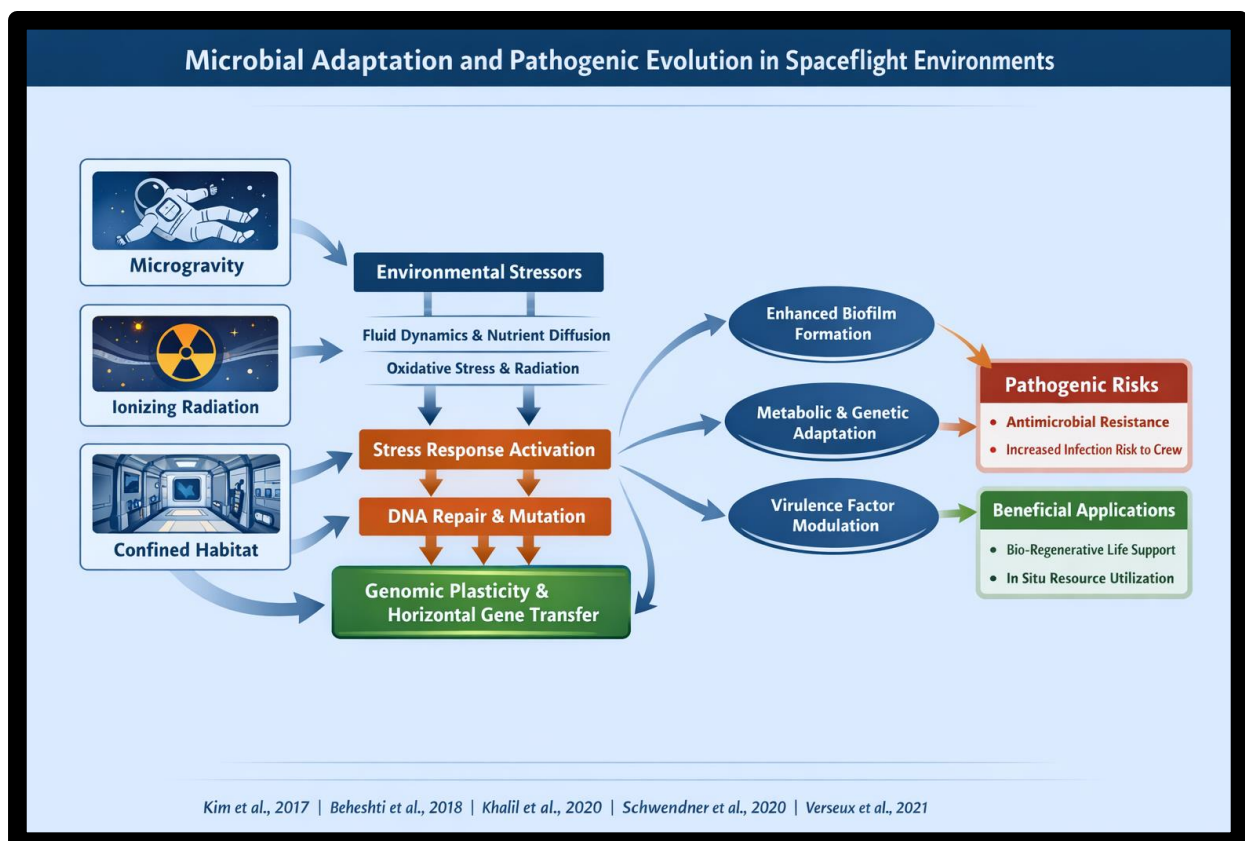
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## **1.3 Significance of the Study**

This study holds significant theoretical and practical importance in advancing the emerging field of space microbiology and astrobiology. Theoretically, it contributes to a deeper understanding of how extreme extraterrestrial stressors—such as microgravity, ionizing

radiation, and confined ecological systems—reshape microbial physiology, genomic plasticity, and evolutionary trajectories. By synthesizing recent findings, this review expands current conceptual frameworks on microbial adaptation, particularly regarding stress-response regulation, horizontal gene transfer, and biofilm architecture under non-terrestrial conditions (Beheshti *et al.*, 2018; Mastroleo *et al.*, 2019). Such insights are crucial for refining models of microbial evolution in closed habitats and for predicting long-term ecological dynamics during extended space missions.



**Figure 1. Mechanistic Schematic of Microbial Adaptation and Pathogenic Evolution under Spaceflight Conditions**

From a practical perspective, the study provides essential knowledge for safeguarding astronaut health and maintaining spacecraft environmental integrity. Space-adapted microbes with enhanced virulence, antimicrobial resistance, and biofilm-forming capacity may pose serious risks to life-support systems and crew immunity during long-duration missions aboard platforms like the International Space Station (Chęcinska Sielaff *et al.*, 2019; Urbaniak *et al.*, 2020). Understanding these adaptive mechanisms supports the development of improved

sterilization protocols, real-time microbial monitoring strategies, and biofilm-resistant materials tailored specifically for microgravity environments.

Additionally, this review highlights the dual-use potential of microorganisms in space biotechnology, including their roles in waste recycling, oxygen regeneration, and in situ resource utilization for sustainable extraterrestrial habitats (Berliner et al., 2021; Verseux et al., 2021). These applications align with ongoing initiatives by agencies such as NASA to integrate microbial systems into bio-regenerative life support frameworks. Therefore, the study not only advances theoretical knowledge of microbial survival in extreme environments but also provides actionable insights for mission planning, planetary protection policies, and the safe development of microbial-based technologies for future lunar and Martian exploration.

**Table 1. Key Studies on Microbial Adaptation and Pathogenic Evolution under Spaceflight Conditions (2016–2026)**

Microorganism / System	Experimental Context	Major Findings	Reference
<i>Pseudomonas aeruginosa</i>	Spaceflight experiment	Enhanced biofilm formation and altered gene regulation under microgravity	Kim et al., 2017
Mixed microbial systems	Spaceflight multi-omics	Global transcriptional and metabolic reprogramming in response to microgravity stress	Beheshti et al., 2018
Various bacterial species	Simulated microgravity	Increased virulence potential and stress-response activation	Huang et al., 2018
ISS surface microbiome	Orbital habitat monitoring	Persistent microbial communities with opportunistic pathogens and resistance traits on the International Space Station	Checinska Sielaff et al., 2019
Biofilm-forming bacteria	Microgravity biofilm assays	Reduced shear forces promote structurally complex and resistant biofilms	Mastroleo et al., 2019

Confined habitat microbiome	Spacecraft microbial ecology	Dynamic microbial adaptation and ecological interactions in closed systems	Mora et al., 2019
Pathogenic bacteria	Simulated microgravity	Physiological changes leading to increased virulence and stress tolerance	Khalil et al., 2020
ISS environmental isolates	Metagenomic resistance profiling	Detection of antimicrobial resistance genes in orbital habitats	Urbaniak et al., 2020
Mixed microbial communities	Long-duration mission analysis	Genomic plasticity and evolutionary risk in confined space ecosystems	Schwendner et al., 2020
Cyanobacteria-based systems	Life-support biotechnology	Potential use of microbes for oxygen regeneration and resource recycling in space habitats	Verseux et al., 2021

## 2. Integrated Theoretical Perspectives, Empirical Evidence, and Emerging Research Gaps in Space Microbial Adaptation and Pathogenic Evolution

Microorganisms have accompanied human space missions since the earliest launches, forming dynamic microbial ecosystems within confined spacecraft habitats. Over the past decade, extensive research has focused on understanding how microgravity, radiation, and closed-loop environmental systems influence microbial survival, physiology, and pathogenic potential. Collectively, these studies demonstrate that spaceflight conditions act as strong selective forces that reshape microbial community composition, enhance stress tolerance, and alter virulence-associated traits (Huang *et al.*, 2018; Taylor, 2019). Investigations conducted in orbital platforms such as the International Space Station have revealed persistent and evolving microbial populations capable of forming resilient biofilms and exhibiting genomic plasticity, emphasizing the need for comprehensive theoretical and empirical analyses (Checinska Sielaff *et al.*, 2019; Mora *et al.*, 2019).

The theoretical foundation of this research is rooted in the interdisciplinary domains of space microbiology, microbial stress adaptation theory, and evolutionary ecology. Stress adaptation theory proposes that exposure to extreme environmental stressors—such as microgravity and ionizing radiation—activates global regulatory networks in microorganisms, leading to altered gene expression, enhanced DNA repair mechanisms, and increased mutation rates that facilitate rapid adaptation (Beheshti *et al.*, 2018; Khalil *et al.*, 2020). These adaptive responses are further explained by the concept of genomic plasticity, wherein horizontal gene transfer, mobile genetic elements, and stress-induced mutagenesis collectively accelerate evolutionary processes in closed habitats (Schwendner *et al.*, 2020).

Additionally, biofilm theory provides a critical framework for understanding microbial persistence in microgravity. Reduced shear forces and altered fluid dynamics promote surface attachment and extracellular polymeric substance (EPS) production, leading to structurally complex biofilms that exhibit increased tolerance to antimicrobials and environmental stress (Mastroleo *et al.*, 2019). From an ecological perspective, the confined and resource-limited conditions of spacecraft resemble closed ecosystems, where microbial interactions, competition, and cooperation drive community evolution and functional adaptation. Integrating these theoretical perspectives enables a comprehensive understanding of how microorganisms act as self-organizing systems that optimize survival under extraterrestrial stress conditions.

Recent empirical studies have significantly advanced knowledge of microbial responses to spaceflight environments. Experiments involving *Pseudomonas aeruginosa* demonstrated enhanced biofilm formation and altered gene regulation under microgravity, suggesting that space conditions promote sessile lifestyles and increased resistance to disinfectants (Kim *et al.*, 2017). Similarly, investigations on *Staphylococcus aureus* and other opportunistic pathogens reported elevated virulence factor expression and changes in antibiotic susceptibility profiles after exposure to simulated microgravity (Taylor, 2019; Khalil *et al.*, 2020). These findings highlight the potential for spaceflight to modulate pathogenic behavior, thereby increasing infection risks during long-duration missions.

Metagenomic and culture-based surveys of spacecraft surfaces have provided further insights into microbial diversity and persistence. Checinska Sielaff *et al.* (2019) characterized viable bacterial and fungal communities on space station surfaces, revealing the presence of opportunistic pathogens and antimicrobial resistance genes. Urbaniak *et al.* (2020) further confirmed the distribution of resistance determinants within orbital habitats, emphasizing the

evolutionary consequences of prolonged exposure to confined environments. Complementary studies have shown that microgravity alters nutrient diffusion and cellular signaling, thereby influencing metabolic pathways and stress-response systems that contribute to enhanced survival and adaptability (Huang *et al.*, 2018; Mora *et al.*, 2019).

Beyond pathogenicity, previous research has also explored the beneficial applications of microorganisms in space biotechnology. Engineered microbial consortia have been proposed for waste recycling, oxygen regeneration, and production of essential biomolecules, supporting sustainable life-support systems for deep-space missions (Berliner *et al.*, 2021; Verseux *et al.*, 2021). While these studies demonstrate the utility of microbes for extraterrestrial sustainability, they also underline the necessity of balancing beneficial applications with biosafety and planetary protection considerations.

Despite extensive investigations, several critical gaps remain in the current body of knowledge. First, most studies focus on single-species experiments under short-term microgravity exposure, limiting our understanding of long-term evolutionary dynamics and interspecies interactions within complex microbial communities. Second, the combined effects of multiple spaceflight stressors—microgravity, radiation, and confinement—are often studied independently, resulting in fragmented insights into their synergistic impact on microbial physiology and virulence evolution (Schwendner *et al.*, 2020).

Furthermore, there is insufficient integration of omics-based surveillance, ecological modeling, and functional assays to predict the emergence of highly resilient or pathogenic “space-evolved” microbial strains. Existing sterilization and microbial control strategies are largely adapted from terrestrial standards, which may not adequately address biofilm-associated resistance and genomic adaptability observed in spaceflight conditions (Checinska Sielaff *et al.*, 2019; Urbaniak *et al.*, 2020). Consequently, a comprehensive synthesis of recent multidisciplinary findings is required to bridge these gaps and develop predictive frameworks for microbial risk assessment in long-duration missions and future planetary habitats.

### **3. Conclusion**

The present review synthesizes recent advances in space microbiology to evaluate how microorganisms adapt, survive, and evolve under the extreme conditions of low-Earth orbit and beyond. Evidence from orbital missions and ground-based simulations demonstrates that

microgravity, radiation exposure, and confined ecological systems collectively drive significant physiological and genomic alterations in microbial populations. These changes include enhanced biofilm formation, increased stress tolerance, accelerated mutation rates, and the emergence of altered virulence and antimicrobial resistance profiles. Such adaptive traits highlight the dual nature of microorganisms in space habitats—as both potential threats to astronaut health and indispensable components of bio-regenerative life support systems. By integrating findings across molecular, ecological, and applied domains, this review emphasizes that microorganisms function as dynamic “architects of survival,” continuously reshaping their biological strategies in response to extraterrestrial environmental pressures. Consequently, comprehensive microbial monitoring and targeted mitigation strategies are essential for ensuring the safety, sustainability, and success of long-duration human space exploration.

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**BIOCHEMICAL CHARACTERIZATION OF SOIL FLORA AND THEIR AMYLASE ACTIVITY FROM MOUNTAINOUS REGIONS OF JUNAGADH**

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**Abstract**

Understanding microbial diversity, enzyme production, and their ecological significance in soil ecosystems depends on the biochemical characterization of soil flora and their amylase activity from mountainous locations. To extract and identify microbiological communities, such as bacteria, fungus, and actinomycetes, soil samples were gathered from multiple locations within a mountainous region. To ascertain the isolates' functional abilities, biochemical tests were conducted, such as morphological characterization and enzyme production assays. The microbial capacity for starch breakdown was demonstrated by quantitative tests and starch hydrolysis, which were particularly used to measure amylase activity. To maximize and comprehend the parameters that support amylase production, environmental elements like pH, temperature, and soil characteristics were investigated. The findings showed that the microbial population was diversified and had a high level of amylase activity. The synthesis of enzymes varied depending on the environment.

In addition to providing insights into the function of soil flora in nutrient cycling and soil health, these studies demonstrate the potential of microorganisms from hilly soils for biotechnological uses, such as in food processing and bio-fuel production.

**Keywords** – Biochemical Characterization, Soil flora, Amylase activity, Starch hydrolysis, Enzyme Production, Soil properties.

**Introduction:**

Soil is a dynamic and complex ecosystem which includes diverse microorganism including bacteria, fungi, actinomycetes and archaea. All these microorganism plays an important role in maintaining soil health and fertility by performing essential bio-geochemical processes

(decomposition, Nutrient cycle). Some microorganism produce amylase, which hold significant importance due to its role in the hydrolysis of starch into simpler sugar which can be used by plants as a energy source. The activity of amylase production is influenced by several factors, including soil pH, organic carbon content moisture and microbial diversity.

The mountainous region of Junagadh, located in the Saurashtra peninsula of Gujarat ,India is characterized by its unique topography, climate conditions and rich biodiversity. This region consist diversity microbes that contribute in soil fertility and ecosystem stability. In this peninsula region limited research has been conducted to explore the biochemical characteristics to explore the biochemical characteristics of its soil flora and their enzymatic potential, particularly amylase activity. In recent some years, amylase producing microbes got attention due to their biotechnological applications in industrial such as food, textiles, paper and bio-fuel production. Additionally, the amylase plays a vital role in soil health by facilitating the decomposition of organic matter and enhancing nutrient availability for plants. However amylase activity remains under explored, particularly in the context of Junagadh unique ecosystem. This study aims to bridge this knowledge gap by characterizing the biochemical properties of soil flora and evaluation their amylase activity in the mountainous region of Junagadh.

Diversity of Microbes in Soil Environments- Protozoa, Actinomycetes, Fungus, Bacteria, and Archaea are all part of the microbial communities found in soil. The most prevalent are usually bacteria, which aid in vital functions like phosphorus solubilization, organic matter breakdown, and nitrogen fixation (Fierer & Jackson, 2006). A subgroup of Gram-positive bacteria known as actinomycetes is well-known for its ability to break down resistant organic materials and produce bio-active substances, such as antibiotics (Goodfellow & Williams, 1983). Both saprophytic and mycorrhizal fungi are crucial for the cycling of nutrients and the stimulation of plant growth.

Because of their elevation, temperature variations, and diverse vegetation, mountainous areas like Junagadh are renowned for their distinctive soil characteristics. According to Singh et al. (2010), these elements lead to unique microbial communities that might contain new species and genetic characteristics.

As a living system, soil: Both macro and microflora (fungi, bacteria, algae, and actinomycetes) and microfauna (protozoa, nematodes, earthworms, moles, etc.) are found in soil (FAO, 200). There are billions of living organisms per gram of soil, which is a very high density. Generally

speaking, the density of organisms is lower in cultivated soil than in uncultivated land, and the population declines as soil acidity increases. Because it receives more oxygen and nutrients, the top soil layer has a higher concentration of microorganisms. There are fewer creatures in the lower layer, or subsoil, because it is devoid of oxygen and nutrients (FAO 2000).

### **Methodology:**

#### **Sampling:**

Soil samples were collected from various mountainous regions of Bhavnath, Junagadh, Gujarat, India. It was collected using sterile and disposable gloves in sterile sampling plastic bags. Samples were transferred into sterile flask and standard methods or tests were performed for the isolation of bacteria. Significant ecological and geological value may be found in soil samples taken from the Jatashankar region of Junagadh, which is situated in the Girnar Hills , Samples of soil from Junagadh's Lal Dhori region provide important information about the region's distinct ecology and geomorphology. Lal Dhori, which is known for its crimson soil, gets its name from the lateritic soil composition, which is rich in iron.

#### **Requirements :**

N-agar

Potato dextrose agar

Mannitol agar Starch agar

#### **Screening for amylase producing microorganism :**

Amylase are enzymes that hydrolyze starch into simpler sugars, playing a crucial role in various industrial applications, including food processing, fermentation, textiles, and pharmaceuticals. Screening for amylase-producing microorganisms is a fundamental step in enzyme biotechnology. One of the most efficient and widely used screening methods is the starch agar plate assay, which allows for the rapid identification of amylase producers based on starch hydrolysis.

Starch agar serves as a selective medium, where microbial colonies capable of producing amylase break down starch into maltose and dextrin. After incubation, the addition of Gram's iodine solution helps visualize the enzymatic activity—iodine forms a blue-black complex with starch, while areas where starch is hydrolyzed remain clear, indicating amylase production. The starch agar plate method is based on the principle of starch hydrolysis by amylase-producing

microorganisms. Amylase enzymes break down starch, a polysaccharide, into simpler sugars like maltose, glucose, and dextrin, which microorganisms can utilize.

When microbial cultures are grown on starch agar, only amylase-producing strains hydrolyze the starch in the medium. After incubation, the plate is flooded with Gram's iodine solution, which binds to intact starch, forming a blue-black complex, while areas where starch has been broken down remain clear. The presence of a clear zone around the colony indicates amylase production, with the size of the zone correlating to enzymatic activity.

### **Identification of amylase producing bacterial strains:**

The amylase producing bacterial strains can be identified by microscopic observation, colony morphology characteristics, biochemical characterization.

### **Colony morphological characterization:**

Colony morphology can provide characterization of bacterial isolates by their colour, size, shape, pigmentation etc.

### **Microscopic observation:**

Microscopic examination reveals the structure of bacterial cell. The most common method used in microscopic examination is Gram's staining. Gram staining is a crucial laboratory technique for differentiating bacterial species into two broad categories, Gram-positive and Gram-negative, based on the composition and structure of their cell walls. Gram-positive bacteria appear purple under the microscope due to the retained crystal violet, while Gram-negative bacteria appear pink or red due to the safranin counter staining. This technique provides valuable insight into bacterial identification and classification.

### **Biochemical characterization:**

#### **Methyl red [MR] Test:**

MR test is used to determine the ability of an organism to produce and maintain stable acid end products from glucose fermentation.

#### **Voges Proskauer [VP] Test:**

VP test is a biochemical test that detects the ability of bacteria to metabolize the pyruvate into a neutral intermediate product called 'acetylmethylcarbinol' or 'acetoin'.

#### **Indole Test:**

It is a biochemical test used to determine whether a microorganism can produce indole from the amino acid tryptophan.

### **Sugar Fermentation Test (Dextrose, Fructose and Lactose):**

This test is used to determine whether a microbe can ferment specific carbohydrate and produce acid or gas as an end product. The sugar fermentation test is based on the ability of microorganisms to metabolize specific carbohydrates (dextrose, fructose, lactose) through glycolysis and fermentation pathways. During fermentation, acid and/or gas are produced as metabolic end products, which are detected using a pH indicator (phenol red) and a Durham tube.

### **Results and Discussions:**

#### **1) Screening of amylase producing microorganisms:**

Screening for amylase-producing microorganisms is a fundamental step in enzyme biotechnology. One of the most efficient and widely used screening methods is the starch agar plate assay, which allows for the rapid identification of amylase producers based on starch hydrolysis. The starch agar plate method is based on the idea that amylase-producing microorganisms hydrolyse starch, a polysaccharide, into simpler sugars that microorganisms can use, such as maltose, glucose, and dextrin. Prepare starch agar plates and potato dextrose agar plates and allow it to solidify. Using a sterile loop, make a scratch onto the starch agar and potato dextrose surface.

Incubate the plates with isolated colonies at an appropriate temperature i.e.; 35 - 37°C for 24 – 48 hrs. After incubation, flood the plate with gram's iodine solution and wait for 1-2 mins. Observe the clear zone. A clear zone around the bacterial growth indicates amylase production, as the starch has been hydrolysed by the enzyme. If iodine stains the starch blue – black, it indicates positive test.



Image 1

Image 2

Image 3

Image 1 - Iodine test of sample G5 on starch agar plate

Image 2 - Iodine test of sample L7 on starch agar plate

Image 3 - Iodine test of sample J3 on starch agar plate



Image 4

Image 5

Image 6

Image 4 - Iodine test of sample G8 on potato dextrose agar

Image 5 - Iodine test of sample L10 on potato dextrose agar

Image 6 - Iodine test of sample J5 on potato dextrose agar

## 2) Estimation of Amylase Activity (by DNSA Method):

The 3,5-dinitrosalicylic acid (DNSA) assay is a widely used method for estimating amylase activity by measuring the amount of reducing sugars (e.g., maltose and glucose) released during starch hydrolysis. The method is based on the reaction between DNSA reagent and reducing sugars, which results in the formation of a red-brown complex that can be quantified spectrophotometrically at 540 nm.

### Proedure :

Take 1 ml of starch solution (0.5,1,2,3,4 and 5% concentration) in each of the 5-test tube except control test tube.

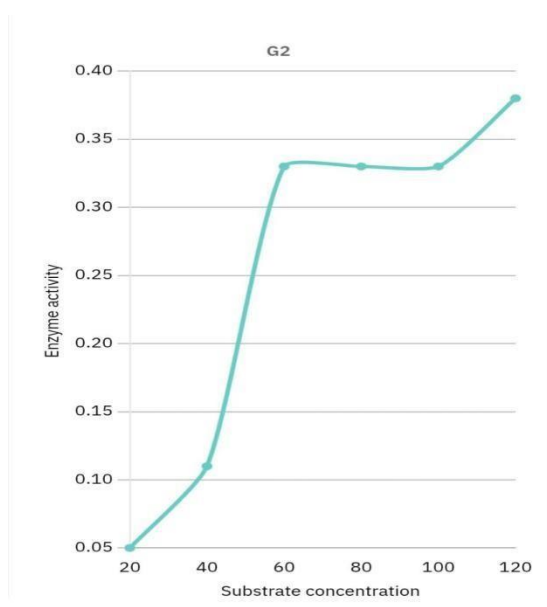
Add 0.5 ml of enzyme extract (amylase sample). Incubate at the optimal temperature (37°C) for 10 mins.

Add 2 N NaOH (0.5 ml) in each test tube.

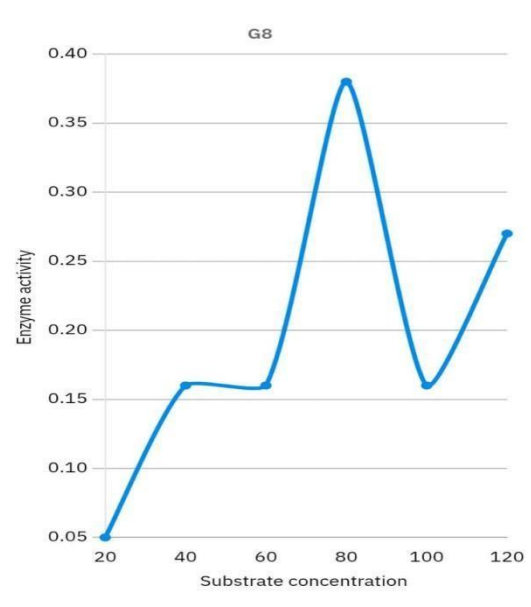
Add DNSA reagent (1ml) in each test tube. Incubate it at 100°C in hot water bath for 5 mins.

Add 9 ml of D/W in each test tube.

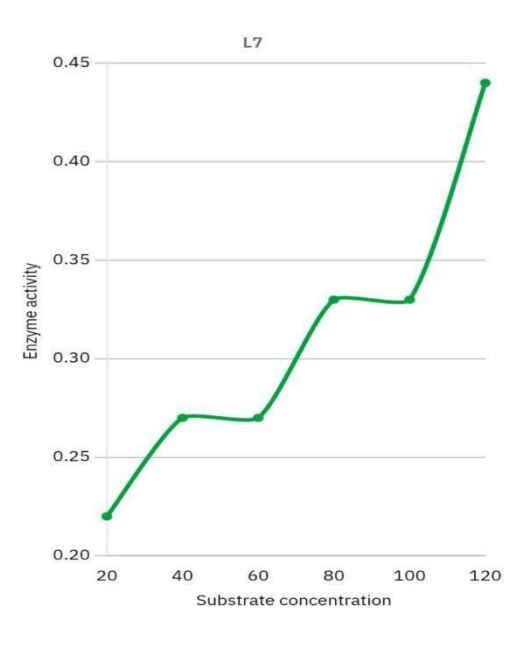
Measure absorbance at 540 nm using a spectrophotometer.



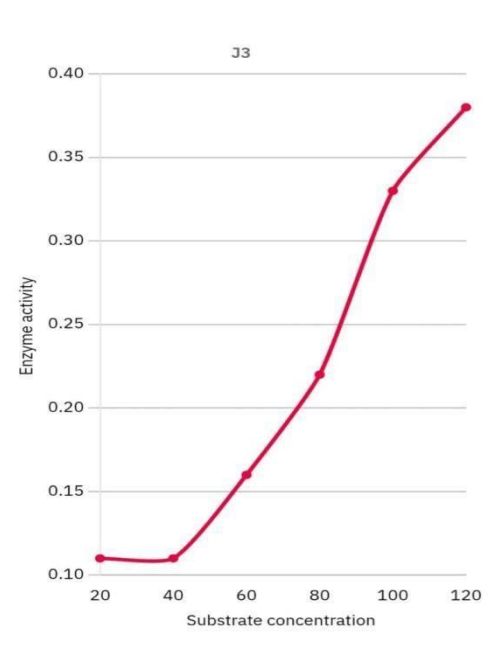
Graph 1 - Amylase activity on G2 soil sample



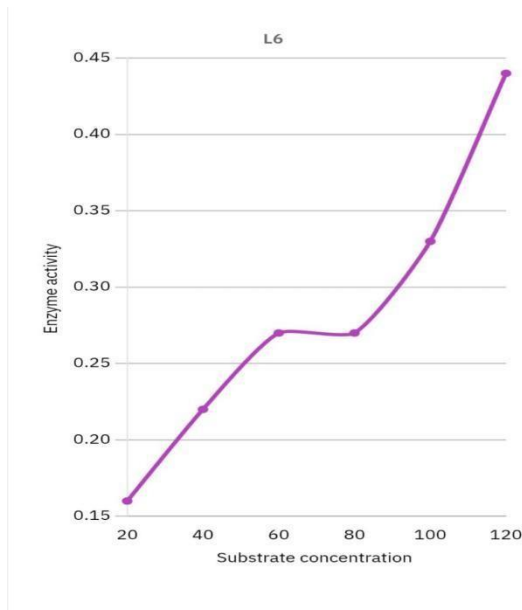
Graph 2 - Amylase activity on G8 soil



Graph 3 - Amylase activity on L7 soil sample



Graph 4 - Amylase activity on J3 soil



Graph 5 - Amylase activity on L6 soil sample

### Conclusion:

In conclusion, the tests conducted on the organism, including MR-VP, indole, sugar fermentation (dextrose, fructose, lactose), antibiotic resistance (ampicillin, streptomycin, penicillin), and amylase production screening, offered valuable insights into its biochemical and antimicrobial properties. The MR-VP test provided information about the organism's fermentation patterns, with the MR test indicating mixed-acid fermentation and the VP test showing potential acetoin production. The indole test confirmed the organism's ability to degrade tryptophan, suggesting the presence of tryptophanase. The sugar fermentation tests demonstrated its ability to ferment different sugars, which is important for understanding its metabolic flexibility. The antibiotic resistance tests highlighted the organism's resistance to commonly used antibiotics, aiding in its potential therapeutic applications. Furthermore, the screening for amylase production on starch agar confirmed the organism's ability to hydrolyze starch, and the estimation of amylase activity quantified its potential for industrial enzyme production. Together, these findings offer a comprehensive profile of the organism's metabolic, antimicrobial, and industrial capabilities, suggesting potential applications in various industries, including biotechnology and pharmaceuticals. Further investigations into the organism's genetic and enzymatic pathways could reveal new opportunities for harnessing its properties.

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