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ISTE SECTION FACULTY CONVENTION 2025 ON RECENT TRENDS IN SCIENCE, TECHNOLOGY & MANAGEMENT

BIHAR & JHARKHAND SECTION

On

31st October - 1st November 2025

In Association with :

Jharkhand University of Technology
Ranchi, Jharkhand

Organised by:

GGSESTC
GURU GOBIND SINGH EDUCATIONAL SOCIETY'S TECHNICAL CAMPUS
GGSESTC, KANDRA (V),
CHAS, BOKARO,
JHARKHAND - 827013

Host :

ISTE
(Bihar & Jharkhand Section)

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Name of Publisher : **Guru Gobind Singh Educational Society's Technical Campus**
Name of Editor : **Dr. Priyadarshi Jaruhar**

GGSESTC

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Last date of Registration	1st October , 2025

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Proceedings

of

ISTE Faculty Convention

(Bihar & Jharkhand Section)

Theme: Recent Trends in Science, Technology & Management

31st October – 1st November 2025

Organized by	**In Association with**	**Host**
Guru Gobind Singh Educational Society's Technical Campus Kandra, Chas, Bokaro, Jharkhand-827013	Jharkhand University of Technology, Namkum, Ranchi, Pin-834010, Jharkhand, India	Indian Society for Technical Education (ISTE) (Bihar & Jharkhand Section)

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भारतीय तकनीकी शिक्षा संस्था

INDIAN SOCIETY FOR TECHNICAL EDUCATION

(Under the Societies' Registration Act XXI of 1860)

Dr. Pratapsinh K Desai
President, ISTE

Date-27-10-2025

It is an honor to be the ISTE Faculty State-level Convention, Bihar-Jharkhand Section, hosted by Guru Gobind Singh Educational Society's Technical Campus. This convention stands as a testament to the commitment of our technical education community to promote innovation, collaboration, and academic excellence. The event's focus on recent trends in science, technology, and management highlights the importance of technical advancements in shaping a sustainable and equitable society.

ISTE continues to provide invaluable opportunities for educators, researchers, and students to engage with the forefront of technological progress. By emphasizing topics like e-learning, renewable energy, cyber security, and social entrepreneurship, this convention encourages critical dialogue and original research for enduring social impact. The participation of distinguished academicians, industry partners, and young minds fosters an environment rich in ideas and diverse perspectives.

May this convention inspire all participants to pursue knowledge with dedication and creativity, leveraging science and technology for the greater good. I extend my best wishes for fruitful discussions, meaningful collaborations, and innovations that will help transform challenges into opportunities for the nation's progress.

Dr. Pratapsinh K Desai
President, ISTE

Message

It gives me immense pleasure to learn that the **ISTE Faculty Convention 2025** is being organized at **Guru Gobind Singh Educational Society's Technical Campus (GGSESTC), Bokaro**, during **October 31 – November 1, 2025**, on the theme **"Recent Trends in Science, Technology and Management."**

The chosen theme is both timely and forward-looking, reflecting the evolving global landscape where the integration of science, technology, and management is essential for sustainable growth and innovation. The accelerating advancements in Artificial Intelligence, Data Analytics, Green Energy, Advanced Manufacturing, and Digital Transformation are reshaping education, research, and industry alike.

Events like this convention serve as powerful platforms for academicians, researchers, and industry professionals to deliberate upon emerging trends, share innovative practices, and explore collaborative pathways. Such engagements not only strengthen the academic ecosystem but also inspire our faculty to inculcate a spirit of curiosity, creativity, and critical thinking among students—qualities essential for building a self-reliant and globally competitive India.

At **Jharkhand University of Technology (JUT), Ranchi**, we are committed to promoting excellence in technical education, research, and innovation across our affiliated institutions. I am confident that the insights and outcomes emerging from this convention will enrich our collective mission of nurturing future-ready technocrats, managers, and innovators.

I extend my heartfelt congratulations to the management, faculty, and organizing committee of **GGSESTC, Bokaro**, and to all participating members of **ISTE** for their dedicated efforts. I wish the convention grand success and hope it becomes a source of inspiration for new ideas and impactful collaborations.

Best wishes for a productive and enlightening convention!

DK Singh

(Prof. DK Singh)
Vice-Chancellor,
Jharkhand University of Technology, Ranchi, Jharkhand.

Message

Shri Tarsem Singh
President, GGES

It is a matter of great pride and pleasure to be part of the **ISTE Section Faculty Convention 2025** on the theme *"Recent Trends in Science, Technology, and Management."* Such academic gatherings play a vital role in fostering innovation, knowledge sharing, and interdisciplinary collaboration among educators, researchers, and professionals.

The rapid developments in science and technology, coupled with the evolving landscape of management, call for a collective effort to integrate new ideas and practical approaches in teaching and research. I believe this convention will provide an excellent platform for exchanging insights and promoting professional excellence in higher education.

I extend my warm congratulations to the organizers, delegates, and participants for their commitment and enthusiasm in making this event a success. May the deliberations and outcomes of this convention contribute significantly to academic advancement and societal development.

With best wishes for a successful and inspiring convention.

— Shri Tarsem Singh
President, GGES Chief Patron

Message

It is a matter of great satisfaction and pride to note that **Guru Gobind Singh Educational Society's Technical Campus (GGSESTC), Bokaro** is hosting the **ISTE Section Faculty Convention 2025** on the theme ***"Recent Trends in Science, Technology, and Management".*** This landmark event marks a significant step toward creating a vibrant academic and professional community that fosters innovation, collaboration, and excellence among educators and researchers.

The convention provides a valuable platform for faculty members to share their experiences, explore emerging ideas, and exchange knowledge that can inspire transformative teaching and research practices. In an era of rapid technological advancement, such initiatives are vital to equipping our educators with the skills and perspectives needed to guide future generations toward meaningful innovation.

I wholeheartedly appreciate the organizing committee for their exceptional efforts in planning and executing this convention. Your contributions to the field are essential, and I am confident that our collective efforts will lead to significant progress and innovation in education. Such platforms not only strengthen the academic and research ecosystem but also inspire educators to adopt forward-looking pedagogical approaches that align with the demands of a knowledge-driven society.

I extend my best wishes to the Director of GGSESTC, Faculties, Researchers and Educators for the grand success of this convention. May this faculty convention of the section become a milestone in strengthening the ISTE fraternity and in promoting a culture of continuous learning and progress across Bihar and Jharkhand.

Prof. (Dr.) M. K. Jha
Principal, M.I.T. Muzaffarpur
Chairperson, ISTE Section Bihar & Jharkhand

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INDIAN SOCIETY FOR TECHNICAL EDUCATION
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ISTE

Dr. S M Ali
Executive Secretary, ISTE

Date-27-10-2025

It is a matter of great pleasure to be part of the *ISTE Faculty Convention 2025* on "Recent Trends in Science, Technology & Management," organized by Guru Gobind Singh Educational Society's Technical Campus, Bokaro, in association with ISTE (Bihar & Jharkhand Section). This convention provides a valuable platform for academicians, researchers, and professionals to exchange innovative ideas and explore new dimensions in education, research, and industry collaboration. The theme reflects the urgent need to integrate emerging technologies with effective management practices for sustainable development. I am confident that the deliberations during this convention will inspire new perspectives, foster multidisciplinary collaboration, and strengthen the spirit of innovation among participants. I extend my best wishes to the organizers, participants, and all stakeholders for the grand success of this convention and for their continued contribution to the advancement of science and technology in our nation.

Dr. S M Ali
Executive Secretary, ISTE

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Message

It is heartening to learn that the ISTE Faculty Convention 2025 (Bihar & Jharkhand Section) is being organized on *"Recent Trends in Science, Technology & Management"* at Guru Gobind Singh Educational Society's Technical Campus (GGSESTC), Bokaro, during 31st October and 1st November 2025, and that the event has attracted research papers and nominations for the ISTE Section and Best Faculty Awards 2025 from esteemed institutions including IIT(ISM), NIT, CIT Ranchi, RVS Jamshedpur, and various Government Engineering and Polytechnic Colleges of Bihar and Jharkhand, reflecting the vibrant academic ecosystem of this region.

The Indian Society for Technical Education (ISTE) has played a pivotal role in shaping the quality of technical education in India through its nationwide faculty and student chapters, professional development programmes, and its relentless emphasis on pedagogical innovation. Faculty conventions like this one serve as vital platforms for knowledge exchange, interdisciplinary dialogue, and recognition of excellence in teaching, research, and institutional development.

It is encouraging to witness institutions such as GGSESTC—accredited by NAAC and steadily building its legacy of academic excellence—hosting this convention to advance the national vision of quality and inclusive education, while demonstrating strong commitment towards fostering collaborative academic initiatives that nurture a culture of innovation, research orientation, and professional ethics among educators.

I extend my sincere congratulations to GGSESTC, ISTE, the participating faculty members, and all contributors to the convention proceedings. May this event inspire new ideas, fruitful collaborations, and a collective commitment to advancing science, technology, and management education for sustainable and equitable growth.

Nikhil Kant

(Dr. Nikhil Kant)
Deputy Director, AICTE
Min. of Education, Govt. of India

Message

It gives me immense pleasure to know that the ISTE Faculty Section Convention 2025 is being organized on 31st October – 01st November 2025, and that a special magazine is being published to mark this academic event. I extend my warm greetings and heartfelt congratulations to the organizers, contributors, and participants for their dedicated efforts in promoting the cause of technical education and innovation.

The Indian Society for Technical Education (ISTE) has always played a vital role in enhancing the quality of engineering education by encouraging faculty members to engage in continuous learning, research, and knowledge sharing. The forthcoming convention, with the impressive participation of educators from reputed institutions such as IIT (ISM) Dhanbad, NIT, RVS Jamshedpur, CIT Ranchi, and various Government Engineering and Polytechnic Colleges of Bihar, truly reflects the vibrant academic spirit of our region.

The receipt of 33 research papers and 21 applications for the ISTE Section Best Faculty Award 2025 demonstrates the growing enthusiasm and professional commitment among teachers to contribute meaningfully to the field of technical education. Such initiatives provide a wonderful platform for faculty members to present their innovative ideas, exchange experiences, and explore new horizons of learning.

The publication of the convention magazine is a commendable effort to capture and preserve the essence of this intellectual endeavor. It will serve as an inspiring document for educators, researchers, and students alike, highlighting the ongoing advancements and academic achievements within our fraternity.

I firmly believe that knowledge sharing through such conventions and publications not only enriches the teaching community but also contributes significantly to nation-building by strengthening our technical foundation. Let this convention become a source of inspiration for all educators to pursue excellence, integrity, and innovation in their respective fields.

On behalf of Guru Gobind Singh Educational Society I convey my best wishes to the ISTE Faculty Section, the organizing committee, and all contributors for the grand success of the convention and the meaningful publication of this magazine. May this event continue to ignite the spirit of learning, collaboration, and academic excellence in the years to come.

With warm regards and best wishes.

Surendra Pal Singh
Secretary
Guru Gobind Singh Educational Society

Message

It is with immense praise and profound appreciation that I herald the arrival of the ISTE Section Faculty Convention 2025 on "*Recent Trends in Science, Technology & Management*". This significant event, a joint effort by the Indian Society for Technical Education (ISTE) Bihar & Jharkhand Section and Jharkhand University of Technology, Ranchi, and organized by Guru Gobind Singh Educational Society's Technical Campus (GGSESTC), Bokaro, marks a pivotal moment for academic and industrial collaboration in this part of eastern India duly supported by industry leaders MECON, BSL, Vedanta, ONGC.

We extend our sincere congratulations to the entire team at GGSESTC, Bokaro, an institution accredited by NAAC, for taking the initiative to host this convention. GGSESTC's commitment to fostering a platform for exploring the latest advancements in science and technology is truly commendable. This dedication aligns perfectly with the spirit of ISTE, a national, professional, non-profit society that has been a bedrock for technological education since 1968.

I particularly appreciate the organizing committee, the ISTE Member Committee, and the Technical Committee, led by the Convenor, Dr. Priyadarshi Jaruhar, Director, GGSESTC, Bokaro, and the Organizing Secretaries, Dr. Manojit De and Prof. Goutam Kumar. Your tireless efforts in bringing together distinguished Chief Patrons, Patrons, and a National Advisory Committee, including Directors Prof. Sukumar Mishra and Prof. Goutam Suthradhar from premier institutes like IIT Dhanbad and NIT Jamshedpur, reflect a remarkable vision for educational excellence.

This convention is more than just a gathering; it's a vital opportunity to delve into technical innovations that drive social reforms, with topics ranging from Smart Cities to Renewable Energy Systems and Recent Developments in AI, ML & IOT.

By facilitating networking and collaboration among young minds and encouraging discussions on addressing global challenges, you are directly shaping a more equitable and inclusive society.

I, offer our best wishes the management body of GGSESTC, Bokaro including Sri Tarsem Singh and Sri S.P Singh for a resounding success for the ISTE Section Faculty Convention 2025. May the discussions be insightful, the collaborations fruitful, and the innovations showcased propel us all toward a brighter future in science, technology, and management.

Prof (Dr.) Sanjay,
Professor & Head Mechanical Engineering,
National Institute of Technology, Jamshedpur

Message

On behalf of the organising committee of ISTE Faculty Convention under ISTE Bihar & Jharkhand Section on **"Recent Trends in Science, Technology, and Management"** (an initiative of IQAC, GGSESTC, Bokaro) - I have great pleasure in welcoming all the delegates to the Convention during 31st October - 1st November, 2025 at Shri Guru Tegh Bahadur Auditorium, GGSESTC, Kandra, Bokaro.

I am thankful to Hon'ble President ISTE, New Delhi, Dr. Pratapsinh Kakasaheb Desai; Hon'ble Vice Chancellor, JUT Ranchi, Prof. (Dr.) D K Singh; Chief partons, ISTE, Dr S. M. Ali; ISTE Chairman (Bihar & Jharkhand Section) & Principal, MIT Muzaffarpur, Bihar partons Prof. (Dr.) M K Jha, who have given the required permission and sanction for organising this convention.

I take this opportunity to express my sincere gratitude to the **ISTE Bihar–Jharkhand Section**, our **Chief Patron**, and all **collaborating institutions** for their constant support and encouragement. I also appreciate the dedicated efforts of the organizing team, faculty members, and student volunteers of **Guru Gobind Singh Educational Society's Technical Campus, Bokaro**, whose commitment and teamwork have made this event possible.

We are proud to announce that the college has been awarded **NAAC B++ accreditation**, reflecting our commitment to quality education. The successful organization of the **ATAL FDP**, **ISTE Students' and Faculty Conventions**, and various national-level programs has brought great recognition to our institution.

It gives me immense pleasure to share that Guru Gobind Singh Educational Society's Technical Campus, Bokaro, has continued its remarkable journey of growth and excellence. We have achieved over 800 registrations and more than 700 new admissions this year. Our students have secured more than 70% placements in reputed organizations.

I acknowledge the unconditional support and encouragement given by the President of GGES Sri Tarsem Singh, and Honorary Secretary of GGES Shri S. P Singh in organizing this ISTE Section Faculty Convention, 2025. I would like to express my heartfelt thanks to Sponsorship for their support. It has been a team work and as a team I appreciate IQAC Coordinator, Organizing Secretary, all coordinators, all HODs, faculty members and non-teaching staff members for giving their best to any task taken up at any given point of time. I congratulate Best Teacher awarded from this platform. A warm and heartfelt thanks to Chief Guest, Keynote address, Plenary session chair, Panelist, Delegates, Author, co-author, participants and last but not the least my dearest students.

Dr. Priyadarshi Jaruhar
Director, GGSESTC Bokaro
Convenor, ISTE Section Faculty Convention 2025

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12	Shri Ravi Kumar Burman, Assistant Professor (Guest Faculty) Data Sc, Jharkhand University of Technology, Ranchi, Jharkhand

13	Shri Santosh Kumar Panday, Lecturer, Mining, (Need based) Govt. Polytechnic, Nirsa, Dhanbad, (Jharkhand)
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31.10.2025

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Principal, MIT, Muzaffarpur, Chairman,
ISTE, Bihar & Jharkhand section

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Implementation of modern recruitment and selection strategies in Human Resource Management

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Abstract

This research article based on actual recruitment process, held in mid-2025 for the recruitment of eligible and competent faculty for GGSESTC, Bokaro. This article discusses the effective, efficient and impactful recruitment process in an era of competition. It has reported the impact on recruited employee quality, the innovative methodology employed includes use of social and online platform for data collection, software, which enhanced the efficiency and candidate reach within a forecasted budget and time frame. It has achieved its set objectives through implementation of modern recruitment and selection strategies.

Key words: Recruitment, Selection, Modern Human Resource Strategies, social media, ATS (Applicant Tracking System), Innovative methodologies

Introduction

GGSESTC is a leading and renowned residential engineering and management college of India with an 840-intake capacity. Established in 2011, a NAAC Bengaluru accredited with a decent grade, aims to provide world class education in almost rural area at a very affordable cost. It has excellent student and staff diversity index in terms of religion, linguistic, regional, talent, gender and economic.

The college seen 40% growth in terms of students' enrolments. Happiness index is also very high among students and faculty.

The organisation aims to create a work force of highly educated, qualified, and motivated people to enhance its academic, research and administrative capabilities. In this context the strategic human resource management recognises the importance of combining its HR practices with its assigned objective. The college employs various important strategies to attract select, develop and retain talents of its field, which are necessary for sustainable growth, and competitive advantages in the fast-changing education market.

GGSESTC has used technology, talent and training in its recruitment talent management processes. Digital platforms for recruitment and assistance of SHRM qualified professionals as well as intern have been shown to improve efficiency and expanded its talent pool. Simultaneously by promoting a culture of collaboration, innovation, core competency and social responsibility, GGSESTC not only enhances employee engagement but also strengthens its brand reputation in the field of education.

Theoretical Review

The recruitment process is not merely about filling vacancies, it involves strategic approach that in the line with goal, objectives and culture. The effectiveness of recruitment strategies and modern selection process can significantly influence organisational performance, employee's retention and overall workplace satisfaction. By emphasis on the quality of hire, organisation, GGSESTC could ensure that they have selected candidates who not only possess the necessary skills but also suitably fit within the organisational culture. The image and reputation of an organisation as an employer, significantly improved its ability to attract a larger pool of qualified candidates, hence enhancing the recruitment outcome. Employer branding and recruitment strategies influence significantly candidates' perceptions and decisions during the job search process. This is particularly relevant in present scenario of competitive market, where candidates often evaluate potential employers based on their ethical stance and corporate social responsibility initiatives.

Methodology

The methodology section of this paper outline process of data collection through interviews and interactions with candidates of all levels for teaching positions. This qualitative approach was chosen to get in depth insights, views and information in to the effective recruitment strategies employed by the organisation and to understand the practical implications of these strategies in the context of modern human resources management.

- Data Collection Process: The data was collected with the identification of suitable candidates after going through theirs CVs, later through online interview and offline interactions during on-going selection process. The interview lasted approximately one hour. Intern student also shared her experience during the shortlisting and application tracking.

- Data analysis: Thematic analysis was employed to identify key themes and patterns within the data. This involved coding the transcript and categorising responses into relevant themes such as recruitment strategies, candidate selection criteria, candidate's preferences and the impact of organisational culture through recruitment advertisement.
- Process Flow Diagram:To visually represent the data collection process, a flow diagram was created. This diagram illustrates the steps involved in the methodology, from the initial requirements of manpower/workforce to placement. Below is a simplified representation of the process.

Figure 1. Process Flow Diagram

Results & Discussion

This section presents the results of the interview conducted with applicant candidates and finally selected candidates, focusing on the effective recruitment strategies employed.

- Interview and interaction question and responses

3. *What are the factors for applying job in this organisation? What was the main attraction?*

Response: The majority of interviewee stated that the GGSESTC has utilised multi-faceted approach towards recruitment and selection process, which includes conventional print media, advertisement, online job postings, social media outreach and employee referrals. They emphasised the importance of employer. The branding is specially being promoted actively through social media platform viz. website, Facebook, Instagram, LinkedIn YouTube, X handle, WhatsApp group.

4. *What role does technology play in your recruitment process?*
   Response: ATS (Applicant Tracking System) assisted in streamlining our recruitment process. It helps us manage applications efficiently and ensures that we do not miss out on qualified candidates.
5. *How does organisation address diversity and inclusion in recruitment?*
   Response: Inclusive and human centric approach and culture attracted talent pan India.
6. *What challenges you have understood during this recruitment and selection process ? and how you cope up with this challenge?*
   Response: The job market is highly competitive, and candidates have usually multiple offers. The value proposition and branding, strong stability conditions resulted impactful recruitment outcomes.

GGSESTC, Kandra, Bokaro had invited applications for the search of (09) eligible and suitable teaching candidates through The Times of India (Accent) in Delhi, Punjab, U.P., M.P, Bihar Bengal, Jharkhand, Chhattisgarh, Bihar, West Bengal, Odisha, Assam edition & Dainik Jagaran (all Jharkhand edition) to enhance its academic, research and administrative capabilities. In response approximately 300 applications were received from every corner of the country. Total 54 candidates (CSE 16; Civil 21: Management 10; Chemistry 07) were short listed and called for online interview (based on PhD and reputation of their college). During 13.9.2025 & 14.9.2025 (Saturday & Sunday) an online interview, was conducted, in presence of expert panel composed of senior faculty members/ HODs from IIT/ ISM, Dhanbad, BIT Mesra, BIT, Sindri & KIITS, Bhubaneswar, Director, GGSESTC, and Hon. Secretary, GGES, Bokaro. Finally 08 candidates among 09 given their willingness for their final joining.

Discussion: The integration of technology, particularly use of ATS, engagement of a combination of online job postings, social media outreach and employee referrals attracted the potential talents. The processed based on structured interview format, questions were focusing on behavioural and situational questions apart from technical knowledge and teaching skills confirmed the reliable and valid hiring decision.

Conclusion

The work presented in the study contributes to the education hiring field by highting the necessity of strategic human resource management practices for organisation. The findings indicate that effective SHRM practices particularly in diversity, and inclusion, employee development and the integration of technology, significantly contribute to enhancing organisational effectiveness and adaptability. The recruitment process achieved its objectives.

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Importance and Need of Digital Signature

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Abstract

Almost every industry is undergoing a rapid digital transformation. This implies that the authenticity and security of the electronic communication are very essential. The use of digital signatures constitutes one of the best encryption methods for the verification of the identity of the sender, the maintenance of data integrity, and the enabling of the feature of non-repudiation in electronic transactions.

In this article, we are reviewing the primary and fundamental need for digital signatures in today's world. This includes seeing the security of digital signatures as the main factor for this and other aspects such as trust-building in digital platforms and the possibility of legal sector like e-governance, finance, healthcare, etc., to make use of the technology for signing. Besides these, it also sheds light on the secrecy methods in the cryptosystems, global legal standards, and the use cases that exist in reality.

On top of that, the paper mentions all these along with the cryptographic mechanisms, international legal standards, and practical scenarios. As cyberattacks rise and businesses are going paperless at a rapid pace, it is logical to infer that digital signatures are the most necessary tools that ensure the safety, speed, and reliability of communication.

Keywords: Digital Signature, Cybersecurity, Cryptography, Public Key Infrastructure (PKI), Authentication, Data Integrity, Non-repudiation, E-Governance, Legal Validity, Electronic Transactions, Quantum Security.

Introduction

The phenomenal increase in electronic communication, online commerce, and electronic governance has led to the necessity for secure, authenticated, tamper-proof, and time-stamped data interchange. Handwritten signatures, which have, heretofore, sufficed, no longer meet the requirements of a digitally based world. For this purpose, digital signatures, which constitute a special case of asymmetric cryptology, become a primary tool for confirming data authenticity, integrity.

Cyber security, being at the cornerstone of the safety of internet activities, greatly depends on the adoption of digital signatures for the reduction of threats such as identity theft, data alteration, and cyber deception.

What is a Digital Signature?

Digital signature is a method of cryptographic verification of the authenticity and the integrity of a digital document or a message. A public key infrastructure (PKI) is employed for verification that the document was not modified and that it had been originated from a trusted sender.

The Key-Components:

- Private Key: Utilized at the sender's end for signature construction.
- Public Key: Employed on the receiver side for signature verification.
- Hash Function: Maintains data integrity.

Cryptographic Foundations (High Level)

Digital signatures are the concept of asymmetric (public-key) cryptography upon which they rely. A private key (to be kept secret) and a matching public key (to be widely distributed) are given to each user.

The general operation of signing consists of the following:

3. Generating a hash of the file to be signed to get a smaller representation (digest) was the main idea.
4. The digest is encrypted with the author's private key (or a signature object is generated with a signing technique like RSA, DSA or ECDSA).

5. The document is combined with the signature and the additional data that allows the recipient to verify the signature by using the public key of the signer.
6. Verification is the procedure of confirming the validity of the signature by matching it with the digest and the public key, as well as ensuring that the public key is reliable (e.g. by a certificate issued by a trusted CA or a web of trust).

Why Digital Signatures Are Needed?

- Authenticity and Identity: The digital signature is the method of connecting the identity with the data in the digital form. The recipient of the message can be sure that the message is from the sender provided by the method.
- Integrity: This is because signatures most of the time include the cryptographic hash of the message, thus if any change is made to the message after signing, signature verification will fail as the signature will not be valid.
- Non-Repudiation and Legal Evidence: On the one hand, digital signatures in combination with other technologies provide more evidence in a dispute than handwritten ones on a scanned paper: cryptographic proofs, audit logs and certificate chains allow event reconstruction and can be used for legal claims.
- Efficiency and Automation: The signatures allow the use of the fully digital workflows: the signing, validation, and archiving of the contracts can be done without printing or manual courier services. This, in turn, leads to a reduction of the turnaround time, the costs and the human mistakes.
- Scalability and Interoperability: One can easily scale the automated verification process to high-throughput as well. Moreover, the implementation of standard formats (like CMS, XMLDSig, PDF Signatures) goes a step further in enabling the interoperability of various systems/vendors.
- Regulatory Compliance and Auditability: One condition most regulations impose is that there must be a robust proof of authorization and record integrity. Digital signatures can be deemed as one of the main contributors that offer cryptographic evidence and timestamping stages suitable for compliance and audit purposes.

Importance of Digital Signatures for Cyber Security: -

- Authentication
- Data Integrity
- Non-Re-Concept
- Universally Acceptable
- Cost-Effective

The Need for Digital Signatures in the Field of Cyber Security:

- Increase in Cyber Threats
- Compliance with Laws and Regulations
- Safe Order Processing
- Technology Change and E-Governance

Categories of Digital Signatures:

1. *No Digital Signature:* Without a digital signature, the information or data is not authenticated or confirmed method. Such communication lacks proof of origin and cannot ensure that information has have not been altered. Without digital signature, e-mail, files, or electronic transactions easily tampered with or forged, which provided an opening to fraud and impersonation. Organizations and individuals face bigger data breaches and identity thefts when no there exists a verification mechanism.

2. *Weak Digital Signature:* A weak digital signature provides little security. In most cases, it is dependent on outdated or weak encryption algorithms like MD5 or SHA-1, or even some shorter key lengths that can be cracked with current computing power. Although it can function as a basic kind of identification, it does not provide data confidentiality and the basic features of data integrity. Weak signature is not appropriate for sensitive information such as banking, legal files, or government information, where stronger verification is needed.

3. *Strong Digital Signature:* A secure digital signature usually employs cryptographic techniques like RSA-2048, SHA-256, or Elliptic Curve Cryptography (ECC). It provides the three-key data security - data authenticity, integrity, and non-repudiation. It ensures data authenticity, integrity, and non-repudiation. Non-repudiation is the aspect that the sender cannot deny subsequently. Safe e-transactions, e-governance, etc., rely on the foundation of secure digital signature and contemporary information-security standards. They are confirmed by reputable Certification Authorities (CAs) and ensure end-to-end digital trust.

Type	Security Level	Data Integrity	Authentication	Example
No Digital Signature	❌ None	❌ Not ensured	❌ Not verified	Plain email/message
Weak Digital Signature	⚠ Low	⚠ Partially ensured	⚠ Partially verified	MD5/SHA-1-based
Strong Digital Signature	✅ High	✅ Fully ensured	✅ Fully verified	RSA-2048 + SHA-256

Since Digital signatures are the locks of the digital world.
A Weak digital signature is a cheap lock — a false sense of security.
A strong signature is like a bank-grade lock — it ensures safety, trust, and longevity of protection.

Applications of Digital Signatures:

Industry	Application
➢ E-Commerce	Secure Transactions, Invoicing
➢ Banking	Online fund transfer approvals
➢ Healthcare	Sepsis - Migraine M
➢ Legal	Digital affidavits and agreements
➢ Education	E-certificate and mark sheets
➢ Government	E-filing, e-tenders, digital governance.

Standards and Formats (Overview)

The use of standards that are well established and broadly accepted is a critical factor in the seamless interoperability between systems as well as their acceptance in a court of law. Some common standards and formats include

- The Public Key Infrastructure (PKI) standards are: X.509 certificates for binding a user's public key to a verified identity.
- Signature formats: CMS (Cryptographic Message Syntax), XML Signature , and PDF digital signatures.
- Time-stamping: RFC-based time-stamping authorities and services to record when a signer has signed.

Challenges and Limitations:

- Management Key Issues
- Knowledge and Usage
- Interoperable
- Hacking of PKI Systems

Comparison: Handwritten vs Digital Signatures:

- *Forgery Causes:* It is possible that handwritten signatures are visually forged; electronic signatures are cryptographically checked and thus are difficult to impersonate if the keys are well kept.
- *Tamper Detection:* A digital signature can recognize a change in the data that has been signed; a handwritten signature on a scanned file cannot.
- *Scalability:* Digital processes scale, manual signing doesn't.
- *Legal Weight:* Subject to jurisdiction, but most legal jurisdictions today give digital signature parity under specified circumstances.

Future of Digital Signatures: With growing advancements of blockchain, quantum computing, and AI-driven threat analysis, the evolved technological advancements on digital signatures will be more resilient and universally applicable across business sectors. - Blockchain allows for a decentralized, tamper-proof electronic signing platform. - Quantum-Resistant Cryptography is being developed for defense of digital signatures against prospective attacks.

Recommendations for Organizations

1. Complete a risk assessment to locate where signature is appropriate and necessary assurance Levels.
2. Adopt standards-based solutions (PDF Digital Signature, CMS, XMLDSig) for interoperability.
3. Secure private keys with hardware-backed methods and good policies.
4. Install certificate lifecycle processes, like timely renewal and revocation.
5. Employ reputable time stamping for long-term verification and auditor ability.
6. Ensure that legal advice verifies compliance with applicable e-signature legislations and industry regulations.

Conclusion: Digital signatures are not a technological gadget, but a cornerstone of cyber security infrastructure. They retain the pillars of confidentiality, authenticity, integrity, and non-repudiation for the virtual world. As there is a proliferation of digital transformation on a cross-industry level, the need for digital signatures will increase rather than decrease. Their adoption for a healthy cyberspace future needs to permeate, standardize, and continuously evolve with changing threats.

In cybersecurity terms:

"Use locks proportionate to the value of your data."

Weak signatures protect nothing; strong ones protect nations.

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Need and Use of Supervised Learning in Cybersecurity

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Abstract

The traditional rule-based security systems that were designed to combat the usual cyber threats have become nearly powerless to the advanced and constantly evolving hacking attacks. Predictive models trained on labelled datasets using Supervised machine learning (ML) provides a strong alternative for the detection of a wide range of malicious activities. This article delves into the requirements of supervised learning in computer security, its main methods, and its practical cases in cybersecurity, including malware detection, intrusion detection, and phishing recognition. Furthermore, the paper briefly elaborates on the core challenges such as data imbalance, adversarial threats, and model generalization. By a thorough survey, we highlight the massive contribution of supervised learning in the followings: facilitating automated threat detection, shortening the time of response, and fortifying cybersecurity infrastructures of the present day.

Keywords: Supervised learning, cybersecurity, malware detection, intrusion detection, phishing detection, data classification, threat detection, ML algorithms.

1. Introduction: Connecting the digital era has made the world more vulnerable, as cyberattacks have become more frequent and are targeting governments, businesses, and individuals. Traditional cybersecurity means like signature-based antivirus solutions and rule-based firewalls continue to operate in a reactive manner, hence they are often totally useless against complicated, new types of threats, for example, zero-day attacks.
Machine learning (ML), particularly supervised learning, the implantation of which in cybersecurity systems is a must-have, is a successful way to fix the problem. Systems with supervised learning techniques can learn from past, labelled data and recognize the patterns that separate normal from harmful activities. Once they have been trained on this kind of data, supervised algorithms can not only correctly detect the known threats but also minimize the number of false alarms.
This research paper summarizes the requirement of supervised learning for cybersecurity, mentions the potential areas of application, recovers the suitable algorithms and datasets, talks about the difficulties, and suggests the future directions to facilitate the acceptance and to make it more effective.

2. Understanding Supervised Learning

2.1 Definition: Supervised learning refers to machine learning methods under which models train on labelled datasets—sets of data with both input and output values—to be able to guess the output value of new data. The main applications are classification and regression.

2.2 Common Algorithms in Cybersecurity

- Decision Trees
- Random Forest
- Support Vector Machines (SVM)
- Naive Bayes
- Logistic Regression
- K-Nearest Neighbours (KNN)
- Neural Networks

One of the major advantages of each algorithm is the ability to discover specific types of threats depending on the characteristics and format of the input data.

2.3 Performance Metrics: For the evaluation of effectiveness, the following metrics are usually used:

- Accuracy
- Precision and Recall
- F1-Score
- False Positive Rate

3. Need for Supervised Learning in Cybersecurity

- **Rising Threat Complexity:** The nature of cyber threats have changed. Attackers are combining polymorphic malware, social engineering, and adaptive intrusion tactics. Most traditional systems can hardly react in such manner unless they have been manually updated.

- **Availability of Labelled Data:** One of the reasons for the growth of the labelled datasets is the sharing of the threat intelligence and the research of the cyber threats for years. These datasets contain labelled malware samples, phishing emails, and attack patterns, which make supervised learning a practical choice.
- **Automation and Scalability:** One of the main advantages of supervised ML is the automation of detection that can be scaled to very large datasets, which in practice means that the need for a human operator is minimized or even eliminated, thus response times can be significantly shortened.
- **High Accuracy on Known Threats:** A supervised model that has undergone rigorous training can be very effective in correctly detecting as well as differentiating from benign instances a set of known threats and thus, by performing additional training on targeted data, it can adapt to the environment of a particular network.

4. Applications of Supervised Learning in Cybersecurity

- **Malware Detection:** One of the ways to detect malware is to classify the code features of the files (static or dynamic) as malicious or benign by supervised models. For example, Random Forests and Neural Networks have made an accuracy of over 95% on malware datasets.
- **Intrusion Detection Systems (IDS):** The features that are used in network and host-based intrusion detection systems are packet size, protocol type, and connection duration through which traffic is classified. In such systems, models like SVMs and Decision Trees provide good performance for real-time threat detection.
- **Phishing Detection:** Supervised learning can be applied for phishing detection in a case of emails or websites with the help of URL characteristics, email headers, and text content. Logistic Regression and Naive Bayes are frequently used.
- **Spam Filtering and Email Security:** Emails are labelled as spam or non-spam with the help of the combination of Natural Language Processing (NLP) and supervised ML models, thus, the safety of the inbox is enhanced.
- **Fraud Detection:** Supervised learning is employed for identifying fraud in transactions of the financial institutions by studying the transaction history and behaviour patterns.

5. Key Datasets Used in Research

- **NSL-KDD:** Intrusion detection
- **CICIDS2017**: Realistic intrusion detection dataset
- **EMBER:** Malware classification dataset
- **Phish Tank:** URL-based phishing dataset
- **DREBIN:** Android malware dataset

6. Challenges and Limitations

- **6.1 Dependence on Labelled Data:** Machine learning relies heavily on appropriately labelled big datasets. The process of turning the data into datasets which are accurately labelled is very costly and takes a lot of time. Besides, a substantial amount of new threats are unlabelled or undiscovered.
- **6.2 Class Imbalance:** Typically, in most datasets the number of normal samples is several times greater than that of malicious ones. Imbalance of this type may result in the development of models that are biased towards the class with more instances.
- **6.3 Adversarial Attacks:** A hacker may modify the input so that the system cannot detect it (for example, adversarial malware or fake phishing pages that look like authorized content).
- **6.4 Overfitting and Poor Generalization:** A model that was trained on a very specific dataset may not be able to operate successfully with the real-world data that are different from it.
- **6.5 Concept Drift:** The attacker changes his scheme gradually. So, without having the models updated, they become outdated and less efficient.

7. Best Practices for Implementation:

- **Feature Selection:** Select features that are relevant and have fewer dimensions to reduce both the noise and the amount of the calculation.
- **Cross-Validation:** Checks model performance on different data segments, thus confirming the model's stability.
- **Data Augmentation:** Generates synthetic malicious instances to even out the dataset.
- **Continuous Learning:** Keep the models up to date by retraining them with the latest data so that they can identify new threats.
- **Explainable AI (XAI):** Gains trust by providing security analysts the understanding of the model's decision-making process.

8. Future Directions

- **Semi-Supervised and Unsupervised Learning:** By using a combination of labelled and unlabelled data, the reliance on large labelled datasets can be minimized, thus extending the use of ML in cybersecurity.
- **Transfer Learning:** The characteristics of pretrained models can be adjusted to suit particular environments, thereby a time and resource costs can be avoided.

- **Adversarial Robustness:** The creation of models that can endure attempts of manipulation by the attackers is among the most important areas of research.
- **Privacy-Preserving Machine Learning:** Methods such as federated learning and differential privacy enable the maintenance of data confidentiality whilst allowing for collaborative training.
- **Integration with Threat Intelligence:** The fusion of ML models with instant threat intelligence feeds can lead to an upsurge in spotting new dangers.

9. Conclusion: Supervised learning is really the core of contemporary security systems which is the most reliable machine-based identification of acknowledged dangers in many areas as malware detection, intrusion response, etc. Its triumphant implementation starts with very good labelled data, precise model tuning and keeping up with the changes in threats. Although they are affected by issues such as adversarial manipulation and data imbalance, the amount of research and development that goes on in this area is what pushes its effectiveness further and further. The use of supervised learning combined with other AI methodologies, privacy-protected models, and interpretable systems will be the main factor in the future security of cyberspace.

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Techniques and Trends in Supervised Learning for Scalable Big Data Analysis

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Abstract:
The exponential growth of data from digital platforms, sensors, enterprises, and cloud services has created unprecedented challenges for large scale data processing and intelligent decision making. Supervised learning, a core machine learning paradigm, plays a central role in extracting actionable knowledge from such massive datasets. This paper presents a comprehensive overview of supervised learning techniques in big data analytics, including their mathematical foundations, algorithmic principles, comparative performance, and real-world applications. It discusses computational trade-offs, scalability concerns, and domain specific challenges while highlighting future research directions such as distributed learning, explainable AI, and privacy preserving computation. The objective is to provide a structured understanding of how supervised learning methods can be adapted and optimized for scalable, efficient, and trustworthy big data systems.
Keywords: Supervised Learning, Big Data Analytics, Machine Learning Algorithms, Data Classification, Scalability, Neural Networks, Ensemble Methods, Predictive Modeling

Introduction:

The rapid proliferation of data generated from online services, social media, IoT devices, enterprise systems, and scientific research has redefined the landscape of computational intelligence. Big data (BD) characterized by high volume, velocity, variety, and veracity requires advanced analytical techniques to extract meaningful insights that support decision making and automation [1]. Traditional statistical tools and relational database systems often fail to scale under such demands, motivating the adoption of machine learning (ML) techniques specifically designed to handle large scale data [2].

Among ML paradigms, supervised learning has emerged as one of the most powerful and widely used approaches. It involves learning a mapping function from input variables to output labels based on annotated training data. This enables predictive modeling, classification, regression, and anomaly detection across a wide range of domains [3]. Examples include fraud detection [1], medical diagnosis [3], sentiment analysis [7], and autonomous navigation [9]. However, the scale and complexity of modern data introduce challenges such as computational cost, memory constraints, labelling difficulties, and model interpretability [4].

This paper aims to present a technical and comparative overview of supervised learning approaches in big data contexts. Section 2 surveys key literature. Section 3 presents the mathematical formulation and methodology. Section 4 outlines major supervised algorithms, while Section 5 compares their performance. Section 6 explores real world applications, Section 7 discusses major challenges and future directions, and Section 8 concludes the work.

Literature Review:

Early research on supervised learning in big data focused on adapting classical machine learning algorithms to large scale computational environments. Suthaharan [4] provided foundational insights into big data classification, emphasizing the need for distributed architectures and parallelization to overcome scalability issues. Melo Acosta et al. [1] applied supervised and semi supervised models for fraud detection, demonstrating the effectiveness of ensemble methods and support vector machines (SVM) in high volume transaction data streams.

Applications in the healthcare sector have also shown significant promise. Shirwaikar et al. [3] leveraged decision trees and logistic regression for neonatal outcome prediction, highlighting how supervised models can support clinical decision making. Padmanabha Reddy and Varma [2] surveyed various algorithms including decision trees, k-nearest neighbors (k-NN), and neural networks and compared their computational characteristics in large scale scenarios.

In specialized tasks, Shahzad et al. [6] demonstrated the value of supervised techniques for process model matching, while Elamin [7] explored sentiment classification using text based supervised approaches. Yang and Lam [8] investigated weakly supervised anomaly detection, and Souza et al. [9] applied supervised models for vision-based navigation in robotics.

While these studies demonstrate the versatility and impact of supervised learning, they also reveal gaps such as scalability limitations, dependency on labelled data, and a lack of interpretability. Addressing these challenges remains a priority for future research and practical deployment.

Methodology and Mathematical Foundation

Supervised learning aims to model a function f that maps input variables $x \in R^n$ to target outputs $y \in Y$ based on a labelled dataset $D = \{(x_i, y_i)\}_{i=1}^{N}$. The objective is to learn a hypothesis that minimizes the difference between predicted and actual outcomes. Mathematically, this can be expressed as an empirical risk minimization problem:

$$f^* = \arg\min_{f \in F} \frac{1}{N} \sum_{i=1}^{N} ((\;)_i, y_i)$$

where:

- F is the hypothesis space,

- L is the loss function (e.g., mean squared error, cross entropy),
- N is the number of training samples.

This general formulation applies to most supervised learning algorithms. Each technique, however, optimizes this objective differently based on its learning strategy and assumptions. Below are the mathematical foundations of key supervised models used in big data analytics.

1.1 Decision Trees

Decision trees recursively partition the feature space by selecting attributes that maximize information gain. Entropy (S), a measure of data impurity, is defined as:

$$(S) = -\sum_{i=1}^{k} p_i \log_2 p_i$$

where p_i is the probability of class iii. The information gain from splitting dataset S on attribute A is:

$$IG(S, A) = H(S) - \sum_{v \in Values(A)} \frac{|S_v|}{|S|} H(S_v)$$

The attribute with the highest IG is chosen for the split. In large scale environments, ensemble techniques like Random Forest and Gradient Boosted Trees extend this principle by aggregating multiple decision trees to reduce variance and improve accuracy.

1.2 Support Vector Machines (SVM)

SVM seeks an optimal hyperplane that separates classes with maximum margin. Given labelled data $(xi, yi), yi \in \{-1,1\}$, the primal optimization problem is:

$$\min_{w,b} \frac{1}{2}\|w\|^2$$

$$s.t.\ y_i\ (w^T x_i + b) \geq 1, \qquad i = 1,2,\ldots,N$$

where w is the weight vector and b is the bias. In large scale scenarios, kernel approximations and distributed SVM implementations improve scalability while maintaining classification accuracy.

1.3 Naïve Bayes Classifier

Naïve Bayes is a probabilistic classifier based on Bayes' theorem, assuming conditional independence between features:

$$P(C_k \mid x) = \frac{P(C_k)\prod_{i=1}^{n} P(x_i \mid C_k)}{P(x)}$$

where C_k is a class, $P(C_k)$ is its prior probability, and $P(x_i \mid C_k)$ is the likelihood of feature x_i given C_k. Despite its simplifying assumptions, Naïve Bayes performs well in large scale text and streaming data due to its low computational cost.

1.4 k-Nearest Neighbors (k-NN)

k-NN classifies a new instance based on the majority label of its k nearest neighbors. The Euclidean distance between two points xxx and x_i is:

$$d(x, x_i) = \sqrt{\sum_{i=1}^{n} (x - x_{ij})^2}$$

While simple and effective, k-NN has high computational complexity $((N))$ during inference, requiring approximate nearest neighbor search or parallelization for big data applications.

Neural Networks

Artificial Neural Networks (ANNs) approximate complex, nonlinear relationships through layers of interconnected neurons. The training objective minimizes the empirical risk:

$$\min_{\theta} \frac{1}{N} \sum_{i=1}^{N} L(f_{\theta}(x_i), y_i)$$

where θ denotes the network parameters (weights and biases). Gradient descent-based optimization algorithms (e.g., SGD, Adam) are used to update parameters iteratively. Deep architectures are particularly effective in high dimensional data tasks such as image recognition and NLP but require significant computational resources.

1.5 Computational Complexity Considerations:

For big data scenarios, the time and space complexity of supervised learning algorithms are critical. Approximate complexities are:

Algorithm	**Time Complexity**	**Space Complexity**
Decision Tree	$O(\text{nlog } n)$	$O(n)$
Random Forest	$O(t \times \text{nlog } n)$	$O(t \times n)$
SVM	$O(n^2) to\ O(n^3)$	(n^2)
k-NN	$O(n)$ per query	$O(n)$
Naïve Bayes	$O(n)$	$O(n)$
Neural Networks	$O(ep \times n)$	$O(n)$

Table 1: the time and space complexity of supervised learning algorithms

Where: n = number of samples, t = number of trees, ep = number of epochs.

Major Supervised Learning Techniques

Supervised learning provides a range of algorithms tailored for different data characteristics, performance requirements, and application domains. Their suitability for big data depends on scalability, accuracy, interpretability, and computational cost. Below is a technical overview of the most widely used approaches.

- **Decision Tree and Ensemble Methods:** Decision trees classify data by recursively splitting based on the attribute that provides the highest information gain. They are computationally efficient, interpretable, and suitable for structured data but prone to overfitting. Ensemble techniques such as Random Forest (RF) and Gradient Boosted Decision Trees (GBDT) improve performance by aggregating multiple trees, reducing variance, and increasing predictive accuracy [2].
  Use cases include fraud detection, credit scoring, and healthcare diagnostics, where both accuracy and explainability are important.
- **Support Vector Machines (SVM):** SVMs aim to maximize the margin between different classes and can handle nonlinear data through kernel functions. They are highly accurate and generalize well but are computationally intensive, with training complexity growing quadratically or cubically with data size [6]. Distributed SVM implementations and kernel approximations improve their scalability for big data scenarios.
  They are widely applied in bioinformatics, text classification, and anomaly detection, where precision is critical.
- **Naïve Bayes Classifiers:** Naïve Bayes (NB) uses probabilistic inference under the assumption of feature independence. Despite its simplicity, it performs surprisingly well on high dimensional data and is computationally efficient (linear time complexity). NB is particularly suited for text classification, spam filtering, and real time event detection [7].
- **k-Nearest Neighbors (k-NN**): k-NN classifies instances based on the majority label among their nearest neighbors. It is easy to implement and requires no prior model training but becomes computationally expensive for large datasets.
  Approximate nearest neighbor search and distributed computation improves scalability. k-NN is commonly used in recommendation systems and similarity-based search tasks [3].
- **Artificial Neural Networks (ANNs) and Deep Learning:** ANNs capture complex, nonlinear relationships in data and have become essential for tasks involving unstructured data. Deep learning architectures, including Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), achieve state of the art results in vision, language, and speech processing [8]. However, they require substantial computational resources and large labeled datasets.
- **Ensemble and Hybrid Models:** Combining multiple algorithms enhances predictive performance and robustness. Bagging reduces variance, Boosting reduces bias, and Stacking integrates heterogeneous models. These approaches are particularly effective for big data scenarios where data diversity and feature complexity are high [6].

2. Comparative Analysis of Algorithms

The choice of supervised learning algorithm depends on trade-offs among scalability, accuracy, interpretability, and computational complexity. Table 2 summarizes key characteristics of commonly used algorithms.

Comparative Performance Overview

Algorithm	Accuracy	Scalability	Interpretability	Training Complexity	Big Data Suitability
Decision Tree	Moderate	High (with pruning)	High	$O(n\ log\ n)$	Good for structured data
Random Forest/ GBDT	High	High	Moderate	$O(t \times \text{n} \log n)$	Excellent for large datasets
SVM	High	Moderate	Moderate	$O(n^2) - O(n^3)$	Effective for medium sized data
k-NN	Moderate	Low (naive) / Moderate (optimized)	High	$O(n)$ per query	Limited without optimization
Naïve Bayes	Moderate	Very High	High	$O(n)$	Excellent for text/streaming
ANN / Deep Learning	Very High	High (with GPU)	Low	$O(ep\ \times n)$	Best for unstructured data
Ensemble (Stacking, Boosting)	Very High	High	Low–Moderate	High	Widely used in production

Table 2: Comparative performance of major supervised learning algorithms in big data contexts.

Analysis:

- **Scalability:** Naïve Bayes and decision trees scale well, while SVM and k-NN face computational constraints. Distributed training and parallelization improve scalability.
- **Accuracy:** Deep learning and boosting techniques consistently outperform simpler models but require significant resources.
- **Interpretability:** Simpler models (e.g., decision trees, Naïve Bayes) offer transparent decision making, essential in regulated sectors.
- **Real Time Use:** Naïve Bayes and optimized k-NN are suited for streaming data due to low inference latency.

No single algorithm is universally superior. The optimal choice depends on the data characteristics, resource availability, and application constraints. In practice, hybrid and ensemble methods often provide the best balance of accuracy, scalability, and interpretability.

Applications across Domains

Supervised learning is widely deployed across domains where labelled data is available and predictive modeling is essential. Its adaptability to structured, semi structured, and unstructured data makes it central to modern data driven decision systems.

- **Financial Fraud Detection**
  Financial institutions leverage supervised models like Random Forest and SVM to analyze transaction patterns and detect anomalies indicative of fraudulent activities [1]. These models learn subtle behavioural signatures and achieve real time fraud prevention, significantly reducing financial losses.
- **Healthcare and Medical Diagnosis**
  Supervised learning models assist in disease classification, patient outcome prediction, and image-based diagnostics [3]. Decision trees and logistic regression are frequently used for clinical decision support, while deep learning enables high accuracy medical imaging analysis.
- **Cyber security and Intrusion Detection**
  Machine learning based intrusion detection systems classify network traffic as benign or malicious based on historical attack data. Naïve Bayes, Random Forest, and ensemble classifiers are widely deployed for anomaly detection in dynamic network environments [7].
- **Sentiment Analysis and NLP**
  Text classification and sentiment analysis rely heavily on supervised learning, with Naïve Bayes, SVM, and LSTM models commonly used to process and classify large scale textual data [6]. These systems support applications in customer feedback analysis, brand monitoring, and social media intelligence.

- **Autonomous Systems and Robotics**
  Supervised learning underpins perception, decision making, and navigation in autonomous vehicles and robotics. Convolutional neural networks (CNNs) classify objects and road elements in real time, while reinforcement augmented supervised models enhance control and planning capabilities [9].

Challenges and Future Directions

Despite their effectiveness, supervised learning systems face several challenges when applied to big data.

- **Scalability and Computational Costs:** Algorithms like SVM and deep neural networks scale poorly with large datasets, requiring distributed architectures and optimization techniques. Future research is focused on scalable training methods and efficient model architectures [4].
- **Data Quality and Labeling Constraints**
  Large scale datasets often suffer from noise, imbalance, and incomplete labels, reducing model performance. Semi supervised and active learning approaches are promising alternatives that reduce dependence on labeled data [2].
- **Interpretability and Transparency**
  Complex models, particularly ensembles and deep networks, lack interpretability a significant concern in domains like healthcare and finance. Explainable AI (XAI) techniques, including feature attribution and model distillation, aim to improve transparency without sacrificing accuracy [7].
- **Privacy and Security**
  Data privacy and security remain critical concerns in supervised learning. Federated learning and differential privacy are emerging as solutions that allow collaborative model training without centralized data sharing [6].
- **Adaptability and Concept Drift**
  Dynamic data environments introduce concept drift, where data distributions evolve over time. Incremental learning, online learning, and transfer learning approaches help models adapt to changing patterns [8].

Conclusion

Supervised learning has become a cornerstone of big data analytics, enabling scalable, intelligent decision making across diverse domains. From fraud detection and healthcare diagnostics to cybersecurity and autonomous systems, its applications continue to expand with the growth of digital data. However, challenges related to scalability, labelling, interpretability, and privacy remain significant barriers to deployment at scale.

Future research will focus on integrating distributed computing, semi supervised learning, explainable AI, and privacy preserving techniques into supervised learning pipelines. These advancements will enable more adaptive, transparent, and efficient models capable of handling the demands of real-world big data environments. As organizations continue to generate and rely on massive datasets, supervised learning will remain integral to building next generation intelligent systems.

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Indian Alchemy made Great Strides in India

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Abstract

It is known that alchemy (the older form of chemistry) had made great strides in India. Ayurveda which used a variety of minerals, also played an important role in the development of chemistry, which was closely related to medicine. The two main incentives for the development of chemistry were the age-old desires of human beings: to live forever and to get rich. Much of chemistry grew out of the early efforts to develop an elixir and to turn base metals into gold. It is also interesting to note that Needham claimed that earliest distillation of alcohols is attested to through the archaeological finds at Taxila. In fact, the ancient name of alcohol is *khola*, which sounds so similar to it.

1. Indus Valley Civilization (2600-1900 BC): The Indus valley civilization was the earliest reported society, which had developed an elaborate urban system depicted in terms of streets, public baths, temples and granaries etc. They also had the means of mass production of pottery, houses of backed bricks and a script of their own. So we can say that the story of early chemistry in India begins from here.

- ***Pottery*:** It could be regarded as the earliest chemical process in which materials were mixed, moulded and fired to achieve desirable qualities of products. Thousands of pieces of pottery were found in the Rajasthan desert, varied in shape, size and colour. They show that prehistoric people knew the art of making pottery by using burnt clay. Coloured and wheel made pottery was found at Harappa. Pottery was decorated with various designs including geometric and floral patterns as well as human and animals figures. Remains of glazed pottery were also found at Mohenjodaro.
- ***Bricks*:** Burnt bricks were manufactured on a large scale for making houses, drains, boundary walls, public bath etc.
- ***Cement*:** Gypsum cement had been used in the construction of a well in Mohenjodaro. It was light grey and contained sand, clay, traces of calcium carbonate and lime.
- ***Minerals***: The Indus valley people used a number of minerals for a variety of useful products such as medicinal preparations, plasters, hair washes etc. Faience, which is a sort of proto-glass, was quite popular with the Harappans and was used for ornaments. They also smelted and forged a variety of objects from lead, silver, gold, and copper and also used tin and arsenic to improve the hardness of copper for making artefacts.

2. The Historic Period: According to *Rgveda*, tanning of leather and dyeing of cotton was practised during this period. During the period of 1000-400 BC they made a particular kind of polished grey pottery known as Painted Grey Ware. Other varieties of pottery, for example, red or Northern Black-Polished (N.B.P.) Ware (600-200 BC), were also made later. These Wares indicate their mastery of control of kiln temperatures as also of the reducing atmosphere. The golden gloss of the NBP Ware is still a chemical mystery and could not be replicated. After the Vedas, came the classical texts like *Brahmanas*, *Upanishadas* and *Puranas*, which also give valuable information about the chemical activities of this period. Kautilya's *Arthasastra* (KA) was a scientific landmark of this period. KA described the production of salt from the sea and collection of shells, diamonds, pearls and corals. *Charaka Samhita* and *Susruta Samhita* were two celebrated Ayurvedic treatises on medicine and surgery. Chemical knowledge of the times especially that related to medicine was compiled in them.

3. Chemical Arts and Crafts in Later Periods: Glass making, pottery, jewellery making, dyeing of clothes and tanning of leather etc. were the major chemical arts and crafts in the early periods. As a result of this expanded activity, the alchemical knowledge increased. Following were the major chemical products that contributed to the development of chemistry.

- ***Glass*:** Glass is a fused solid mixture of a number of substances like lime, sand, alkali and metallic oxides. It is of various kinds - transparent, opaque, coloured and colourless. No glass objects were found at the sites of the Indus valley civilization, except for some glazed and faience articles. A number of such glass objects were found at Maski in south India (1000-900BC), Hastinapur and Taxila (1000-200BC). In this period glass and glazes were coloured by the addition of colouring agents like metal oxides. *Ramayana*, *Brhatsamhita*, Kautilya's *Arthasatra* and *Sukranitisara* mention the use of glass. There is ample evidence to suggest that ancient India glass making was quite widespread and a high degree of perfection was achieved in this craft. There was a traditional glass factory at Kopia in Basti district of Uttar Pradesh. Glass slag was found at Kolhapur, Nevasa, Paunar and Maheshwar. Glass furnaces of late medieval period were found at Mysore. The Mughal period (AD1526-1707) saw the flourishing of the art of glass making in India.
- ***Paper*:** From the Chinese traveller I-tsing's account it appears that paper was known to India in the seventh century AD. In the beginning the process of papermaking was simple and more or less similar in all parts of the country. The main centers of paper making in medieval India were Sialkot, Zafarbad, Murshidabad, Ahmedabad, Mysore etc.

- ***Soap*:** For washing clothes ancient Indians used certain plants and their fruits like the soap nuts of Ritha and Sikakai. Fruits like *Sriphala* and *Sarsapa* (*Brassica compestris*) were also used to wash different kinds of clothes. Guru Nanak's prayer written in the late sixteenth century AD contains the earliest reference to soap. There were references to soap like substances called *Phenaka* in the second and third century AD texts like *Manusmrti* and *Yajnavalkyasmrti*. Indians definitely began to make proper soaps in the eighteenth century AD. In Gujarat, the oil of Eranda (*Ricinus communis*), seeds of plant Mahua (*Madhuca indica*) and impure calcium carbonate were used by them. These were used for washing but gradually soft soaps for bathing were made.
- ***Dyeing*:** Plants and their products like madder, turmeric and safflower were the principal dyeing materials. Orpiment and some insects like lac, cochineal and kermes were the other materials used for dyeing. A number of classical texts like *Atharvaveda* (1000 BC) mentioned some dye stuffs. Dyes were extracted from inorganic substances by repeatedly soaking and mixing them in water and allowing the materials to settle. Then the solution was taken out and spread on a pot and evaporated to get the dry dye. Some other substances having tinting properties were Kampillaka (*Mallotus phillippinesis*), Pattanga (*Cesalpinia sappan*) and Jatuka (a species of *Oldenlandia*). A large number of other materials were also used for dyeing. Synthetic dyes were made by mid-nineteenth century.
- ***Cosmetics and Perfumes*:** A large number of references to cosmetics and perfumes in Sanskrit literature were found like in *Brhatsamhita* of Varahamihira. Cosmetics and perfumes making were mainly practised for the purpose of worship, sale and sensual enjoyment. The Bower Manuscript (*Navanitaka*) contained recipes of hair dyes which consisted of a number of plants like indigo and minerals like iron powder, black iron or steel and acidic extracts of sour rice gruel. *Gandhayukti* gave recipes for making scents. It gives a list of eight aromatic ingredients used for making scents. They were: *Rodhara, Usira, Bignonia, Aguru, Musta, Vana , Priyangu*, and *Pathya*. The *Gandhayukti* also gave recipes for mouth perfumes, bath powders, incense and talcum powder. The manufacture of rose water began perhaps in the nineteenth century AD.
- ***Ink*:** An inkpot was unearthed during the excavations at Taxila, which suggests that ink was known and used in India from fourth century BC. The Ajanta caves displayed some inscriptions that were written with coloured ink, made from chalk, red lead and minium. Chinese, Japanese and Indians had used Indian ink for quite a long time. The recipe for ink was also given in *Rasaratnakara* of Nityanatha. The ink made from nuts and myrobalans kept in water in an iron pot was black and durable. This ink was used in Malabara and other parts of the country as well. Special ink prepared from roasted rice, lampblack, sugar and the juice of plant Kesurte (*Verbsina scandens*) was used in the Jain manuscripts. Ink was made both in liquid and solid forms, by using lampblack, gum of the plant *Mimosa indica* and water in the nineteenth century. Tannin's solution became dark blue-black or greenish by the addition of ferric salts and it seems that this fact was known to Indians during late medieval period, and they used this solution for ink making.
- ***Alcoholic liquors*:** *Somarasa*, which was mentioned in the Vedas, was probably the earliest evidence of the use of intoxicants in India. Kautilya's *Arthasastra* listed a variety of liquors such as *Medaka, Prasanna, Asava, Arista, Maireya* and *Madhu*. *Caraka Samhita* also mentioned sources for making various *Asavas*: cereals, fruits, roots, woods, flowers, stems, leaves, barks of plants and sugar cane. About 60 Tamil names were found in Sangam literature, which suggest that liquors were brewed in south India since the ancient times. Medieval alchemical texts also mentioned fermented liquors and their methods of preparation. Alcoholic liquors were classified into the following categories depending on their applications in alchemical operations:

1. *Dasanapasani Sura*: used in dyeing operations
2. *Sarvacarani Sura*: used in mixing operations of all kinds
3. *Dravani Sura*: used in dissolving substances
4. *Ranjani Sura*: used in dyeing operations
5. *Rasabandhani Sura*: used in binding mercury
6. *Rasampatani Sura*: used in distillation of mercury

Susruta-Samhita used the word *khola* for alcoholic beverages; perhaps the modern word alcohol is derived from it. A large number of alcoholic preparations were described in various texts.

More startling is the fact that Needham attributes the earliest distillation of alcohol to India. In Vol. V (4) of *Science and Civilisation* (especially pages 85-6,97,104-7 and 131-2), Needham offers a fundamental reconstruction of the history of liquor distillation in India, and, by its reconstruction has forced a review of the theory prevalent until recently that the production of alcohol originated in the Mediterranean world in the thirteenth century. Habib informs us that Needham shows much respect for Mehdi Hassan, who had in many papers drawn attention to possible evidence of early liquor-distillation in India; and he had, of course, before him Ray's *History of Hindu Chemistry*, with its citations of early medieval texts on distillation. None of this, even the linguistic curiosity inherent in the double meaning of *sunda* (elephant's trunk, side tube), gave any certainty of India's role in the early history of alcohol production. But Needham carefully analysed the archaeological evidence of stills from Taxila, first brought to light by Marshall and A. Ghosh and others with numerous remains of stills from the Shaikhan Dheri (Charsadda, NWFP, Pakistan) excavation. Needham gave these stills the name of "Gandhara stills", compared them with the western or Hellenistic type of his still-classification, and then propounded that they were essentially "retorts" and, because of their early date (150 BC-150 AD), they might well be "the origin of all such forms of still". The pottery remains at Shaikhan Dheri were so extensive, viz. one alembic, 130 receivers so capacious, that one must assume alcohol (not, for example, mercury) to be the intended product. This would give precedence to India over all other countries in liquor distillation.

Needham's discussion does not, however, make clear what degree of success the Gandhara stills could obtain in producing pure alcohol. It could have given only a heavily diluted alcohol, and, if the fire was kept low, to reduce dilution, the pace of collection must have been very slow.

The modifications that were introduced in Italy in the twelfth century (possibly in close exchange or ideas with the Arab world, as some terms tend to show) were designed to improve cooling so as to increase pure alcohol collection at a low level of heat. The "Moore's head" had a water-container set over a spoon-like alembic, a concave roof and annular rim-collection, connected by a tube with the receiver. This undoubtedly led to the achievement of a much higher degree of purity in the distilled alcohol than under any other device. There is a possibility, that, travelling through the Islamic world, the new stills would have soon reached India. The fresh wave of alcohol extraction, then, which India seems to have witnessed by stills now received.

It is true that by this time there were alternative forms of stills also available, as Needham shows: these are what he calls the "Mongol still" (condensation in a catch-bowl within the still) and the "Chinese still" (with the catch-bowl connected by the side-tube with receiver outside), the former depicted on the wall of a cave of the period 1031-1227, and the latter shown in a drawing of 1163 in China (*Science and Civilisation*, V (4), pp. 62-68, 78-79). But neither of these devices could have probably competed successfully with the improved stills from the Mediterranean.

The famous passage of *ca*. 1595 in the *A'in-I Akbari* of Abu'l Fazl, in which three kinds of liquor-stills are described, is examined by Needham (pp. 106-7). From Blochmann's translation he identifies the three kinds respectively as the Mongol, the Chinese and the Hellenistic types. Habib asserts that while one may let pass the identification of the first still as "Mongol", the second is clearly Gandharan. Abu'l Fazl expressly states that the condenser was the receiver itself placed in cold water. The third, which Needham identifies as "Hellenistic" is still more interesting, since it clearly has the Moore's head (water at the top and still-head shaped like a "spoon", so expressly described). It was, in other words, the medieval Italian-Arab still.

Needham observes that it was the Gandharan still, which sometime between the seventh and twelfth centuries, was recognized as more practical than the Mongol and Chinese types and "adopted accordingly" (Pp. 265-268).

It may be mentioned here that the early invention of distillation must have helped production of pure zinc by distillation. India was the first in designing retorts, which could control distillation of such a volatile metal as zinc. In fact, for the medieval times zinc production reached industrial scale levels.

- ***Pharmaceuticals*****:** Medicines were chiefly derived from plants, although a few ingredients originated from animals. Preparations of medicines involved collection of the ingredients, their purification, extraction of their essences and compounding of these extracts by means of processes like grinding, pasting and maceration. Processes like dissolution, distillation, sublimation, precipitation, combustion, dilution and decocting were carried out in these preparations. Mercury and gold were also used in a number of drugs.
- ***Saltpetre and Gunpowder*****:** The discovery of saltpetre (i.e. potassium nitrate) and its chief application in gunpowder was a crucial factor in the history of chemistry. Firearms were mentioned in ancient Sanskrit texts like *Rgveda, Atharvaveda, Kautiliya's Arthasastra* and *Manusmrti*. A verse in the Sanskrit alchemical text *Rasopanishada* narrated the preparations of a gunpowder mixture. Tamil texts also describe the preparation of fireworks using sulphur, charcoal, saltpetre, mercury, arsenic, camphor etc. Sukracarya's *Sukra-Nitisara*, written in the sixteenth century AD, mentions gun and gunpowder. It also gave a recipe for a gunpowder mixture consisting of saltpetre, sulphur and charcoal in specific proportions.

4. Medieval Alchemy (AD 800-1300): Alchemy in India flourished in the medieval period. The Indian alchemy had two characteristic streams: gold making and elixir synthesis. The two faces of the alchemical practice, the metallurgical and the physico-religious, were superimposed to get a single picture wherein mercury and its elixirs were used in the so called transmutation of the base metals into noble ones, as well as for internal administration for purifying the body, rejuvenating it and taking it to an imperishable and immortal state. Numerous alchemical texts were written between the ninth and the fourteenth centuries AD. Some texts are such that the alchemical ideas form only a part of them, while some other texts are wholly devoted to alchemy. Those that come under the second category include the following:

1. *Rasahrdayatantra* by Govind Bhagwatpad
2. *Srasaratnakara* by Siddha Nityanatha
3. *Rasarnava* by an unknown author
4. *Srasendracudamani* by Somadeva
5. *Rasaratnasamuccaya* by Vagbhatta
6. *Rasaprakasasudhakara* by Yasodhara
7. *Rasarajalaksmi* by Ramesvara Bhatta
8. *Rasendracintamani* by Dhundukanatha
9. *Rasendracintamani* by Ramacandra Guha
10. *Rasasara* by Govind Acarya

11. *Rasakaumudi* by Sarvajnacandra
12. *Rasabhesajakalpa* by Surya Pandita
13. *Rasasamketakalika* by Camunda
14. *Lohapaddhati* by Suresvara
15. *Kankaligrantha* by Nasirshah
16. *Rasamuktavalina* by Devanatha

Besides, there are several works whose authorship and dates have not yet been established. Among them may be mentioned *Dhatukalpa, Dhatumanjari, Dhatumaranam, Rasagrantha, Rasakalpalata, Rasanibhandha, Suvaranatantra, Tamrakalpa, Abhrakakalpa, Paradakalpa, Jaranamaranadi, Sutapradipa* etc. These texts are either fragments of major texts or generally based on them. Practitioners of the Siddha system of medicine wrote a number of alchemical texts known as Mappu texts in the Tamil language. The more prominent Siddhas were Agastyar, Bogar, Ramdevar and Karuvurar. There were alchemical texts written in other Indian languages as well, for example, in Hindi, Telugu, Kannada, Marathi, Bengali and Oriya.

***Importance of Mercury*:** The texts of Indian alchemy (*rasavidya*) reveal that a wide variety of inorganic and organic substances were used and plant as well as animal products, but more of the former. The important minerals are generally referred to as *rasas* and, in later texts they are classified into *maha* (superior) and *upa* (subsidiary) *rasas*. Mercury, though a metal, is extolled as the king of *rasas*, the *maharas*, and has several names in the *rasasastra* texts: *parada, sita, rasendra, svarnakaraka* (maker of gold), *sarvadhatupati* and, more significantly in a mythological setting, *Sivaja* (born of Siva); *Siva virya* (semen of Siva) and *Harabija* (seed of Siva). More than two hundred names of plants have been mentioned in the texts, but many of them have not been properly identified from the point of view of modern botanical nomenclature. Generally their roots, leaves or seeds are used for aiding digestion processes. As for the animal products, their excreta, flesh or some other parts of their bodies were diligently processed and used.

The texts written in the medieval period primarily dealt with gold-making and elixir syntheses. Elixir or *Rasayana* was a substance that could transform other base metals in to gold and silver, as well as confer longevity and immortality when taken internally. If an elixir proved successful in transmutation of metals it was supposed to be safe for internal administration as well. Owing to its heavy weight, silvery white and shiny appearance, fluidity, and its property of readily combining with other substances, mercury was considered as the most potent of all substances and as possessing divine properties. The potions containing mercury were supposed to give longevity and immortality, thus making it the main ingredient of the powders used in the transmutation and as elixirs. Mercury had to undergo 18 processes before it could be used for transforming either metals or human body. These processes were as follows:

1. *Svedana*: steaming or heating using water bath
2. *Mardana*: grinding
3. *Murchana*: swooning or making mercury lose its form
4. *Utthapana*: revival of form
5. *Patana*: sublimation or distillation
6. *Rodhana*: potentiation
7. *Niyamana*: restraining
8. *Sandipana*: stimulation or kindling
9. *Gaganabhaksana*: consumption of essence of mica
10. *Carana*: amalgamation
11. *Garbhadruti*: liquefaction (internal)
12. *Bahyadruti*: liquefaction (external)
13. *Jarana*: calcinations
14. *Ranjana*: dyeing
15. *Sarana*: blending for transformation
16. *Sankramana*: acquiring power of transformation or penetration
17. *Vedhana*: transmutation
18. *Sevana*: becoming fit for internal use

These were known as the *samaskaras*. Briefly the processes are as follows:

Svedana consists in streaming mercury with a number of vegetables and mineral substances; *mardana* involves rubbing the streamed mercury in a mortar with vegetable and acidic substances to remove some more impurities; in *murchanam* mercury is rubbed in a mortar with another set of vegetable substances, till it loses its own character and form; in *utthapana* the mercury is steamed again in alkalis, salts, the three myrobalans, alum, etc.; *patana* involves distillation (3 types: *urdhva, adah* and *tiyak*); *rodhana* involves mixing the distilled mercury with saline water in a closed pot; in niyamana the process is continued by streaming mercury for 3 days with a number of plant products, alum borax, etc.; *sandipana* involves steaming with alum, black pepper, sour gruel, some alkalis and some plant substances; *ganganagrasa* involves fixation of the desired degree of the essence of mica for its consumption; in *carana* mercury is boiled with sour gruel and leaves of some kinds of cereal plants, alum etc.; *garbhardrti* involves treating mercury with other metallic substances; in bahyadrti the essences of the minerals or metallic substances are utilized in the molten or liquid state; *jarana* involves heating mercury with the desired minerals or metals, alkalis and salts; *ranjana* involves colouring by a complex process; in *sarana* mercury is digested with gold, silver etc. in an oil base; *kramana* requires smearing mercury with a number of plant extracts, mineral substances, human milk etc. and then heating them ; *vedhana* consists in rubbing the treated mercury with oil and a few other materials so that it acquires the power of transmutation; and finally *sarayoga* it is available for internal use.

Nagarjuna and Rasarnava: The earliest available alchemical text in Sanskrit, *Rasaratnakara* by Nagarjuna was probably part of a larger text *Rasendramangala* written by the same author. Nagarjuna was the most prominent scholar in the field of Indian alchemy. There appeared a number of alchemical treatises in the eleventh to twelfth century AD namely, *Rasarnava, Rasahrdaya, Rasarnavakalpa* etc. Among them, *Rasopanisad* and *Rasarnava* were the largest consisting of about 2600 verses.

5. Modern Chemistry: Chemistry developed mainly in the form of alchemy and iatrochemistry during AD 1300-1600. But from the early seventeenth century onward a marked decline in the alchemical writings was observed. Alchemy that was practised with full enthusiasm started to fade from the beginning of the Tantric period. This was possibly on account of the realization that alchemy could not deliver the goods it promised. Now it was a period of the ascendance of iatrochemistry. After the decline of alchemy, iatrochemistry probably reached a steady state over the next 150-200 years, but then it too, declined due to the introduction and practice of western medicine in the 20th century. During this period of stagnation, the pharmaceutical industry based on Ayurveda continued to exist, but it too gradually declined. There was a large time gap between the giving up of old methods of production of certain chemicals and the adoption of newer methods based on modern chemical ideas. When the old ones become out fashioned, it took about 100-150 years for the Indians to learn and adopt new techniques and during this time the foreign products poured in. As a result the indigenous units using traditional techniques gradually declined, due to the adverse policies of the rulers. Decline in demand was the other main reason for this.

The Indian dyes were superior in quality and low priced and brought a large return to the Europeans trading companies. Therefore, the East India Company till the beginning of the nineteenth century supported the indigo plantation. But, when Huemann discovered synthetic indigo in 1890, the indigo cultivation in India suffered and finally stopped. Thus the synthetic dyes completely overtook the natural dyes. Modern science appeared late on the Indian scene, i.e., only in the later part of the nineteenth century. By the mid nineteenth century European scientists started coming to India. A science college was established in Calcutta in 1814. The study of chemistry was first introduced in the Presidency College of Calcutta in 1872, followed by post-graduate teaching in chemistry in 1886. The Indian Association For Cultivation Of Sciences was established in 1876. Early chemists like P.C.Ray and Chuni Lal Bose were actively associated with it. P.C.Ray was well aware and proud of the fact that Indians had made considerable progress in the field of chemistry during the ancient and medieval periods, as was evident from his two volumes on *History of Hindu Chemistry*. After Ray, Chandra Bhusan Bhaduri and Jyoti Bhusan Bhaduri were the ones who conducted significant researches in the field of inorganic chemistry. R.D. Phookan sowed seeds of research in physical chemistry. Thus a bunch of young scientists started taking keen interest in modern scientific research activities. P.C.Ray established the Bengal Chemical Of Pharmaceutical Works Ltd. in Calcutta; J.K.Gajjar with the help of Kotibhaskar and Amin established the Alembic Chemical Works in 1905 at Baroda; and Vakil in 1937 established the alkali industry under Tata's patronage and Tata Chemicals Ltd. came into existence. The Indian chemical industry was thus established and it continued to grow with a slow but a steady pace in the 20th century.

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Health Care & Medtech; AI Based Diagnosis and Monitoring

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Abstract:

Artificial Intelligence (AI) has transformed the foundations of modern healthcare by revolutionizing diagnostic accuracy, enhancing patient monitoring, and improving clinical outcomes through predictive analytics and automation. By 2025, AI systems are deeply integrated across hospital networks, diagnostic imaging centers, and telemedicine platforms, providing data-driven intelligence that supports physicians and empowers patients. As healthcare systems confront rising costs, workforce shortages, and complex disease burdens, AI-driven diagnosis and monitoring solutions provide a pathway toward efficiency, personalization, and equitable access to care.

Introduction to AI-Based Diagnosis and Monitoring

AI integration within healthcare is dependent on its capability to quickly and accurately process large multimodal datasets. Medical images, genetic sequences, electronic medical records (EMRs) and electronic health records (EHRs), and real-time sensor signals from wearable technology add to the perpetual data influx. Machine learning and deep learning algorithms review these datasets to determine patterns not discernable by the naked eye and allow for early disease diagnosis and determination of risk prior to the onset of symptoms and perpetual monitoring to understand patient well-being. By 2025, an estimated 80% of the world's hospitals deploy AI to some degree to bolster diagnosis and administrative processes [7].

As reported by Docus Research's outline for 2025, the worldwide AI healthcare market increased from $32.3 billion in 2024 to an estimated $47.8 billion in 2025 and is expected to touch $431 billion by 2032[2]. Scalability has increased the pace at which AI-enabled devices and medical software are developed dramatically, and this has all been in areas that were data-rich but insight-poor until now.

Technological Architecture and Data Architecture

Next-generation AI diagnostics integrate many different levels of technology: data ingestion, preprocessing, algorithmic modeling, clinical integration, and monitoring. Clinical AI platforms start with large data ingestion pipes that take in medical imagery, patient histories, genotypic data, and labs. All these data are anonymized and normalized to render them safe and interoperable with regulations like HIPAA and GDPR [7].

Deep learning algorithms such as convolutional neural networks (CNNs) dominate image analysis and achieve 90–94% accuracy on early disease diagnosis — especially oncology, radiology, and dermatology [5][11][12]. NLP and transformer models such as GPT-style architectures extract knowledge from unstructured clinical notes and medical texts and enhance decision support systems among professionals [7]. Interoperability with data platforms such as the Fast Healthcare Interoperability Resources (FHIR) ensures real-time interoperability with EHRs and constructs common patient records shared across healthcare systems.

AI-Based Diagnostic Breakthroughs

AI diagnostics have also become invaluable to diagnose diseases efficiently and accurately. Radiological applications of AI identify early tumors, fractures, or organ abnormalities, and pathology AI platforms refine the accuracy of biopsy examination and blood cell classification. Cardiovascular AI models examine ECG and echocardiogram information and accurately predict arrhythmias and cardiac failure.

For the field of oncology, the system identifies breast, lung, and colon cancers approximately one year prior to standard screening techniques by monitoring faint textural signals within imaging scans [5]. In the case of dermatology, image-enabled AI platforms such as DeepDerm and Derm Assist equal or exceed human dermatologists in the diagnosis of melanoma and psoriasis. Ophthalmic uses including IDX-DR and Eyenuk's Eye Art make diabetic retinopathy screening automated with more than 95% sensitivity and expand the reach of eye care to the underserved[7][5].

Additionally, AI-driven lab test interpretation platforms now mechanize the explanation of 78% of laboratory results, more educating patients about the CBC and lipid panels and reducing the burden on physicians [2].

AI-Based Ongoing Monitoring and Predictive Care

AI-powered patient monitoring is one of the best medtech advances within the last ten years. Using wearable sensors, IoT-enabled devices, and remote patient monitoring algorithms, AI detects physiological changes long prior to clinical deterioration is imminent. According to the National Center for Biotechnology Information's review of 2025, AI patient monitoring reduced ICU transfers by 48% and saved approximately $72 million annually on operational costs within large US healthcare networks [8].

These systems operate continuously through analytics to monitor key signs such as heart rate variability, oxygen saturation, blood glucose levels, and sleep pattern. Through predictive models, disease flare-ups are forecast and the clinician/carer is alerted by mobile health applications. For chronic diseases the systems improved patient adherence by 20–25% and reduced readmission to the hospitals by up to 30%\ [8\] \ [13\].

Under mental health, chatbots and voice assistants powered by AI facilitate early diagnosis in mood disorders. Nearly 46% of the users of the AI symptom checker in the year 2025 reported consultations about symptoms of anxiety and depression, indicating growing accessibility to mental health using digital platforms [2].

Efficiency and Economic Transformation

Adoption of AI in healthcare has generated tangible gains in efficiency and cost savings. Automated radiology triaging systems decreased report turnaround time from hours to seconds. Automated staffing models help save hospitals hundreds of thousands of operating costs by predicting workloads and patient inflows. McKinsey's data to 2025 estimated that the US healthcare system could save $150 billion each year through automation and predictive modelling through the adoption of AI.

One key catalyst to this change is workflow enhancement. Patient intake, appointment booking, and claims processing are now automated by the AI systems with almost zero error rates and overcome the traditionally induced inefficiencies due to administrative costs. Big healthcare organizations cite increased patient discharge by an additional 10–29%, reduced 7-/30-day readmissions, and drastic reduction in the average stay duration by harnessing the operational insights provided by AI-powered systems [8].

Global Adoptations and Regional Trends

AI adoption in healthcare is geographically variable but is quickly growing. North America in 2025 continued to be the greatest adopter with an 80% adoption rate and highest market value at $14.3 billion USD [14]. Europe adopted at 60%, where ethical models and standardization of regulations took center stage. Asia-Pacific, led by cost-effective diagnosis and telemedicine platforms via smartphone [15], adopted at 55%.

Emerging markets in Latin America and Africa registered increased interest, mainly through the use of mobile diagnostics and artificial intelligence-assisted triage platforms. India's mission on digital health is an exemplary illustration thereof where public hospitals embedded artificial intelligence predictive analytics to track infectious disease epidemics and follow-ups on chronic diseases [15].

Clinical and Social Significance

AI-powered diagnosis revolutionized patient outcomes through the achievement of measurable increments in survival rates, earlier diagnosis, and personalized treatments. Most recent studies on 2025 report that AI models achieved an accuracy rate of 90% against breast cancer screening, 88% against COVID-19 pneumonia diagnosis, and 94% against the diagnosis of diabetic retinopathy [5][12]. Also, the predictive capability of AI has enhanced preventive medicine through reducing emergency activation by over 65% and refining resource allocation within critical units [8].

Moreover, AI has fortified the doctor–patient relationship by availing real-time transparency. Test results, diagnostic information, and individualized recommendations can be accessed by patients through AI-driven dashboards to enhance engagement and health literacy.

Problems and Ethical Issues

Even with notable advances, the inclusion of AI in healthcare is complex. Primary challenges are:

- Data Security and Privacy: Safeguarding patient data against breaches and unauthorized uses continues to remain an overarching concern with the heightened popularity of cross-country telemedicine and cloud projects.

- Algorithmic Bias: Machine learning algorithms can unintentionally learn biases within the data during the training process and output imbalances along ethnic or gender lines.

- Regulatory and Ethical Oversight: Generative and predictive AI models developed at lightning pace far surpass existing medical device regulations in most places and call out for the unification of frameworks.

- Interpretability: Clinicians often require model transparency to trust AI recommendations, necessitating investments in explainable AI (XAI) technologies.

These agencies now require "algorithmic auditing" of medical software AI falling within the Software as a Medical Device (SaMD) category to be safe and to be held accountable [10].

Future Research

The second decade of AI-driven healthcare growth will be about integration, patient centrality, and decentralization of diagnostics. Precision medicine will benefit immeasurably from AI-powered analysis of genomics that tailors the regimen to the individual's molecular fingerprint. Multi-modal AI fusing imaging modalities and text and wearable and sensor data will allow us to see patient health holistically and intervene at the early stage on many different disease areas.

Additionally, federated learning models will allow hospitals and research institutions to collaborate without exchanging sensitive data, addressing privacy concerns while enriching AI algorithms. The emergence of explainable and context-aware AI tools will bridge the interpretability gap, making decision-making more transparent to clinicians and regulators.

The collaboration between robotics and artificial intelligence in surgery, rehabilitation, and long-term care will also surge dramatically to facilitate autonomous procedures such as precision-guided biopsy and robotic-assisted endoscopy. With wearable computing evolving to the state of permanent diagnosis platforms, healthcare will shift from bedside monitoring inside hospitals to a ubiquitous network of home-centered care supplemented by AI analytics.

Conclusion

AI-enabled diagnosis and monitoring are now the core keystones to today's healthcare, transforming from experimental technology to clinical standard infrastructure. By integrating big data, automation, and human knowledge, AI has transformed healthcare from reactive treatment to predictive, preventive, and personalized healthcare. With the combination of state-of-the-art machine learning, internet-of-things-enabled devices, and strong data ecosystems, AI is not only an innovative technology but also a healthcare revolution.

As global adoption accelerates, the focus must shift toward transparency, ethics, and equity to ensure that AI benefits all populations. The path ahead will witness a healthcare landscape defined by intelligent systems capable of working alongside clinicians, supporting their expertise while making care faster, safer, and universally accessible.

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Structural and Phonon Behavior of Doped Barium Titanate Synthesized at Low Temperature

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Abstract: $BaTiO_3$ (BT) is one of the most widely used ferroelectric materials having perovskite structure (ABO_3) and widely used due to excellent dielectric, piezoelectric and ferroelectric properties. This study reported the synthesis of BT and modified BT in low temperature solid state method by using $Ba(NO_3)_2$ as precursor and study on structural, phonon mode properties of the synthesized samples. $BaTiO_3$ and $Ba_{0.9}R_{0.1}TiO_3$ (R=Fe, Ni) ceramics were prepared by low temperature solid state ceramic method, samples sintered at 850˚C for 8 hours. X-ray powder diffraction (XRD) was employed to check the formation of phase in the synthesized material. X-ray diffraction pattern confirms single phase formation having tetragonal structure for all compositions, which is also confirmed by room temperature Raman analysis. However a decrease of crystalline size and increase in lattice strain has been observed due to substitution in $BaTiO_3$ unit cell. Continuous decrease of tolerance factor confirms about octahedral tilting in unit cell.

Keywords: Lead free materials; X-ray powder diffraction; Raman Spectroscopy

1. Introduction: The ban on lead triggered many research groups for materials development and research effort for lead free materials to replace well established lead zirconate titanate (PZT) compound. The lead free ferroelectrics or piezo-electrics are classified in four distinct classes [1]. $BaTiO_3$ (BT) is one of the most widely used ferroelectric materials having perovskite structure (ABO_3) and widely used due to excellent dielectric, piezoelectric and ferroelectric properties. BT was first discovered in the early 1940s. BT as a typical lead-free FE ceramic has been widely used in dielectric capacitors materials due to the massive dielectric constant and long-range ordered spontaneous polarization. This lead-free ferroelectric pure BT ceramic has relatively lower piezoelectric (d_{33}: ~190 pC/N) and dielectric (ε: ~1700 and low loss at room temperature) properties usually published values than lead-based ferroelectric ceramics. However, its unique characteristics make BT ceramic a more suitable choice for many applications such as capacitors, multilayer capacitors, and energy storage devices [2-4]. Recently, investigations on incorporation of impurities (i.e., transition metals) in the BT structure determined that substitutions can induce ferromagnetic properties, which results in a multifunctional material.

In perovskite oxides, larger difference in charge and size generally leads to cation ordering whereas similar change and size of cation give disorder structure with cation displacements and oxygen octahedra tilting. These distortions lead improvement in dielectric properties. Properties of BT ceramics significantly depends on its microstructure, which is influenced by characteristics of the starting BT powder. Therefore, much attention has been focused on the synthesis of high quality BT nano-particles. However, in the conventional solid phase methods, BT powders were usually produced via the reaction between the mechanically mixed $BaCO_3$ or BaO and TiO_2 powders followed by calcination at above 1000 °C. Unfortunately, the reactions at such high temperatures are beyond control and the resultant powders often have large particle size and wide particle size distribution [5]. Therefore for industrial applications, it is still desirable to develop an alternative low temperature solid state method for preparation of BT powders. Researchers have tried to synthesize BT powders at lower temperatures by replacing $BaCO_3$ by other compounds such as $Ba(OH)_2$, $Ba(NO_3)_2$ etc. [6]. In this communication, we have reported the synthesis of BT and modified BT in low temperature solid state method by using $Ba(NO_3)_2$ as precursor and study on structural, phonon mode properties of the synthesized samples.

2. Experimental Technique: BT and $Ba_{0.9}R_{0.1}TiO_3$ (R = Fe and Ni) powder was prepared by solid state method using $Ba(NO_3)_2$, TiO_2, NiO and Fe_2O_3 (all chemicals are AR grade used without further purification) as the starting materials. Initially, all the powders were grinded in dry medium then for better mixing acetone was added in. After grinding 4 hours homogeneously mixed powders were calcined at temperature 800 °C for 8 hours in a furnace with controlled heating rate in air medium. Fine calcined powder was pressed into disc-shaped pellets by hydraulic press with a uniform pressure of 4×10^6 Nm^{-2}. The pellets were sintered in presence of air using controlled heating and cooling rates in a programmable furnace at temperature 850 °C for 8 hours. The sintered pellets and calcined powders both are subjected for different characterization.

X-ray powder diffraction (XRD) was employed to check the formation of phase in the synthesized material. The XRD of as calcined samples were taken by Rigaku Smart Lab (Japan) X-ray diffractometer with CuKα1 (λ= 0.154056 nm) radiation at room temperature with a wide scale range of 20°-80° (scan rate= 2°/min). Raman spectra of sintered pellets were taken by STR-500 Micro-Raman Spectrometer (Japan) at room temperature (using LASER having wavelength 532 nm).

3. Result and Discussion

3.1 XRD Analysis: Fig. 1a shows the XRD pattern of all samples. For BT sample, the splitting of the (200)/(002) diffraction peak (near 45 ˚) was observed, indicating that the sample is in tetragonal phase (JCPDS No. 15-0780) or pseudo-cubic phase with slight tetragonal distortion at room temperature. Due to change of the dopant, the peak is shifting towards the higher angle indicating that the lattice parameter is decreasing .The lattice parameter is decreasing because of the atoms with lower atomic radii (r_{Fe} = 0.75Å; r_{Ni} = 0.83Å) are incorporated at Ba-site (r_{Ba} = 1.35Å).

The average crystallite size of the synthesized BT and BRT powder was calculated from the X-ray line broadening of the (110) peak using Scherrer's formula [7]. The strain can be estimated by Williamson-Hall analysis method [8]. The strain is estimated from the slope of the fitted straight line using the following equation

$$\beta Cos\theta = 4sSin\theta + \frac{k\lambda}{D}$$

where *s* is the strain present in the sample, D is the average grain size, λ= wavelength of X-ray used, and β is the width of the diffraction peak at half maximum for the diffraction angle 2θ. Fig. 1b show the Williamson-Hall plots for all samples. As presented in the Fig. 1b, the slope of the fitted straight line has an increasing tendency with doping; this can be because of ionic radii mismatch between host and dopant ions. Tolerance factor (t) also calculated by formula proposed by Goldschmidt's. For perfect perovskite structure (ABO_3) t is unity i.e. for undistorted structure; when t < 1 then distortion occur in the perovskite structure indicating tilting or rotation in TiO_6 octahedra. The decrease of tolerance factor with doping concentration confirms the increase of octahedral rotation. It is well established that if the tolerance factor is less than unity, oxygen octahedra tends to rotate to realize the lattice [9]. All the parameters calculated from XRD listed in Table-1.

Table 1. Values of crystalline size and strain for various compositions

Sample	Crystalline Size (nm)	Stain	Tolerance Factor (t)
$BaTiO_3$	30.15	0.4583	0.9223
$Ba_{0.9}Ni_{0.1}TiO_3$	28.42	0.4434	0.9039
$Ba_{0.9}Fe_{0.1}TiO_3$	25.05	0.4721	0.9011

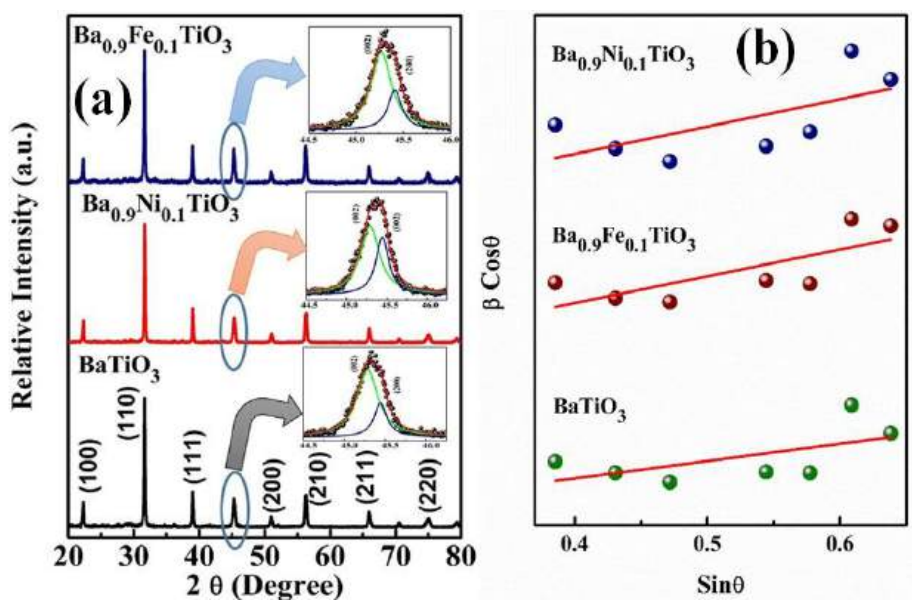

Fig. 1. (a) XRD pattern of all samples; inset image shows the splitting of XRD peak at 2θ ~45°**. (b)** Williamson-Hall pattern of all samples

3.2 Micro-Raman Spectral Analysis: Micro-Raman spectroscopy was used to characterize the phonon modes present in the synthesized samples. Fig. 2 depicted the Raman spectra of pure $BaTiO_3$ sintered pellet. Here, Raman peaks at approximately 186 cm^{-1}, 252 cm^{-1}, 308 cm^{-1}, 715 cm^{-1} and broad peaks at 518 cm^{-1} matches well with that expected for the tetragonal $BaTiO_3$phase. Specifically, peak at 308 cm^{-1} is assigned to the transverse and longitudinal coupling optical mode of B_1 symmetry ([B_1, E (TO + LO)] mode), a clear evidence of high tetragonality in NPs. The small peaks at 186 cm^{-1} are related to the damping of A_1 (TO) modes caused by internal pressure or lattice defects in nano-sized grains. The peak at 715 cm^{-1}

represents the highest frequency longitudinal optical mode of A_1 symmetry of TiO_6 octahedra, which is related to the local distortion caused by Ba-site substitution in $BaTiO_3$ lattice according to previous research [10]. The band at approximately 518 cm^{-1} shifted to low frequencies (512 cm^{-1}). In addition, the intensity of the band decreased with the mol% of Ni and Fe. The characteristic band at 718 cm^{-1} exhibited a minor relative intensity for BRT compared to that for BT, which may be due to defects, such as oxygen vacancies, in the BRT lattice [11].

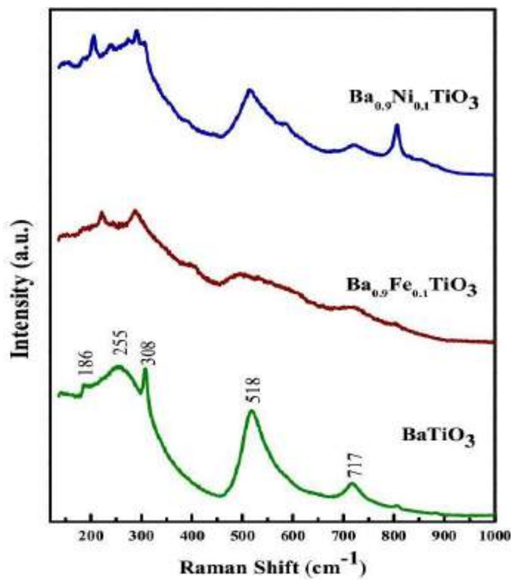

Fig. 2. Room temperature Raman Spectra of doped $BaTiO_3$ compared with pure $BaTiO_3$

4. Conclusions: A low temperature solid state method is used for synthesis of BT and BRT; XRD analysis confirms formation of single phase tetragonal structure of both pure and doped compositions. The splitting in XRD pattern $2\theta \sim 45°$ confirms about teragonality of the samples which can be verified by room temperature Raman spectra. The decrease of tolerance factor confirms about the octahedral rotation in the unit cell of $BaTiO_3$.

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Developing an ESP32 and fuzzy logic control smart farming monitoring system to increase agricultural productivity

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Abstract

The study outlines a new strategy for increasing agricultural productivity through the development and application of a fuzzy logic-controlled smart farming monitoring system. To continuously evaluate environmental factors, the system integrates a variety of sensors, including water level, light intensity, soil moisture, temperature, and humidity. According to experimental testing of the system output, the developed model's accuracy and efficiency in predicting and operating the water pump are 96.5% and 95.3%, respectively. With a 98.7% water pump operation rate, the model has proven to be highly reliable and responsive, with the system identifying the need for modification within one minute of the altered setting. It is now clear that fuzzy logic is the most effective method when compared to either the current farmer strategy or an alternative control design. Specifically, it guarantees accuracy, minimizes wasteful inputs, lowers labour costs, and lessens the risk of malpractice, all of which contribute to the system's superiority. It follows that fuzzy logic technology has the potential to revolutionize the traditional method of agricultural management. It enables the development of waste-avoidance and risk-proof strategies, enabling sustainable performance in the face of shifting environmental pressures.

Keywords: *Smart farming, Fuzzy logic control, Sensor technology, Agricultural productivity, Environmental monitoring*

1. Introduction

Agriculture is at a turning point and needs to change course. helping to feed the world, address climate change, and resolve environmental and soil-related issues in the twenty-first century. Given this, the data indicates that in order to boost food production, agriculture must now employ cutting-edge technology, but not at the expense of environmental degradation [1– 4]. Precision agriculture, sometimes referred to as smart farming, is one substitute. In order to maximize resource efficiency and optimize the agricultural production process, it makes use of technologies like the Internet of Things. Automation, IoT devices and data, and sensors enable smart farming. Information from multiple sensors and control systems placed in the field or greenhouse is gathered by the system using a central hub. After processing and analysing the data, the computer system instructs the field or greenhouse's actuator with the necessary commands. This system uses a smartphone application to send data and alarms to the manager or owner [5– 8].

The study's goal is to create and evaluate a smart farming monitoring system with fuzzy logic control. Based on the data, the system will automatically evaluate the condition of the plant and the surroundings thanks to a collection of intelligent, self-governing sensors. The farmer will receive the data and analysis findings through a smartphone application. Equipment and management arrangements will be created using data from the system sensors. In contrast to a traditional approach, this one is being tested in practice and responds to the major trends in agriculture today, which makes it novel. The study is significant because it has the potential to improve the efficiency and sustainability of agriculture.

2. Literature Review

One solution to the problems facing modern agriculture is smart farming. It might have the power to completely alter farming practices and the agricultural management system. The system can deploy monitoring operational data on farms because it is based on sensor technology, IoT devices, and data analytics. Sensors for temperature, humidity, soil moisture, light intensity, and water level are frequently used to gather information and keep an eye on crops, soil, and environmental conditions. These sensors are typically found in smart farming systems, which allow farmers to monitor data in real-time and promptly take appropriate action to optimize operations and maximize yields [9 – 12].

In smart farming solutions, fuzzy logic control systems are becoming more and more common. By comparing the brightness of light bulbs or clouds, the technology enables decision-making. Because agricultural environmental conditions are unpredictable, unknown, and subject to change, fuzzy logic algorithms can be used. As a result, among other agricultural duties, they can be applied to pest control, nutrient management, and irrigation scheduling. Fuzzy logic can be used in smart farming to optimize resource use and agricultural operations [13 – 16].

Smart farming has been the subject of extensive research. Numerous studies have demonstrated its ability to boost resilience, sustainability, and yields. The technology has been examined in relation to multi-sensors, pressure-sensitive seats, and ammonia sensors. Data analytics, automation, and decision support systems have all been the subject of other studies. To address present issues and advance the systems' implementation, more research must be done. The primary issues with smart farming are interoperability, scalability, and cost. To support the technology and create a sustainable and food-secure system for future generations, more innovation in the field is required [17 – 20].

In order to optimize irrigation scheduling, nutrient supply, and pest control at an agricultural site, this research is framed as the development and implementation of a smart farming monitoring system using a fuzzy logic control system that would incorporate various sensors for monitoring environmental parameters like temperature, humidity, soil moisture, light intensity, and water level. The monitoring system would use variations of imprecise reasoning. [21– 23]. The primary focus of the research is on using data and cutting-edge technology to improve agricultural productivity and sustainability. The system would be created and explained in the current work, but it could be further examined to maximize its effectiveness and identify possible application areas. [24 – 27].

3. Methodology

In order to ensure that a complete smart farming monitoring system is accomplished, this study made use of sensor technology, the ESP32 microcontroller, cloud communication, and fuzzy logic control algorithm. Installing a variety of sensors to help measure various environmental parameters was the first step in the hardware assembly of the smart farming monitoring system. In particular, sensors for temperature, humidity, soil moisture, light intensity, and water level were positioned in various locations to allow for the collection of data on the crops' development and health in real time. These sensors were chosen because of their accuracy, dependability, and compatibility with the ESP32 microcontroller. Programming was the next step, which was required to enable communication with each sensor and allow for the periodic collection of data. Instead of acting as a bridge between the sensors and GPRS, the ESP32 took on the function of other microcontrollers, processing the data gathered and directing system control using a fuzzy logic algorithm. To lower the likelihood that data would be processed, it made use of error and exception handling procedures.

As a result, the fuzzy logic control algorithm was also created to evaluate sensor data and guarantee well-informed choices about pest control, nutrient application, and irrigation. Furthermore, it was predicated on a set of linguistic variables, membership functions, and fuzzy rules to define the operations and decision-making in cases where the given data is imprecise or fuzzy. The algorithm's primary responsibility was to automatically regulate the system to modify the frequency of irrigation, the quantity of nutrients to be applied to the crops, and the level of pest control based on real-time data and inspection findings. Another essential component of the monitoring system was communication, and the cloud needed to be set up. The ESP32 was connected via Bluetooth or Wi-Fi wireless communication when data analysis from the cloud was required. Every fifteen minutes, data packets were transmitted, and they included sensor data, system status, control action, and cloud storage for later use. Figure 1. illustrates how the suggested system operates in its entirety.

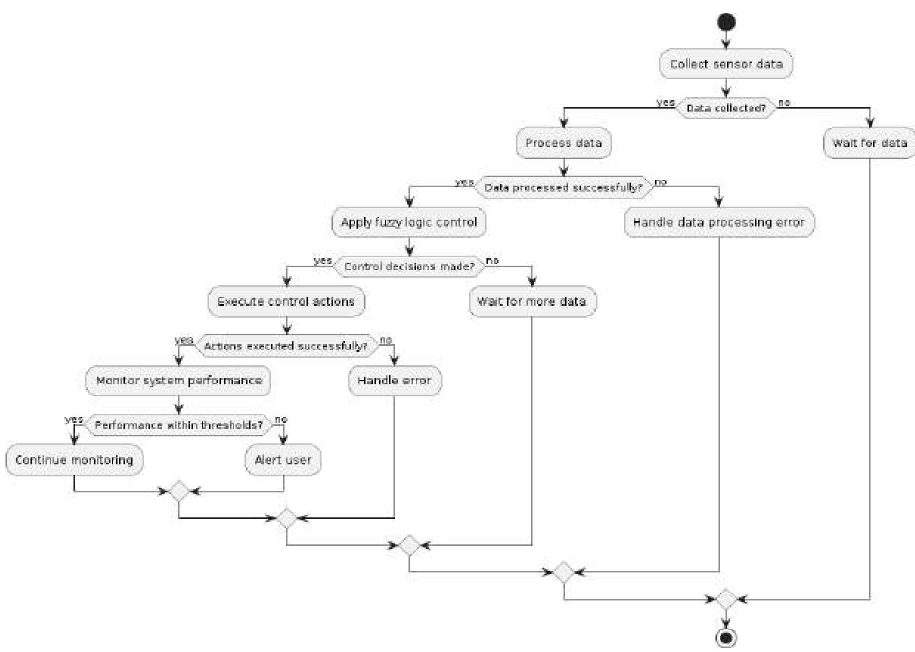

Fig. 1. Working of the proposed system

In the cloud environment, incoming data was analysed using the data analytic method in order to draw conclusions, make inferences, and review system trends appropriately. It's possible that machine learning algorithms could have improved the system's resilience and enabled more precise data analytics for the best possible decision-making. The final interface was created as a graphic user to allow farmers to remotely monitor the system and notify others when issues arose.

3.1 Dataset used in this research

Using a dataset made up of the parameters associated with plant growth and health maintenance, a fuzzy logic model was created. Sensor readings for temperature, humidity, soil moisture, light intensity, and water level are included in the dataset. The model has processed 3422 cloud-stored readings over the past few years. The model gained knowledge of the particulars of the agricultural environment by examining the dynamics of these readings. The reason for this is that sensors record the changes and variations and send the data to the system. Thus, the model learned how to carry out routine tasks like crop irrigation and maintenance, such as using chemicals to protect plants from certain pests. The model system allows the irrigation pump to water plants when it detects readings below the predetermined thresholds. The fuzzy model makes this choice because of the following: According to the standard readings, the plant environment is either too hot or too dry, and if crops are not watered promptly, they may quickly dry out. Growers do not need to be physically present or keep an eye on the soil during this process because the system is automated. With the aid of an automatically operating pump-and-sensor complex, the system thus establishes an ideal condition for watering the plants, giving them precisely the correct amount of water. Similarly, based on the readings, the system can regulate soil fertilization and advise farmers on the ideal concentration of specific nutrients.

3.2 Fuzzy logic model

Using real-time sensor data from the agricultural environment, the fuzzy logic model employed in this study addresses decisions about pest control, nutrient management, and irrigation scheduling. Figure 2 illustrates how the suggested model operates. The model's linguistic variables, membership functions, fuzzy rules, and inference mechanisms work together to analyze the complex state of the environment and produce pertinent decisions. Linguistic variables that represent the input and output values of the control system are at the heart of the fuzzy logic model. These variables, which are defined as "temperature," "humidity," "soil moisture," "light intensity," etc., reflect the qualitative aspects of the phenomena under consideration. In addition to the variables themselves, there are linguistic terms that describe the parameters—low, medium, high, etc.—in relation to the various levels that the sensors in the environment experience.

A membership function that specifies "the degree of membership of a given input value to the variable" in a corresponding linguistic term is also linked to each linguistic variable. The degree of truth of each linguistic term to a variable's input value is described by membership functions, which are shown as triangular, trapezoidal, or Gaussian curves. A membership function for the term "low temperature," for example, would show a high degree of truth value at low temperatures and progressively drop as the temperature rose. The reasoning process that enables the model to make decisions is implemented by fuzzy rules.

The if-then statements that explain the connection between the input values and the control actions are represented by these rules. The expert's knowledge, experimental findings, or other information about the ideal system behavior are all incorporated into the rules. The fuzzy rule might be, for instance, "increase irrigation frequency if temperature is high and soil moisture is low."

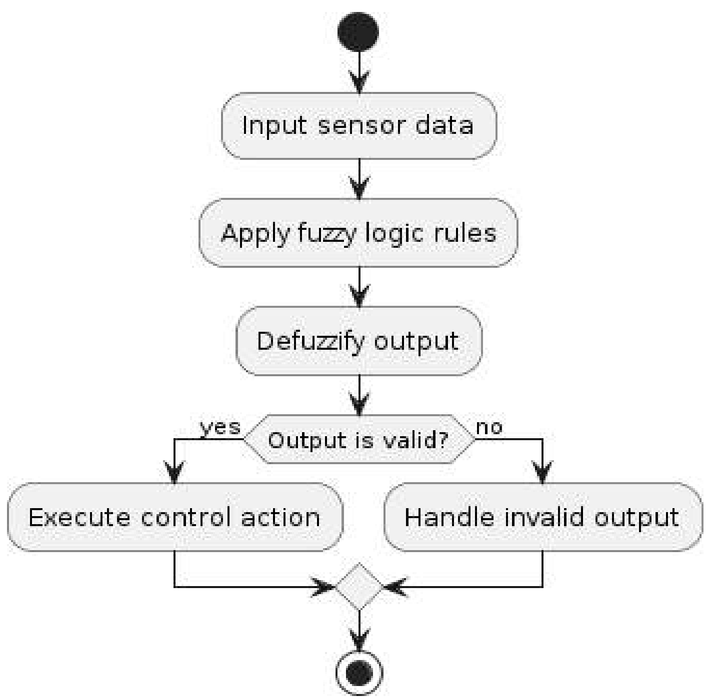

Fig. 2. Working of the fuzzy System

Based on the ideas of fuzzy logic, the fuzzy inference mechanism generates clear output values or recommendations using the fuzzy rules, membership functions, and linguistic variables. Fuzzification and defuzzification are the two stages of the inference process. The first step involves using the proper membership functions associated with each linguistic variable to transform the sharp input values picked up by the sensors into fuzzy sets. Each linguistic term is used to estimate the input values' degree of truth or applicability. The next step involves applying the fuzzified values to the rules. This is done by analysing each rule's antecedents to determine which premise has the greatest degree of application. Following defuzzification, which turns the fuzzy set into a distinct value, the premises and conclusions of the applied rules are then merged into a single fuzzy set. Consequently, the input data from the weather station and sensors is used to generate a recommendation. The historical sensor data that is stored and aggregated in the cloud is used to train the fuzzy logic model.

They are then combined with sensor data to test the model and make improvements over time. To increase the model's decision-making efficiency, the training process focuses on optimizing the fuzzy rules and membership functions. Determining the ideal values for the facility's parameters during training is also crucial. Usually, such optimization is used to carry out this process, methods such as genetic algorithms, gradient descent, and various heuristic optimization techniques. In particular, during the training processes, the weights of the fuzzy rules and the parameters and form of the membership functions are continuously changed.

The validation process can then be used to demonstrate the model's efficacy and validity. This step typically entails evaluating the model on a different validation dataset, though it can also be tested in a simulation experiment with various performance settings. Lastly, based on the current sensor level, the developed and validated model can be used in the agricultural environment to provide real-time recommendations for irrigation, nutrient management, and pest protection.

3.3 Performance score used in research

Several key performance indicators have been employed to assess the effectiveness of the fuzzy logic model of water pump operation and prediction for smart farming. First and foremost, the model's output accuracy was crucial because it indicated how likely it was that the pump would function effectively and dependably in the intended setting. Here, the number of instances of correctly identified times when the plantation requires watering, thus precisely forecasting when the pump should operate, allowed for the determination of the model's prior accuracy. When the plantation is not in need of watering, it is appropriately marked as not requiring activation, which is still a crucial component of operational accuracy.

The assessment of the frequency and duration of the pump's operation, however, demonstrates the operational accuracy of the fluid logic model. The metric also takes into account how well the model can predict when crops will actually need to be irrigated. Therefore, evaluating the model's capacity to prevent crop over- and under-irrigation is just as crucial as evaluating its noted accuracy. The operational performance score in this instance includes a metric that characterizes the fuzzy logic model's capacity to operate the pump during believable irrigation periods while referencing a few evaluation-accepted points of inaccuracy.

A test to ascertain the readiness to work based on the assessment of a change in characteristics or other factors in the test sample is an additional component of the evaluation of the fuzzy logic model related to headphones. The effectiveness of the fuzzy logic model was assessed in this testing environment based on its quality and concentration from all errors. However, the operation's dependability was assessed based on the pump's performance during the designated irrigation periods rather than in many crop-irrigation scenarios.

4. Result and Discussion

The fuzzy logic model's performance is rigorously tested following implementation. In order to determine the applicability and dependability of this machine learning model, various kinds of Metrics like precision, effectiveness, responsiveness, and dependability are evaluated. Additionally, the algorithm's ability to forecast how a water pump will operate in a smart farming application is evaluated. Table 1 displays the performance's outcomes. First, accuracy indicates how well the model uses the sensor data to make irrigation decisions. It reaches 96.5%, indicating that the model makes the right irrigation decision 96.5% of the time, demonstrating its high degree of accuracy and ability to determine when irrigation is required. Second, efficiency is a measure of how well the model works to only activate the water pump when necessary. It reaches 95.3%, indicating that the model only activates the pump when necessary and does not waste resources. Third, since it impacts crop care success, the model's responsiveness—that is, how quickly it adjusts the water supply in response to changes in the environment—is crucial. One minute is the model's response time, which appears to be enough to adapt the irrigation to the changes. Lastly, given the fuzzy logic rules and the various environmental circumstances, it makes sense to talk about the modelled water pump's dependability. The model appears to be dependable and achieves 98.7% pump uptime. In summary, the findings are useful for learning more about the model's ability to preserve the crisp inputs' sensitive values. The results make it possible to determine that the fuzzy model can be defined by its high degree of accuracy, efficiency, responsiveness, and reliability, all of which enable it to have an impact on an agricultural smart farming system.

Table 1. Performance of the Model

Performance Metric	Value
Accuracy	96.5%
Efficiency	95.3%
Responsiveness	Within 1 minute
Reliability	98.7% uptime

Figure 3 displays the system's effectiveness both before and after it was put into place. Prior to implementation, water usage was 75% effective. This indicates that agriculture made efficient use of 75% of the water resources. At 150 kW per day, the energy consumption was high. This data point showed that a lot of energy was needed for irrigation and other agricultural operations. Lastly, the conveyed level of agricultural management had a low cost-effectiveness of 30%. As a result of the improvements seen in every area, the new system's implementation brought about positive changes. The efficiency of water use rose by 15%, or more than 90%. Since the energy used for irrigating and other agricultural processes became more efficient, the level of energy consumption decreased until it reached 100kW/day. Lastly, cost-effectiveness was over 80%, and this parameter had a notable positive change.

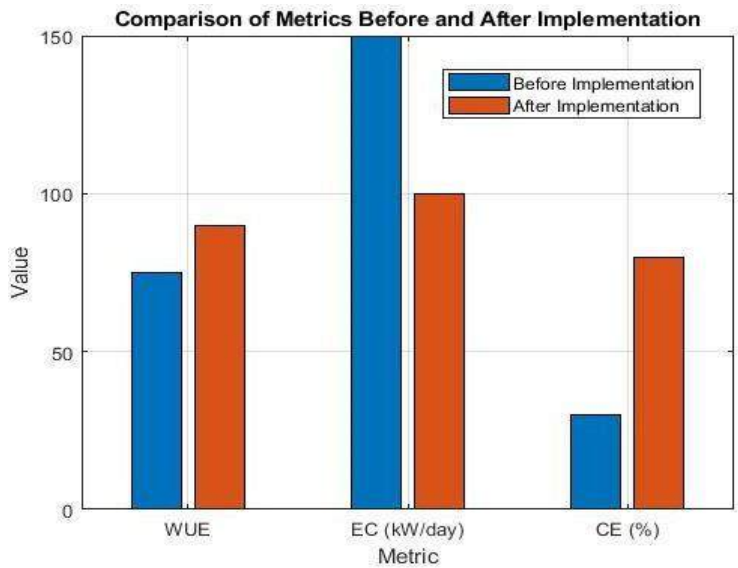

Fig. 3. Before and after implementation of system

The sensor readings and actions of a smart farming system aimed at improving irrigation management are displayed in table 2 below. Over the course of a day, each parameter is measured hourly. Temperature, humidity, light, and moisture are among the environmental variables that are monitored, so we get information about each of the related elements simultaneously. The parameter that focuses on the reservoir's water level, which is expressed in centimetres, is particularly pertinent. The smart system will use the pump to make sure the plants get the water they need for healthy growth if this level falls below the permitted minimum. However, the pump won't run if the water level is higher than the permissible minimum, allowing for energy conservation and a reduction in water waste. The dynamics of the level as provided by the sensors will therefore have a significant influence on the pump's operation. The action will cause the pump to supply water if the soil's moisture content drops noticeably, as indicated by the corresponding factor in the table. In order to prevent water waste and overuse, the system will activate the pump to deliver water, ensuring that the plants continue to receive the necessary amount of moisture.

Table 2. Sensor Reading and Response

Time (HH:MM)	Temperature (°C)	Humidity (%)	Soil Moisture (%)	Light Intensity (lux)	Water Level (cm)	Pump Operation
08:00	25	60	40	500	20	Off
09:00	26	58	42	550	18	Off
10:00	28	55	45	600	15	On
11:00	30	52	48	650	12	On
12:00	32	50	50	700	10	On
13:00	33	48	52	750	8	On

14:00	34	47	54	800	6	On
15:00	33	48	53	780	7	On
16:00	32	50	51	760	9	On
17:00	31	52	49	740	11	On
18:00	30	54	47	720	13	On
19:00	28	56	45	700	15	On
20:00	27	58	43	680	17	On

If the performance of the fuzzy logic model and optimal or alternative control strategies were directly compared, it would be evident that the latter consistently performs worse than the former in terms of precision, resource optimization, yield, labour, and risk management. The imposition of a strict structure that doesn't alter the regular operating schedule could be the cause of the former. Because of this, the amount of water, fertilizer, and pesticides used is set at present levels and does not adapt to the needs of various crops or shifts in the real environment. The workload varies as a result, as does the amount of money spent on resources or the use of equipment. Overall, by enabling precise, prompt corrections, the application of the fuzzy logic model would result in increases in these corresponding measures. Farmers would save a great deal of time by using automated systems, which would not only apply the necessary actions at the right times but also lessen the need for manual labour and monitoring. Crucially, the application of the fuzzy logic model aids in risk control by predicting and responding to possible emergencies such as droughts and floods. All things considered, a comparison of the fuzzy logic model with traditional or alternative approaches shows how revolutionary the former can be in transforming agriculture and raising the profitability of these businesses.

7. Conclusion

By creating a smart farming and monitoring system using fuzzy logic system monitoring and controlling, this study sought to increase agricultural yield. Significant environmental factors, including temperature, humidity, soil moisture, light, and water level, were measured using a variety of sensor types. By using a fuzzy logic rule-based system and decision-making technique, this smart farming system shows how irrigation facilities can be used at the right times to improve farming, monitoring, and pest control, ultimately leading to increased agricultural productivity. After analysis and testing, the fuzzy logic sensor's performance appears to be precise and suitable for the water pump motor system with the speed motor's effective operation and prediction. The fuzzy logic system is adaptable to changes in temperature and humidity, makes efficient use of the resources available, and offers chances to boost agricultural productivity and farmer income while centralizing farming. Comparing it to other control techniques and farming-based systems reveals its significance and potential, and the most successful and efficient computerized structure is a smart farming system that uses fuzzy logic. It is recommended that future studies focus on improvements in sensor systems and the use and expansion of creation of cutting-edge IT systems. Improvements in farming systems can be made based on the interdisciplinary aspect, and it may be beneficial to the agricultural sector to enable development. Thus, the significance of artificial intelligence and sensor technology through the use of fuzzy logic technology appears to be recognized, and both contribute to the agricultural sector's prosperity in terms of sustainability and viability from a fresh perspective.

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Wind-Induced Torsional Behavior of Low and Medium-Rise Structures: Codes, Experiments, and Mitigation

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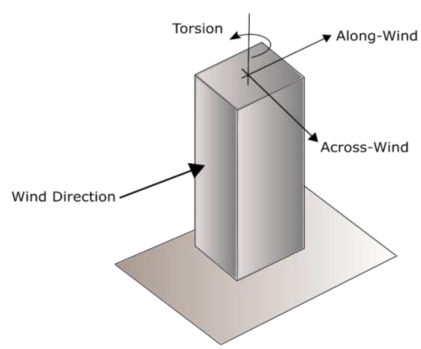
Abstract

The non-uniform distribution of wind pressure on building surfaces generates torsional moments, significantly altering the overall pattern of wind-induced forces acting on the structure. Recognizing the importance of these effects, this study systematically examines international codal provisions that address torsional wind loading in low- and medium-rise buildings. It further reviews key findings from wind tunnel investigations that provide insight into the mechanisms and magnitudes of such torsional responses. In addition, various mitigation strategies are discussed to assist designers and engineers in developing effective solutions to minimize the adverse impacts of wind-induced torsion. By integrating codal requirements, experimental evidence, and practical mitigation approaches, this paper contributes to a comprehensive understanding of design considerations associated with torsional wind effects in low- and medium-rise structures.

Introduction

Effective mitigation of wind loads in building design hinges predominantly on the thoroughness of code provisions and adherence to wind load standards. Despite significant advancements in understanding along- and across-wind forces on buildings over the past decades, research on wind-induced torsional loads remains notably scarce. The wind-induced loads and their components are represented in Figure 1. The current trajectory of constructing increasingly intricate building shapes and structural systems introduces the potential for heightened unbalanced wind loads, consequently elevating torsional moments. Torsional motions pose a unique challenge as they provide occupants with an extra sensation caused by a perceived rotating horizon, unlike other elements of wind loads. In tall buildings, occupants are more likely to be disturbed by torsional motion than translational motion [1]. Ferrareto et al. [2] proposed an alternative method to evaluate human comfort in response to wind-induced motion. The torsional loading of a building is primarily influenced by its cross-sectional shapes. Findings by Cheung et al. [3] and Beneke & Kwok [4] indicate that the triangular-shaped model exhibits a significantly more robust dynamic torsional response compared to other shapes. Low-rise buildings, being the prevalent type globally, are particularly susceptible to increased damage during catastrophic events associated with high winds. For tall buildings, resonant responses are significant; however, dynamic responses of medium-rise buildings are influenced by quasi-steady gust loading with small resonant effects. Studies of wind load combinations including torsion for medium-rise buildings were conducted by Tamura et al. [5] and Keast et al. [6]. Isyumov and Case [7] conducted wind tunnel experiments measuring wind-induced torsion on three low-rise buildings with varying aspect ratios, proposing the application of partial wind loads analogous to those used in medium-rise building design, as a potential enhancement until more relevant data is accessible. As a result of a wind tunnel study, Elsharawy et al. [8] recommended that wind-induced torsional loads on low and medium-rise buildings must be improved.

Figure 1 *Direction of wind loading and its component.*



Codal Guidelines

Despite the numerous wind tunnel tests conducted to estimate torsional wind loads, there is a noticeable scarcity of international codes offering specific guidelines for the incorporation of torsional wind loading. This section succinctly encapsulates the directives pertaining to torsional wind loading delineated in various prevailing international wind loading codes.

American Code Guidelines

As per the regulations outlined in the American code, a structure qualifies as low-rise if its mean roof height (*h*) is below 18 meters, and *h* is also less than the smallest horizontal building dimension. ASCE 7-22 [9] introduces two loading scenarios: maximum torsion accompanied by shear and maximum shear accompanied by torsion.

In accordance with the ASCE 7-22 [9] guidelines, for low-rise buildings, the assessment of maximum torsion involves the utilization of 75% of the highest wind loads and an equivalent eccentricity of 15% of the building's dimensions. ASCE 7-22 [9] has exempted the requirement for calculating torsional wind loads for buildings with flexible diaphragms. It further specifies that buildings with torsional eccentricity exceeding 5% of their width should be avoided in cases where the buildings have rigid diaphragms. This precautionary measure aims to prevent significant shear forces resulting from torsion effects and the consequent torsional story drift, thereby averting damage to interior walls and cladding.

Canadian Code Guidelines

The Canadian code [10] classifies a low-rise building as having a height (*h*) less than 10 meters or, alternatively, less than 20 meters with *h* being smaller than the smallest horizontal dimension The National Research Council of Canada [10] provides guidelines for the evaluation of the maximum torsion by taking 56% of the maximum wind load with eccentricity of (15%) of building dimensions.

European Code Guidelines

According to the European standard [11], a building is categorized as low-rise if the height (h) is less than 15 meters. The European code [11]considers the maximum torsion as 0.70 of maximum wind load with an additional equivalent eccentricity of 7% of building dimensions.

Codal comparison study

Elsharawy *et al.* [8] assessed wind-induced torsional loads on three suburban medium-rise buildings (aspect ratio 1 to 3) using American, Canadian, and European codes. Comparing results, significant variability was observed. Torsional coefficients as shown in Fig. 2, increased with higher side ratios, with the American standard predicting the highest, and the European standard the lowest coefficients.

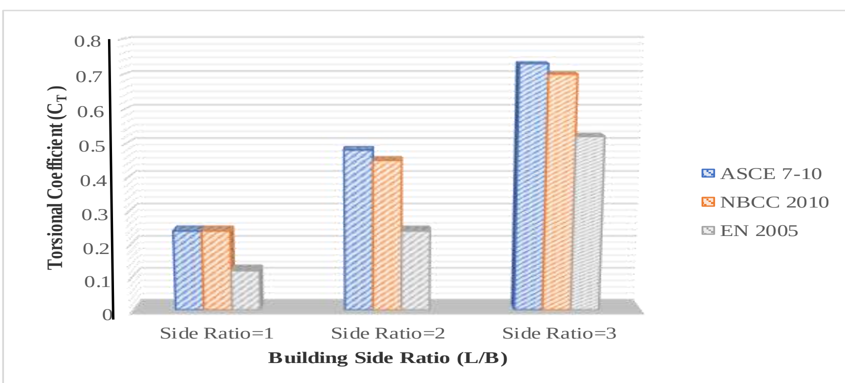


Figure.2 Torsional coefficients for medium rise buildings (B=30 m, H=60m, L/B=1, 2 and 3)

Wind tunnel studies

In the evaluation of wind loads on structures, wind tunnel tests have demonstrated consistent reliability and effectiveness over recent decades, largely attributed to their ability to replicate the actual wind conditions surrounding buildings.Tallin and Ellingwood [12] initiated early efforts to establish the generalized torsional load, drawing upon wind tunnel data provided by Reinhold [13].Utilizing a linear mode shape in their analysis, their results revealed that the root mean square (RMS) value of the actual modal torque constituted 57% of the torque determined through a force balance and 51% of the torque computed employing a cantilever mode shape. Holmes[14], Stathopoulos [15], and Krishna[16] have provided extensive reviews of past field measurements, wind tunnel experiments, and analytical studies concerning wind loads on low-rise buildings. Tamura[5] conducted thorough investigations into wind load combinations applicable to buildings of varying heights, including low-, medium-, and high-rise structures. The study involved testing diverse building models under both open and urban terrain exposures. While emphasizing wind load combinations, the primary focus was directed towards scenarios where the wind was perpendicular to the building face. Keast [6] investigated wind load combinations, incorporating torsion, particularly for medium-rise buildings. The study involved testing three building models, two featuring rectangular planes and one adopting an L-shape. The findings from these tests suggest that, for rectangular buildings, the maximum overall torsion coincides with 30-40% of the peak overall drag force. To validate and extend these results, further experimental data for various building configurations is deemed necessary. Table 1 shows the comparison of three wind tunnel study on low rise buildings.

Table 1: Comparison of wind tunnel studies

Experimental Variables	**Tamura *et al.* [5]**	**Keast *et al.* [6]**	**Elsharawy *et al.* [8]**
Wind tunnel technique	High frequency pressure integration	A 6 degree-of- freedom high frequency balance	High frequency pressure integration
Buildings (m)	L= 42.5, B= 30, h= 12.5	L= 40, B= 20, h= 60	L= 61, B= 39, h= 12
Aspect ratio (L/B) Scale	1.4	2	1.6
Scale	1:250	1:400	1:400
Open terrain exposure (α)	0.16	0.16	0.15
Torsional Coeff (C_T Max.)	0.24	0.20	0.22

Mitigation of wind load

Mitigation of wind load on low rise buildings can be obtained by changing the geometry of roof. Numerous research endeavors have explored the alteration of roof shapes through the implementation of mitigation techniques, aiming to alter the flow pattern, diminish wind loads, and subsequently lower the risk of damage to low-rise buildings. Techniques like pergolas and parapets, when strategically placed on edges and corners, serve as effective modifications. These elements can function as enduring architectural features or be utilized for rehabilitation purposes. In historical contexts, parapets found common application in the flat-roof versions of early Mediterranean revival-style homes (Bitsuamlak *et al* [17]). Surry and lin [18] suggested Sawtooth parapets and porous parapets. Al-Chalabi and Elshaer [19] proposed corner and ridge line parapets for the mitigation of wind load. Some of the mitigation strategies are summaries in Table 2.

Table 2 Various mitigation strategies

Mitigation Strategy	**Note**
Wind load mitigation through roof geometry	The alteration of roof shapes has been identified as an effective strategy for mitigating wind loads on low-rise buildings.
Strategic placement	Pergolas and parapets, when strategically placed on edges and corners of buildings, have demonstrated effectiveness in modifying wind loads.
Versatility of mitigation elements	Pergolas and parapets can serve as enduring architectural features or be applied for rehabilitation purposes, showcasing their versatility in wind load mitigation.
Suggested parapet types	Sawtooth parapets and porous parapets were proposed by Surry and Lin (1995) as effective elements for wind load mitigation.
Corner and ridge line parapets	Al-Chalabi and Elshaer (2023) recommended the use of corner and ridge line parapets for effectively mitigating wind loads on low-rise buildings.

Conclusions

The introduction highlights the importance of code provisions and the scarcity of research on wind-induced torsional loads in low and medium rise buildings. Codal guidelines from American, Canadian, and European codes are presented, revealing variations in approaches. Various wind tunnel studies are discussed to understand the current understanding regarding wind load. The mitigation section suggests altering roof geometry and presents historical and contemporary techniques like pergolas and parapets. This paper provides a comprehensive overview of the challenges posed by wind loads, the existing guidelines, and various research contributions and practical solutions for mitigating wind impact on low and medium rise buildings.

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Development and Deployment of Advanced Sensor Technologies in Wireless Sensor Networks for Real-Time Infrastructure Integrity Monitoring: A Case Study

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Abstract

The structural health of critical infrastructure such as bridges, buildings, and tunnels is essential for public safety, economic stability, and disaster prevention. The manual and time-consuming nature of traditional inspection techniques limits their capacity to identify early-stage issues or offer real time insights. This paper presents the development and deployment of an advanced Wireless Sensor Network (WSN) system a case study for continuous, real-time monitoring of infrastructure integrity. The system integrates a suite of specialized sensors—including strain gauges, vibration sensors, and acoustic emission detectors—into low-power wireless nodes capable of collecting and transmitting structural data with high temporal resolution. A robust communication protocol is implemented to ensure reliable data delivery in complex environments, while energy-efficient mechanisms are used to extend system lifespan. The prototype system is evaluated through a case study on a simulated bridge structure, demonstrating high accuracy in detecting structural anomalies, low latency in data transmission, and resilience in adverse conditions. The proposed solution offers a scalable, cost-effective, and intelligent approach to proactive infrastructure maintenance and monitoring, paving the way for smart city applications and real-time structural health diagnostics.

Keywords: - Wireless Sensor Networks (WSNs)**,** Infrastructure Integrity Monitoring**,** Structural Health Monitoring (SHM)**,** Smart Infrastructure**,** Predictive Maintenance**,** Remote Monitoring Systems**,** Low-Power Electronics**,** IoT-Based Monitoring & Civil Infrastructure Safety

1. Introduction

Modern infrastructure systems such as bridges, buildings, tunnels, and pipelines are vital components of a nation's economy and public safety. As these structures age, they are increasingly susceptible to wear, environmental degradation, and unexpected stress, all of which can compromise their integrity and functionality. Traditional methods of infrastructure inspection—typically manual, periodic, and labour- intensive—are often inadequate for detecting early-stage failures or sudden structural changes. These limitations highlight the urgent need for more advanced, continuous, and automated monitoring solutions. Wireless Sensor Networks (WSNs) have emerged as a transformative technology in the domain of Structural Health Monitoring (SHM), offering real-time data collection, remote monitoring capabilities, and scalable deployment over large or complex infrastructures. By embedding networks of distributed, low-power sensors within or around a structure, WSNs enable the continuous monitoring of critical parameters such as stress, strain, vibration, displacement, and temperature. This not only improves the accuracy and frequency of assessments but also significantly reduces the risk of catastrophic failures by enabling early warning systems and predictive maintenance strategies. Recent advancements in sensor technologies—including microelectromechanical systems (MEMS), acoustic emission sensors, and fibre optic sensing—have enhanced the precision, sensitivity, and versatility of WSNs in infrastructure monitoring. However, challenges still exist in terms of sensor calibration, energy efficiency, data communication reliability, and environmental durability, especially in harsh operating conditions. Furthermore, integrating heterogeneous sensors into a unified, energy-efficient wireless system that can perform reliably over extended periods remains an area of active research.

This paper presents the design, development, and real-world deployment of a WSN-based infrastructure monitoring system utilizing advanced sensors for real-time data acquisition and anomaly detection. The proposed system aims to address existing challenges by incorporating multi-modal sensing, optimized wireless communication protocols, and low-power operation strategies. A prototype is tested on a real or simulated infrastructure model, and performance is evaluated based on sensor accuracy, communication reliability, and system energy efficiency.

The goal of this research is to contribute toward smarter, safer, and more sustainable infrastructure systems by leveraging the synergy of advanced sensors and wireless communication. Ultimately, the proposed system provides a foundation for scalable, cost-effective, and proactive infrastructure health management applicable in both urban and remote environments.

2. Literature Review

Real-World Case Studies in Infrastructure Monitoring Using WSN

2.1 The Golden Gate Bridge Structural Health Monitoring

- **Location**: San Francisco, USA
- **Overview**: The Golden Gate Bridge has been instrumented with a variety of sensors including accelerometers, strain gauges, and environmental sensors linked via wireless sensor networks.

- **WSN Role**: Wireless sensor nodes deployed across the bridge collect real-time data on vibrations, strain, and temperature fluctuations. This data is used to detect stress caused by traffic loads, wind, and seismic events.
- **Outcome**: Enabled continuous, automated monitoring reducing the need for manual inspections, improving safety, and extending the bridge's operational life. [1]

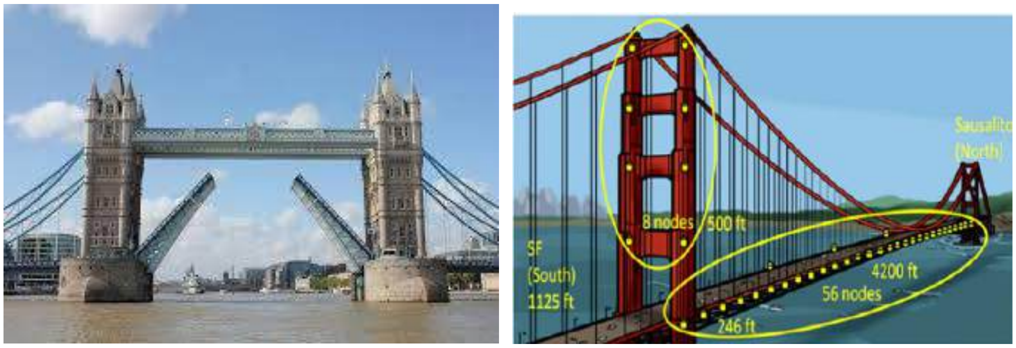

Fig: 2.1 Golden Gate Structure in USA Bridge

2.2 Tsing Ma Bridge SHM System in Hong Kong

Location: Hong Kong

- **Overview**: One of the world's longest suspension bridges equipped with a comprehensive SHM system using WSN for strain, displacement, and vibration monitoring.
- **WSN Role**: Wireless nodes transmit data from sensors to a central gateway that processes structural response to typhoons and heavy traffic.
- **Outcome**: Early warning system implemented to trigger maintenance alerts and prevent catastrophic failures. [2]

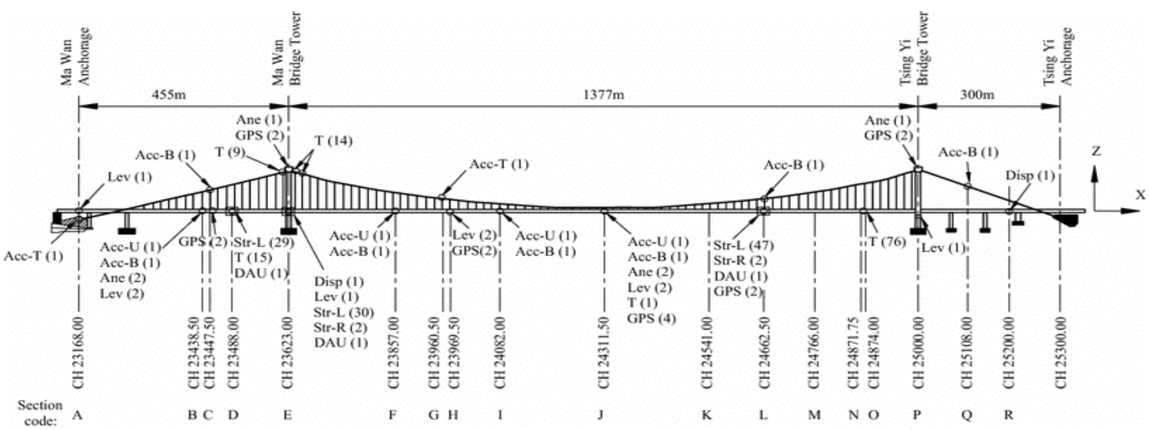

Fig: 2.2 Tsing Ma Bridge SHM System in Hong Kong

2.3. European Smart Road Bridges (COST Action TU0901)

- **Location**: Various European countries
- **Overview**: This project involved deploying wireless sensor nodes with strain and acceleration sensors on road bridges to monitor structural health under traffic loads.
- **WSN Role**: Real-time data collection facilitated condition assessment and informed maintenance scheduling.
- **Outcome**: Demonstrated that WSNs can provide reliable, scalable, and cost-effective SHM solutions for civil infrastructure. [3]

Fig: 2.3 **European Smart Road Bridges (COST Action TU0901)**

2.4 Tokyo Skytree SHM Deployment

- **Location**: Tokyo, Japan
- **Overview**: The Tokyo Skytree, one of the tallest towers globally, utilizes a network of wireless vibration and displacement sensors to monitor structural response to wind and earthquakes.
- **WSN Role**: Provides continuous remote monitoring with alerts for abnormal structural movement.
- **Outcome**: Enabled enhanced safety measures and real-time feedback during seismic events. [4]

Fig: 2.4 **Tokyo Skytree SHM Deployment**

2.5 Smart Campus Infrastructure Monitoring – UC Berkeley

- **Location**: Berkeley, California, USA
- **Overview**: A smart campus initiative deployed WSNs with multiple sensor types across campus buildings and bridges to monitor environmental and structural parameters.
- **WSN Role**: Integrated environmental data (temperature, humidity) with strain and vibration measurements for holistic monitoring.
- **Outcome**: Reduced maintenance costs and improved safety by enabling predictive maintenance strategies. [5]

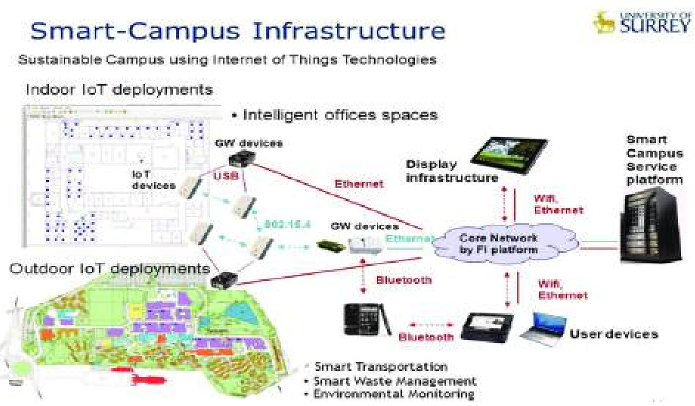

Fig: 2.5 **Smart Campus Infrastructure Monitoring**

3. Methodology

This section outlines the design, implementation, and evaluation of a Wireless Sensor Network (WSN)-based system equipped with advanced sensors for real-time monitoring of infrastructure integrity. The methodology includes sensor selection and integration, system architecture, communication protocols, power management strategies, and performance evaluation through a case study deployment.

3.1 System Design Overview

The proposed system consists of distributed wireless sensor nodes deployed across critical points of an infrastructure (e.g., bridge piers, beams, or joints). Each node is equipped with multiple sensors to measure structural parameters such as strain, vibration, temperature, and acoustic emissions. The nodes wirelessly transmit collected data to a central gateway, which processes, stores, and forwards the data to a cloud-based monitoring dashboard.

3.2 Sensor Selection and Integration

The choice of sensors was based on their relevance to infrastructure health and compatibility with low-power embedded systems. The selected sensors include:

- **Strain Gauges**: For detecting deformation in structural components.
- **Accelerometers**: To monitor vibrations and dynamic responses.
- **Acoustic Emission Sensors**: For identifying crack initiation and propagation.
- **Temperature Sensors**: To account for environmental influence on material behaviour.

All sensors were interfaced with a microcontroller unit (MCU) via analog or digital input channels. Signal conditioning circuits were used to amplify and filter sensor outputs before digitization.

Table 3.1 Sensor Specifications and Characteristics

Sensor Type	Measurement Parameter	Technology Used	Range	Accuracy	Power Consumption	Application in Infrastructure Monitoring
Strain Gauge	Strain (deformation)	Resistive Wheatstone Bridge	±3000 με	±1 με	Low (~10 mW)	Detecting stress, crack initiation
MEMS Accelerometer	Vibration (acceleration)	Capacitive MEMS	±16 g	±0.01 g	Very Low (~5 mW)	Dynamic response, earthquake monitoring
Acoustic Emission Sensor	Crack detection	Piezoelectric	100 kHz – 1 MHz	High frequency range	Moderate (~15 mW)	Early fracture detection
Temperature Sensor	Ambient temperature	Thermistor / RTD	-40°C to 125°C	±0.5°C	Very Low (~2 mW)	Environmental compensation, thermal stress analysis

Fiber Bragg Grating	Strain & Temperature	Optical Fiber Sensor	±5000 με, -40°C to 85°C	±1 με, ±0.1°C	Passive (requires light source)	Long-distance strain measurement, corrosion monitoring

3.3 Wireless Sensor Node Architecture

Each sensor node comprises the following components:

- **Microcontroller Unit (MCU)**: ESP32 for onboard processing and Wi-Fi communication.
- **Sensors**: As listed above, calibrated and sampled at defined intervals.
- **Wireless Communication Module**: Integrated Wi-Fi or LoRa module for data transmission.
- **Power Supply**: Rechargeable Li-ion battery with solar energy harvesting (optional).
- **PCB Design**: Compact, weather-resistant enclosure for outdoor deployment.

Nodes operate using a duty cycling mechanism, waking periodically to sample data, transmit readings, and then return to a low-power sleep mode.

Table 3.2 Wireless Communication technologies Compression

Communication Protocol	Range	Data Rate	Power Consumption	Network Topology	Suitability for Infrastructure Monitoring
Wi-Fi	~100 meters	Up to 54 Mbps	High (~400 mW)	Star, Mesh	High data rate but limited range and higher power
ZigBee (IEEE 802.15.4)	10-100 meters	Up to 250 kbps	Low (~30 mW)	Mesh	Good for low data rate, multi-hop sensor networks
Lo Ra WAN	Up to 15 km (line of sight)	Up to 50 kbps	Very Low (~10 mW)	Star	Ideal for long-range, low data rate and low power
Bluetooth Low Energy (BLE)	~50 meters	Up to 2 Mbps	Low (~10 mW)	Star	Suitable for short-range, low power monitoring

3.4 Communication Protocol and Network Topology

All sensor nodes connect directly with a central gateway node in a star architecture, which was chosen for its simplicity and low latency. Depending on the deployment area, either **Wi-Fi** (for short range, high data rate) or **LoRa** (for long range, low power) was selected.

The communication stack included:

- **MQTT protocol** for lightweight messaging and reliability.
- **Data encryption** for secure transmission over public networks.
- **Time-synchronized sampling** to ensure temporal consistency across nodes.

Table 3.3 System performance Evaluation Summary (Prototype Deployment)

Parameter	Metric / Value	Description
Sampling Rate	10 Hz	Frequency of sensor data acquisition
Data Transmission Latency	< 500 ms	Time delay from sensor to gateway
Packet Delivery Ratio	98.7%	Successful data reception percentage
Battery Life (Node)	~30 days	Duration on a single charge with duty cycling
Detection Accuracy (strain)	±1 με	Compared to calibrated reference instruments
Anomaly Detection Response	< 2 seconds	Time to trigger alert after anomaly detection
Operating Environment	-20°C to 60°C	Tested temperature range

3.5 Data Aggregation and Anomaly Detection

All sensor node data is gathered by the gateway node, which then locally aggregates it before sending it to a distant server. An edge-processing algorithm was implemented to detect abnormal patterns (e.g., sudden strain spikes or unusual vibrations) and trigger real-time alerts.

Key features:

- Threshold-based alerts (customizable for each sensor type).
- Rolling average filters for noise reduction.
- Optional cloud-based machine learning module for anomaly classification.

3.6 Energy Optimization Strategy

Energy efficiency is crucial for long-term deployment. The following techniques were used:

- **Duty cycling**: Sensors and transceivers operate only during sampling windows.
- **Low-power sleep modes**: MCU enters deep sleep between tasks.
- **Adaptive sampling**: Increased sampling during detected anomalies, reduced during normal conditions.
- **Energy harvesting**: Solar panels used for supplemental power in remote deployments.

3.7 Prototype Deployment and Testing

A prototype system was deployed on a scaled-down bridge model constructed in a controlled lab environment. Sensors were placed at critical load-bearing points. Data was collected over a 14-day period under varying simulated load conditions.

Performance was evaluated based on:

- Sensor accuracy (compared to reference instruments)
- Data transmission success rate
- Power consumption over time
- Responsiveness to induced structural anomalies

Table 3.4 Comparative Summary of Existing WSN – based Infrastructure Monitory Systems

Study / Deployment	Sensor Types	Wireless Tech Used	Key Features	Limitations
Golden Gate Bridge (Spencer et al.)	Strain gauges, accelerometers	Wi-Fi, ZigBee	Real-time monitoring, seismic detection	High power consumption
Tsing Ma Bridge (Ni et al.)	Strain, displacement and vibration	ZigBee and Wi-Fi	Typhoon response and early warning	Difficult network maintenance
COST TU0901 Project (Europe)	Strain, acceleration	LoRa, ZigBee	Long-range, multi-hop scalability	Limited data rate
Tokyo Skytree (Otani et al.)	Vibration, displacement	Custom WSN protocols	Earthquake response, edge computing	Proprietary system, cost

4. Conclusion

Sensor Technology for Infrastructure Monitoring

Wireless Sensor Networks rely heavily on the types and capabilities of sensors deployed to monitor the health and integrity of infrastructure systems. Sensor selection has a direct impact on the monitoring solution's precision, dependability, and reach.

4.1 Strain Sensors

- **Purpose**: Assess the strain or deformation of structural elements when they are under load.
- **Technology**:
  - **Strain Gauges**: When crushed or stretched, resistive components alter their resistance.
  - **Fiber Bragg Grating (FBG) Sensors**: Use light wavelength shifts in fiber optics to detect strain.
- **Use in WSNs**: Provide precise measurements of stress variations; critical for detecting cracks, bending, and structural fatigue.

4.2 Vibration Sensors

- **Purpose**: Detect vibrations and dynamic responses caused by traffic, wind, earthquakes, or machinery.
- **Technology**:
  - **Piezoelectric Accelerometers**: Generate voltage when subjected to mechanical stress.
  - **MEMS Accelerometers**: Compact, reasonably priced microelectromechanical devices that work well with wireless nodes.
- **Use in WSNs**: Early detection of abnormal vibration patterns can signal structural damage.

4.3 Acoustic Emission Sensors

- **Purpose**: Monitor high-frequency waves generated by crack formation and propagation.
- **Technology**: Piezoelectric transducers sensitive to ultrasonic frequencies.
- **Use in WSNs**: Detect micro-cracks and fractures before they become visible or cause failure.

4.4 Temperature Sensors

- **Purpose:** Measure ambient and material temperatures, which affect structural properties.
- **Technology**: Thermistors, RTDs (Resistance Temperature Detectors), or semiconductor-based sensors.
- **Use in WSNs**: Helps in compensating sensor readings and identifying thermal stresses.

4.5 Displacement Sensors

- **Purpose**: Measure movements or deflections in structural elements.
- **Technology**: LVDT (Linear Variable Differential Transformer), laser displacement sensors.
- **Use in WSNs**: Useful for monitoring subsidence or shifting foundations.

4.6 Humidity and Environmental Sensors

- **Purpose**: Track environmental conditions influencing corrosion and material degradation.
- **Technology**: Capacitive or resistive humidity sensors.
- **Use in WSNs**: Complement structural data for a holistic understanding of infrastructure health.

Integration Considerations

- **Power Consumption**: Sensors must be low-power or support duty-cycling for WSN use.
- **Size and Weight**: Miniaturized sensors like MEMS are preferred for ease of deployment.
- **Signal Conditioning**: Necessary for amplifying and filtering raw sensor outputs.
- **Communication Compatibility**: Sensors should interface seamlessly with microcontrollers in WSN nodes.

Emerging Trends

- **Multi-Modal Sensors**: Devices combining several sensing modalities in one unit.
- **Energy Harvesting Sensors**: Sensors powered by ambient energy (solar, vibration).
- **Wireless Passive Sensors**: Sensors that communicate without batteries, such as RFID-based.

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Transport and Fate of PFAS and Micro/Nanoplastics in Groundwater

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Abstract
Landfills and wastewater treatment plants have become major sources of new types of pollution, particularly microplastics and chemicals called PFAS. These PFAS chemicals are especially worrying because they're found everywhere in our environment, they don't break down naturally, and they can harm living things. That's why health experts are really concerned about them. Both landfills and wastewater facilities are releasing lots of these new pollutants, including tiny plastic particles and PFAS chemicals, into the environment. What makes this worse is that these substances are completely artificial - they don't exist in nature at all.

PFAS is actually a huge group of different chemicals that manufacturers use to make things like non-stick pans, waterproof clothing, paper products, and firefighting foam. Companies love using these chemicals because they're great at repelling water and oil, they can handle extreme temperatures, and they reduce friction. After decades of making and using these chemicals, they've ended up scattered throughout our environment. When PFAS gets into groundwater, it behaves pretty much like other dissolved pollutants - it moves around through processes like water flow, spreading out, sticking to soil particles, and getting diluted.

Researchers are only beginning to grasp just how harmful PFAS can be to both people and nature. Certain kinds, especially PFOA and PFOS, are really troublesome since they move through water systems so easily, stick around forever without breaking down on their own, and keep accumulating in plants and animals as time goes on.

Keywords: groundwater pollutant, Microplastics, per- and polyfluoroalkyl substances, Diffusion, zwitterion.

1. Introduction

Underground water serves as a crucial freshwater supply for no less than two billion people around the globe, and people rely on it for everything from drinking water to farming, household needs, and manufacturing activities. (Re, 2019). Sadly, underground water sources can get polluted by all sorts of new contaminants that come from human activities. (Lap worth et al., 2012), such as per– and poly-fluoroalkyl substances (PFASs) and pharmaceuticals (Sui et al., 2015). This could stop people from being able to use groundwater in helpful ways and might mean expensive and difficult cleanup work has to be done. (Siegel, 2014). Groundwater gets polluted mainly from farm chemicals washing away (Abdalla and Khalil, 2018), recycled sewage and organic waste (Lapworth et al., 2012), and factories dumping stuff (Xu et al., 2021). Since plastic production really started booming back in the 1950s, we've become absolutely obsessed with these materials at a crazy pace. We went from making just 1.5 million tons of plastic each year back in the 1950s to churning out more than 370 million tons by 2019 (Kumar, Verma et al. 2021). What's really troubling is that about 79% of all the plastic we make ends up in landfills or scattered throughout our environment, while only a tiny 9% actually gets recycled properly (Geyer et al. 2017). Because of this, plastic waste and tiny plastic particles are now everywhere you look in nature. These microscopic plastic bits keep showing up in rivers, lakes, and streams, and researchers have even found them contaminating our underground water supplies (Hoellein et al., 2017; Lenaker et al., 2019; Panno et al., 2019; Xu, Ou et al., 2022). PFAS make up a big group of chemicals that companies use to make things like non-stick pans, fabrics, paper goods, certain firefighting foams, and tons of other stuff we use every day. What makes these chemicals so popular is that they're really good at keeping oil and water away, they can handle really hot or cold temperatures without breaking down, and they help reduce friction between surfaces. The thing about PFAS is that they come in all different sizes and shapes at the molecular level, with various structures and parts that do different jobs. Because we've been making and using these chemicals for so many years, they've ended up spreading throughout our environment.

2. Physical Properties

The way PFAS behaves in the environment - like what form it takes and how it spreads around - depends on both the physical and chemical makeup of these compounds and the specific conditions of the environment they're in.

2.1 Physical State/Appearance

At room temperature, you'll typically find most PFAS as solid materials that look crystalline or powdery. But here's the thing - the ones with shorter chains, like the acid versions of PFCA and PFSA, along with FTS and FTOH that have 4 to 6 carbon atoms in their tail, actually stay liquid when they're at room temperature.

2.2 Density

When liquid PFAS compounds are denser than water, they can sink down through groundwater or surface water as what scientists call DNAPL - basically a heavy liquid that doesn't mix with water. Take 4:2 FTOH as an example - it's liquid at room temperature, weighs about 1.59 grams per cubic centimeter, and dissolves in water at around 974 milligrams per liter. If you spilled pure 4:2 FTOH into the environment, it would act a lot like carbon tetrachloride, which has similar density and dissolving properties. But here's the thing - when 4:2 FTOH actually dissolves in water, the mixture doesn't get heavy enough to form its own separate layer. Interestingly, researchers have noticed that when PFOA and PFOS are mixed with water at really high concentrations, you can actually see separate liquid layers floating on top.

2.3 Melting/Boiling Points

These characteristics decide if a particular pure PFAS chemical will be liquid, solid, or gas at normal environmental temperatures. You'll find that this information can differ between different sources. While we have predicted melting and boiling points for most PFAS chemicals, we don't have actual measured values for many of them. The predicted numbers are helpful for getting a sense of what physical state these PFAS chemicals might be in, but we really don't know how accurate these predictions are - that's something that needs more research. What we do know from the available information is that PFAS chemicals tend to have higher melting and boiling points when their fluorinated chains get longer. Take PFBA for instance - it melts at -17.5°C, but perfluorotetradecanoic acid (PFTeDA) melts somewhere between 130 and 135°C.

2.4 Solubility

Solubility is determined by looking at how much of a substance can dissolve in a liquid under specific temperature and pressure conditions. It's usually expressed in units like milligrams per liter or moles per liter. Right now, we have actual lab measurements for the water solubility of many well-known PFAS chemicals, but we're still missing data for the ones that haven't been studied as much. It's important to keep this data gap in mind when you're working with PFAS solubility information. Most of the numbers you'll see in research are actually predictions or computer models rather than real experimental results, and even the numbers used to create those models might be educated guesses.

2.5 Partitioning to Fluid-Fluid Interfaces

PFAAs have a dual nature - they're made up of water-loving heads attached to water-repelling tails, which makes them act just like regular surfactants. What this means is that they naturally gather at the boundaries between different fluids, like where air meets water or where oil meets water. When they line up along these boundaries, they position themselves so their water-repelling tails stick out into the air while their water-loving heads stay in the water.

3 Chemical Properties

3.1 Carbon-Fluorine (C-F) Bond Properties

The characteristics of PFAS mainly come from what makes the carbon-fluorine bond so special.

Table 1: Fluorine characteristics

Fluorine Characteristic	Description	Effect	Resulting Property of PFAS
High electronegativity	Tendency to attract shared electrons in a bond	Strong C-F bond	Thermal stability
		Polar bond with partial negative charge toward F	Chemical stability (low reactivity)
			Strong acidity (low pKa)1
Low polarizability	Electron cloud density not easily impacted by the elec	Weak intermolecular interactions	Hydrophobic and lipophobic surfactant properties2
		Low surface energy	
Small size	Atomic radius of covalently bonded fluorine is 0.72 Å	Shields carbon	Chemical stability (low reactivity)

1. When paired with an acid functional group such as a carboxylic or sulfonic acid.
2. When paired with a functional group that is hydrophilic (for example, a carboxylate)
3. Smallest of the halogen atoms.

Fluorine has some pretty special characteristics - it's highly electronegative and really small, which creates an incredibly strong bond with carbon that's actually the toughest covalent bond you'll find in organic chemistry. Since fluorine doesn't get polarized easily, it doesn't interact much with other molecules through things like Van der Waals forces or hydrogen bonds. These distinctive traits are what make many PFAS compounds so good at repelling both water and oil, which is why they work great for stain-resistant products and as surfactants. They're also incredibly stable when exposed to heat or chemicals. That said, not every PFAS compound has all of these features - surface activity, for instance, isn't something you'll see across the board.

3.2 Functional Group Properties

PFAS contain various functional groups like carboxylates, sulfonates, sulfates, phosphates, amines, and several others. Whether these groups are dissociated or not plays a big role in how PFAS behave and move around in the environment. Basically, whether a compound has an electrical charge affects its physical and chemical characteristics, which then determines what happens to it in nature.

Because PFAAs have really low acid dissociation constants, you'll almost always find them as negatively charged anions in the environment - it's extremely rare to see them any other way. Some PFAS compounds can actually break apart into either positive or negative ions when they're in water, depending on the pH levels. Take PFOA, for example - when it dissolves in water across most pH ranges, it splits into a perfluorooctanoate anion and a hydrogen ion. The part of ionic PFAS that contains the fluoroalkyl chain can end up being negatively charged, positively charged, or even both at the same time as a zwitterion.

PFAS can be grouped into four different categories depending on their functional groups.

- Anionic means it has acidic parts like carboxylic acids, sulfonic acids, sulfates, and phosphates that can give off a hydrogen ion, which creates a negatively charged particle called an anion.
- Cationic substances have basic functional groups like amines that can pick up a hydrogen ion to become positively charged, or they might already have a permanent positive charge like you'd see with quaternary ammonium groups.
- A zwitterionic compound has two or more functional groups where at least one can become negatively charged and another can become positively charged.
- Nonionic substances don't break apart into charged particles - alcohols are a good example of this type of compound.

Given how other positively and negatively charged surfactants behave, we'd expect positively charged PFAS to move through the environment differently than negatively charged PFAS.

3.3 Thermal Stability

The ability of a chemical to stay stable when heated up, known as thermal stability, helps us figure out how long that chemical might stick around in our environment. Chemicals like PFOA and PFOS, which belong to a group called PFAAs, are incredibly tough - they don't break down easily when exposed to heat or other chemical processes, and they resist both degradation and oxidation. What makes these PFAAs so remarkably stable when heated comes mainly from the super-strong bonds between carbon and fluorine atoms in their fluoroalkyl chains, though how stable they are also depends on what specific functional group is attached to that fluoroalkyl part. Among fluorinated surfactants, PFCAs and PFSAs are the champions when it comes to handling heat. Different studies give varying numbers for the temperatures needed to break down PFAS, but it looks like you might need temperatures over 1,000 degrees Celsius to destroy PFAS that's in soil. Earlier research showed that even at 700 degrees Celsius, only a limited amount of PFOS, PFOA, and PFHxA actually got completely broken down - we're talking about 72% or less.

3.4 Chemical Stability

Just like how we look at thermal stability, understanding how chemically stable a molecule is helps us figure out how long it will stick around in the environment. PFCAs and PFSAs have proven to be really persistent out there in nature. PFCAs can resist breaking down from oxidation in normal environmental conditions, though scientists have managed to transform them when using strong oxidizing agents under really intense pressure. In the fluorinated chain part of these alkyl acids, you've got the strong bond between carbon and fluorine, plus the way fluorine atoms shield the carbon, and the pull effects from fluorine being so electronegative - all of this adds up to make these molecules really chemically stable. Think about it this way: there are these electron-rich molecules called nucleophiles that would normally be drawn to the slightly positive carbon atoms. But if these nucleophiles could actually get close enough to bond with the carbon, the reaction that follows might kick out a fluorine atom and replace it with the nucleophile, which could then make the whole molecule more susceptible to breaking down.

4 Fate and Transport Processes

4.1 Partitioning

PFAS move around, get transported, and change form across different types of environments. The PFAS chemicals we usually find in nature have a special structure - they've got a carbon-fluorine "tail" part and a regular "head" part that contains a polar group. You can see this setup in Figure 2 with PFOS and PFOA as examples. The tail part repels both water and fats, while the head part attracts water.

Several key things control how PFAS behave in the environment, including their tendency to avoid water and fats, electrical attractions between charged particles, and how they act at boundaries between different materials. That water-and-fat-avoiding behavior makes them stick to organic matter in soil. The electrical interactions depend on whether the polar head group is charged or not.

Generally speaking, PFAS with longer tails stick around more and move more slowly through soil compared to those with shorter tails. This means short-chain versions of PFSAs and PFCAs don't get held back as much as the long-chain ones. Also, PFSAs typically stick to surfaces better than PFCAs when they have the same tail length, and the branched versions don't stick as well as the straight-chain ones.

4.2 Transport

Since most PFAS chemicals don't break down naturally through biological processes or environmental conditions - aside from when precursor compounds transform - the way they physically move through the environment becomes really important for understanding how they spread and where people might come into contact with them.

4.2.1 Advection, Dispersion, Diffusion

The movement of PFAS chemicals through different environments gets heavily affected by things like advection, dispersion, and diffusion. When we talk about advection, we're basically talking about how these compounds get carried along by flowing fluids like water or air - and this is actually what drives PFAS movement in most situations. The thing is, advection just moves the chemicals around without actually making them less concentrated as they travel.

When air currents and water flow speeds change on a smaller scale, they end up scattering contaminants in various directions. This leads to quick vertical mixing of PFAS and helps them jump between different environments - like going from surface water into sediment or falling from the air onto soil.

Diffusion is what happens when molecules move around because of concentration differences - you see this in both air and water. When water or air gets turbulent and creates mixing, scientists also call this eddy diffusion. In groundwater, people usually don't worry much about diffusion because it happens really slowly compared to advection. But here's the catch - when contaminants spread through diffusion into materials that don't let much through, like clay, bedrock, or concrete, it can actually make PFAS stick around in groundwater for much longer periods.

4.2.2 Deposition

Although most PFAS don't easily turn into gas, some of them can still travel through the air when they're released from factories and industrial plants, like through smokestacks. When these chemicals get into the air, sunlight can break them down and they can be carried by wind currents. Eventually, they settle back down to earth and build up in dirt and water sources where we can actually measure them. This settling process happens in two main ways - either the chemicals just fall out of the air on their own along with tiny particles, or they get washed out when it rains or snows. The dry way happens when PFAS stick to small droplets or particles floating in the air and naturally fall down through gravity or other natural processes. The wet way is basically when rain or snow picks up these contaminated particles as it falls and brings them down to the ground.

4.2.3 Leaching

When it rains or when areas get irrigated, PFAS chemicals found in soil that isn't completely saturated tend to get washed downward as water dissolves these pollutants that are stuck to soil particles. This washing process can move PFAS from the surface soil down into groundwater and nearby water sources, which is especially concerning since these chemicals often end up on the surface through spills or falling from the atmosphere in the first place. This same leaching process can also affect how plants take up PFAS, particularly around landfills that don't have proper systems to control contaminated water runoff. How much leaching actually happens depends on things like the soil's pH level and how much organic matter it contains, as well as the specific characteristics of the PFAS chemicals themselves, such as their electrical charge and the length of their molecular chains.

4.2.4 Surfactant Properties and Micelle Formation

PFAS act like surfactants because they have parts that repel water and parts that attract it, making their movement through the environment complicated and poorly understood. Many PFAS are designed to naturally gather at the boundary between air and water, with their fluorine-containing tails pointing toward the air and their water-loving heads staying in the water. This tendency affects how they travel through the air in tiny droplets and settle out, and it means PFAS tends to build up at water surfaces. This same preference for air-water boundaries probably matters when PFAS moves through soil above the water table, since there's lots of contact between air and water in those spaces. When PFOS and PFOA stick to these air-water boundaries, it can slow down how fast they move through water.

5. PFAS Transformation

PFAA formation can happen when certain polyfluorinated substances called precursors go through natural biological processes or chemical changes in the environment. But once PFAAs are formed, they're pretty much stuck that way - they don't break down under normal environmental conditions. The precursor PFAS are different from the fully fluorinated PFAAs because they have carbon-hydrogen and carbon-oxygen bonds that can actually react and change through various biological and chemical processes, eventually turning into final products. Most of what we know about how these precursor PFAS transform comes from laboratory studies done under controlled conditions, but several real-world field studies have shown that these precursors play a significant role at different locations, like the research done by Weber and colleagues in 2017 and Dassuncao and team that same year.

5.1 Abiotic Transformation

They can create Non-living processes can change chemical precursors into other compounds when they're exposed to normal environmental conditions. These processes include breaking down with water, breaking down with light, and reacting with oxygen. When some precursors break down with water and then get processed by living organisms, PFCAs and PFSAs. Take PFOS, for instance - it comes from a compound called perfluorooctane sulfonyl fluoride when it breaks down this way, as Martin and his team found in 2010. Similarly, PFOA and other PFCAs form when fluorotelomer-based precursors break down with water, according to Washington and Jenkins' 2015 research.

While scientists haven't seen PFAS compounds break down directly from sunlight, some precursors do break down indirectly from light exposure. This happens especially with fluorotelomer alcohols in the atmosphere, which can lead to PFCA deposits falling back to earth. Armitage, MacLeod, and Cousins documented this in 2009, and Yarwood's team did similar work in 2007.
There's another group of compounds called perfluoroalkane sulfonamides that can break down in the atmosphere through oxidation reactions. When this happens, they produce PFCAs at rates that might be ten times higher than what you get from fluorotelomer alcohols, based on Martin's 2006 research. Even shorter-chain compounds like PFBS can form when hydroxyl radicals react with sulfonamido derivatives through oxidation, as D'Eon and colleagues showed in 2006.
Sometimes these non-living transformation processes don't immediately create any PFAA compounds, but they might still lead to PFAA formation eventually, according to Martin's 2010 findings.

5.2 Biotic Transformation

Although PFOA, PFOS, and similar PFAAs can't be broken down by microbes, researchers have found that many of their precursor compounds can be transformed by biological processes, much like the non-biological changes we've talked about. What we know from research shows there are many ways these transformations happen when oxygen is present, they occur pretty quickly, and it looks like all these polyfluorinated precursors could potentially be converted into PFAAs through these oxygen-dependent biological processes. There hasn't been as much research done on what happens when oxygen isn't available. Scientists have seen that FTOHs can change without oxygen, but they seem to turn into stable polyfluorinated acids instead of becoming PFCAs or PFSAs. Researchers also noticed that PFOA and PFOS lost some of their fluorine atoms when ammonium was processed without oxygen in conditions where iron was being reduced.

6. Conclusion

The movement of PFAS chemicals through groundwater happens through the same basic processes we see with other contaminants - they get carried along by water flow, spread out through dispersion, stick to soil particles, and get diluted. How fast these chemicals move depends mainly on how quickly the groundwater flows and how much they stick to the surrounding soil and rock materials.
The chemistry of the groundwater itself and what the underground materials are made of play a big role in determining where PFAS ends up and how it moves around. When groundwater is more acidic, has more calcium, or contains more dissolved minerals, PFAS tends to stick better to the soil, which can slow down how fast it spreads and reduce how much stays dissolved in the water. Having more organic matter in the soil or mineral surfaces with positive charges also helps trap many types of PFAS, making them move more slowly through the ground.
The specific makeup of different PFAS chemicals affects how they behave underground too. These chemicals can have carbon chains that are short or long, straight or branched, or even formed in rings, and all of this influences how well they stick to soil. Generally, PFAS with longer, straight chains are more likely to get held up by sticking to soil particles. These chemicals also have a polar "head" that makes them interact with electrical charges.
What makes PFAS different from many other groundwater pollutants is that most of them don't break down naturally - they just stick around indefinitely. Some related chemicals called precursors might partially break down, but they just turn into the more stable PFAS that then persist without changing further. This means these chemicals can actually build up over time instead of disappearing like other contaminants might.
Even though most PFAS act like soaps or detergents, the amounts we typically find in the environment are usually too low for them to form the structures that soaps make when concentrated. Still, even at these lower levels, PFAS molecules might clump together in small groups.

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Advancement in the World of IoT and Network Security

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Abstract

The Internet of Things (IoT) has become a revolutionary technological domain that connects billions of smart devices across the globe, transforming sectors such as healthcare, transportation, and manufacturing. With the rapid growth of IoT networks, new and complex security vulnerabilities have emerged, requiring advanced protective measures. This paper investigates the latest progress in IoT development and the concurrent enhancement of cybersecurity mechanisms aimed at safeguarding interconnected systems. It discusses evolving cyber threats, modern security frameworks, integration of artificial intelligence, applications of blockchain, and future trends in fortifying IoT infrastructures. The findings highlight that although notable advancements have strengthened IoT security, the continuously changing threat environment calls for persistent innovation and adaptive defense strategies.

Keywords: Internet of Things, Network Security, Cybersecurity, Edge Computing, Blockchain, Artificial Intelligence, Zero Trust Architecture

1. Introduction

The Internet of Things represents a fundamental shift in how physical and digital worlds interact, with estimates suggesting over 75 billion connected devices by 2025. This unprecedented connectivity promises enhanced efficiency, automation, and data-driven decision-making across sectors. However, the proliferation of IoT devices has simultaneously created an expanded attack surface for malicious actors, making network security paramount to the sustainable growth of IoT ecosystems.

Unlike traditional computing systems, IoT devices often operate with limited computational resources, inconsistent update mechanisms, and diverse communication protocols. These constraints, combined with the critical nature of many IoT applications—such as medical devices, industrial control systems, and smart city infrastructure—elevate the importance of robust security measures. This paper synthesizes recent advancements in both IoT technology and the security frameworks designed to protect them, providing insights into current challenges and future trajectories.

2. Evolution of IoT Architecture

2.1 From Centralized to Distributed Systems

Traditional IoT architectures relied heavily on centralized cloud computing for data processing and decision-making. Recent advancements have shifted toward distributed architectures that leverage edge computing and fog computing paradigms. Edge computing processes data closer to the source, reducing latency and bandwidth consumption while enhancing privacy by minimizing data transmission to central servers. This architectural evolution not only improves performance but also introduces new security considerations at the network edge.

2.2 5G Integration and Enhanced Connectivity

The deployment of 5G networks has revolutionized IoT connectivity by providing ultra-reliable low-latency communication (URLLC), massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB). These capabilities enable real-time applications such as autonomous vehicles, remote surgery, and industrial automation. However, 5G's network slicing technology, which creates virtual networks tailored to specific applications, introduces complex security challenges that require sophisticated segmentation and isolation mechanisms.

3. Emerging Security Threats in IoT Ecosystems

3.1 Botnet Attacks and DDoS Campaigns

IoT devices have become prime targets for botnet recruitment due to weak default credentials and inadequate security implementations. The Mirai botnet demonstrated the devastating potential of compromised IoT devices in launching distributed denial-of-service (DDoS) attacks. Recent variants have become more sophisticated, employing polymorphic techniques and targeting specific device vulnerabilities to evade detection.

3.2 Data Breaches and Privacy Violations

IoT devices collect vast amounts of sensitive data, including personal health information, location data, and behavioral patterns. Inadequate encryption, insecure APIs, and poor access controls have resulted in numerous high-profile data breaches. The aggregation of data from multiple IoT sources also enables sophisticated profiling attacks that can compromise user privacy even when individual data points appear innocuous.

3.3 Supply Chain Vulnerabilities

The complex global supply chains involved in IoT device manufacturing introduce multiple points of potential compromise. Hardware trojans, backdoors, and counterfeit components can be introduced during manufacturing, assembly, or distribution phases. These supply chain attacks are particularly insidious as they may remain undetected throughout the device's operational lifetime.

4. Advanced Security Mechanisms and Protocols

4.1 Lightweight Cryptography

Traditional cryptographic algorithms often exceed the computational capabilities of resource-constrained IoT devices. Recent advancements in lightweight cryptography have produced algorithms specifically designed for IoT environments. The NIST Lightweight Cryptography Standardization Project has evaluated numerous candidates, with algorithms like ASCON showing promise for providing robust security with minimal computational overhead. These lightweight primitives enable end-to-end encryption on devices with limited processing power and battery capacity.

4.2 Zero Trust Architecture for IoT

The Zero Trust security model, which assumes no implicit trust regardless of network location, has gained traction in IoT deployments. This approach requires continuous verification of device identity, authentication of communications, and authorization of each action. Micro-segmentation divides networks into isolated zones, limiting lateral movement in the event of a compromise. Implementation of Zero Trust in IoT environments involves device attestation, secure boot mechanisms, and continuous behavioral monitoring to detect anomalies.

4.3 Blockchain for IoT Security

Blockchain technology offers decentralized security solutions particularly suited to distributed IoT ecosystems. Smart contracts can automate access control policies and enforce security protocols without centralized authorities. The immutable ledger provides tamper-proof audit trails for device actions and data transactions. Lightweight blockchain implementations, such as directed acyclic graph (DAG)-based architectures like IOTA, address the scalability and resource constraints inherent in IoT environments while maintaining security properties.

5. Artificial Intelligence and Machine Learning in IoT Security

5.1 Anomaly Detection and Threat Intelligence

Machine learning algorithms excel at identifying unusual patterns in network traffic and device behavior that may indicate security incidents. Supervised learning models trained on labeled attack data can recognize known threats, while unsupervised and semi-supervised approaches detect novel attacks by identifying deviations from normal behavior baselines. Deep learning architectures, particularly recurrent neural networks (RNNs) and long short-term memory (LSTM) networks, effectively model temporal patterns in IoT data streams for real-time threat detection.

5.2 Automated Incident Response

AI-driven security orchestration and automated response (SOAR) systems can react to detected threats faster than human operators. These systems integrate threat intelligence, analyze security events, and execute predefined response playbooks to contain threats, isolate compromised devices, and initiate recovery procedures. Reinforcement learning approaches enable adaptive response strategies that improve through experience, optimizing security actions based on environmental feedback.

5.3 Adversarial Machine Learning Considerations

As AI becomes integral to IoT security, adversaries have developed techniques to subvert machine learning models through adversarial examples, data poisoning, and model inversion attacks. Ongoing research focuses on developing robust machine learning models resistant to adversarial manipulation, employing techniques such as adversarial training, defensive distillation, and ensemble methods.

6. Regulatory Frameworks and Standards

6.1 Global Regulatory Initiatives

Governments worldwide have recognized the critical need for IoT security regulation. The European Union's Cybersecurity Act and the proposed Cyber Resilience Act establish security requirements for IoT manufacturers. The United States has introduced the IoT Cybersecurity Improvement Act, mandating security standards for government-procured IoT devices. These regulations typically require secure-by-design principles, vulnerability disclosure programs, and minimum security baselines.

6.2 Industry Standards and Certifications

Organizations such as the Internet Engineering Task Force (IETF), Institute of Electrical and Electronics Engineers (IEEE), and International Organization for Standardization (ISO) have developed standards specifically for IoT security. Notable examples include IEEE 802.1AR for device identity, ISO/IEC 27001 adaptations for IoT, and the IETF's Constrained Application Protocol (CoAP) for secure communications. Certification programs like ETSI EN 303 645 provide verifiable security assurance for IoT products.

7. Quantum Computing Implications

The advent of quantum computing poses both threats and opportunities for IoT security. Quantum computers could potentially break current public-key cryptographic systems, rendering existing security mechanisms obsolete. Post-quantum cryptography research focuses on developing quantum-resistant algorithms suitable for IoT deployment. Lattice-based, hash-based, and code-based cryptographic schemes show promise for protecting IoT systems in the post-quantum era. Organizations must begin transitioning to quantum-safe protocols to ensure long-term security of IoT infrastructure.

8. Edge Intelligence and Secure Processing

Edge computing architectures process sensitive data locally rather than transmitting it to cloud servers, enhancing privacy and reducing attack surface. Secure enclaves and trusted execution environments (TEEs) such as ARM TrustZone and Intel SGX provide isolated execution spaces for sensitive operations on edge devices. Federated learning enables collaborative machine learning model training across distributed IoT devices without centralizing raw data, preserving privacy while enabling collective intelligence.

9. Future Directions and Challenges

9.1 Autonomous Security Systems

Future IoT security systems will increasingly incorporate autonomous capabilities, self-healing networks that automatically detect, isolate, and remediate security incidents without human intervention. Cognitive security systems will employ advanced AI to predict threats before they materialize and proactively adapt defenses. The integration of digital twins—virtual replicas of physical IoT systems—enables security testing and simulation in safe environments.

9.2 Interoperability and Standardization

The heterogeneous nature of IoT ecosystems, with diverse devices, protocols, and platforms, complicates security implementation. Achieving seamless interoperability while maintaining security requires continued standardization efforts and the development of universal security frameworks that accommodate diverse device capabilities and use cases.

9.3 Human Factors and Security Awareness

Technical solutions alone cannot secure IoT ecosystems; human factors remain critical. Many security breaches result from poor password practices, failure to apply updates, and social engineering attacks. Improving user security awareness and designing intuitive security interfaces are essential components of comprehensive IoT security strategies.

10. Conclusion

The rapid evolution of Internet of Things (IoT) technology has reshaped industries and everyday life, driving new levels of innovation, automation, and efficiency. Yet, alongside these advancements arise serious security concerns that demand ongoing adaptation and resilience. Breakthroughs in lightweight cryptography, AI-enhanced threat detection, blockchain-based trust mechanisms, and Zero Trust models highlight the cybersecurity community's continued efforts to safeguard IoT environments.

The future of IoT protection depends on dynamic, intelligent systems capable of detecting and mitigating threats in real time. Ensuring robust IoT security requires active collaboration among developers, policymakers, researchers, and end users to develop frameworks that ensure both safety and performance. With quantum computing on the horizon and IoT devices increasingly integrated into vital infrastructure, proactive and forward-looking security measures have become indispensable.

Organizations adopting IoT technologies must embed security in the design phase, apply multi-layered defense mechanisms, and continuously assess and update their networks. The combined power of emerging technologies—such as 5G, edge computing, artificial intelligence, and blockchain—provides new avenues to strengthen IoT defenses. However, achieving effective security will depend on coordinated progress across technical, regulatory, and educational dimensions. Only through a holistic and adaptive approach can society fully harness the benefits of IoT while minimizing its vulnerabilities.

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Chaotic-Map Guided Hybrid Swarm Algorithm for Linear Antenna Array Synthesis with Ultra-Low Side Lobes and Enhanced Directivity

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Abstract

The optimization of antenna array patterns to achieve low side-lobe levels (SLL) and high directivity remains a persistent challenge in electromagnetic design. This paper presents a Chaotic-Map Guided Hybrid Swarm Algorithm (CH-HSA) that combines the global search capability of Particle Swarm Optimization (PSO) with the adaptive refinement of Genetic Algorithms (GA). A chaotic-map mechanism dynamically modulates swarm parameters to maintain diversity and avoid premature convergence. The algorithm optimizes amplitude and phase excitations of non-uniform linear arrays using a dual-objective fitness function that minimizes SLL and maximizes directivity. Simulations conducted on 16- and 20-element arrays demonstrate that CH-HSA achieves SLL values below −28 dB and directivity exceeding 12 dBi, outperforming GA, PSO, and Chebyshev tapering. Convergence analysis confirms faster stabilization and greater robustness. The integration of chaos-driven control within a hybrid swarm framework provides a scalable and efficient solution for next-generation radar and wireless communication systems.

1. Introduction

Antenna arrays are fundamental components in communication and radar systems where radiation pattern control—especially side-lobe suppression and directivity enhancement—determines system performance. Designing excitation distributions that simultaneously achieve both goals represents a complex nonlinear optimization problem. Traditional analytical methods such as the Dolph–Chebyshev (Dolph, 1946) and Taylor (Taylor, 1955) distributions provide deterministic tapering solutions but are limited in flexibility and cannot manage multi-objective trade-offs.

Metaheuristic algorithms, including Genetic Algorithms (Goldberg, 1989) and Particle Swarm Optimization (Robinson & Rahmat-Samii, 2004), have been widely adopted to address these challenges. GA provides strong exploration but converges slowly, while PSO converges faster yet may stagnate in multimodal landscapes. To improve convergence and solution stability, hybrid PSO–GA models have been proposed, combining the social learning of PSO with the genetic diversity of GA (Khorshidi & Vali, 2019).

However, maintaining a balance between exploration and exploitation remains challenging. Chaos theory introduces deterministic randomness through chaotic maps, such as Logistic and Tent sequences, improving swarm diversity and avoiding premature convergence (Ghasemi & Neshat, 2007). This paper presents a Chaotic-Map Guided Hybrid Swarm Algorithm (CH-HSA) that integrates PSO, GA, and chaotic modulation for adaptive and efficient antenna array synthesis.

2. Literature Review

Research on antenna array synthesis has evolved from deterministic models to adaptive metaheuristic frameworks. Early analytical designs, including the Taylor and Dolph–Chebyshev distributions, offered mathematical control of SLL but lacked adaptability under nonlinear constraints (Balanis, 2016). Genetic Algorithms introduced stochastic optimization capable of amplitude and phase control (Singh & Pattnaik, 2002), while Haupt (1997) demonstrated GA's efficiency for phase-only null steering.

Particle Swarm Optimization emerged as a faster alternative (Khodier & Christodoulou, 2005), showing effective global search but limited parameter sensitivity (Mishra & Choubey, 2004). Hybrid frameworks combining PSO and GA improved convergence (Das & Abraham, 2008), and chaos-based strategies further enhanced global search diversity (Panda et al., 2020; Upadhyay & Tripathi, 2023). Despite this progress, very few studies have integrated adaptive chaotic modulation into hybrid swarm systems for simultaneous SLL reduction and directivity enhancement. The proposed CH-HSA addresses this research gap.

3. Methodology

3.1 Problem Definition

The objective is to design a non-uniform linear antenna array with low SLL and high directivity. The CH-HSA algorithm combines PSO's exploration, GA's refinement, and chaos-based parameter control to identify optimal amplitude–phase excitations.

3.2 Array Modeling

For an N-element array with spacing d=λ/2, the normalized array factor is given by:

$$AF(\theta) = \sum_{n=1}^{N} \omega_n \, e^{j[kd(n-1)cos\theta+\emptyset_n]} \quad \text{------------------}(1.1)$$

where ω_n and $\emptyset_n$ denote amplitude and phase excitations, $k = 2\pi/\lambda$ is the wave number, and θ is the observation angle.

3.3 Objective Function

Two objective functions are minimized simultaneously:

$$f_1 = \max_{\vartheta sll} |AF(\theta)| - \max_{\vartheta main} |AF(\theta)|$$

$$f_2 = 10\,\log_{10}\left(\frac{|AF(\theta)_0|^2}{\frac{1}{2\pi}\int_0^{2\pi}|AF(\theta)_0|^2 d\theta}\right)$$

The combined fitness function is:

$$F = \alpha\,\frac{|f_1|}{|f_{1,ref}|} - \beta\,\frac{f_1}{f_{2,ref}}$$

where α=β=0.5.

3.4 Chaotic-Map Guided Hybrid Swarm Algorithm

Fig. 1. Flowchart of the Chaotic-Map Guided Hybrid Swarm Algorithm (CH-HSA).

CH-HSA merges PSO and GA under chaotic modulation. The PSO coefficients ω_1, c_1, c_2 are dynamically updated using the logistic map:

$$x_t+1=4x_t(1-x_t)$$

This introduces chaos-based ergodicity, enhancing diversity. GA crossover and mutation operations are applied periodically to elite particles. The algorithm terminates when the improvement in fitness falls below a threshold ε or the maximum number of iterations is reached.

3.5 Simulation Configuration

Table 1. Simulation parameters for CH-HSA optimization.

Parameter	Symbol	Value / Range
Number of elements	N	16, 20
Spacing	d	0.5 λ
Frequency	f	5 GHz
Swarm size	—	30
Iterations	—	200
Chaotic maps used	—	Logistic, Tent
Weighting factors	α, β	0.5, 0.5
Comparison algorithms	—	GA, PSO, Hybrid PSO–GA
Platform	—	MATLAB R2023a, CST Studio 2023

4. Results and Discussion

The proposed CH-HSA was applied to 16- and 20-element arrays. For N = 16, CH-HSA achieved SLL ≈ −28.3 dB and directivity ≈ 12.2 dBi, outperforming PSO (−23.2 dB, 11.0 dBi) and GA (−20.5 dB, 10.4 dBi). The convergence curve stabilized within 110 iterations, faster than PSO (160) and GA (190).

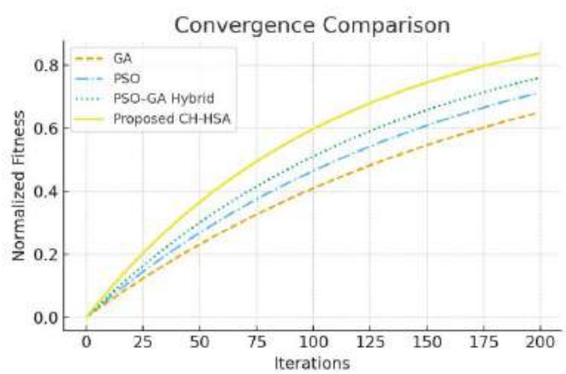

Fig. 2. Convergence comparison of GA, PSO, PSO–GA, and the proposed CH-HSA algorithm.

Table 2: Performance comparison of CH-HSA and baseline algorithms.

Algorithm	Min SLL (dB)	Max Directivity (dBi)	Iterations	Stability Index
GA	−20.5	10.4	190	0.18
PSO	−23.2	11.0	160	0.15
PSO–GA	−25.1	11.4	140	0.12
CH-HSA	−28.3	12.2	110	0.08

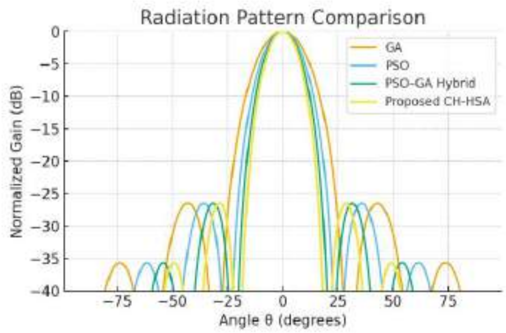

Fig. 3. Normalized radiation pattern comparison for a 16-element array optimized using GA, PSO, PSO–GA, and CH-HSA.

The radiation pattern showed narrower main lobes and deeper nulls compared with benchmark algorithms. Chaotic modulation improved exploration during early iterations, while GA-based mutation enhanced local exploitation, leading to faster convergence and higher stability.

5. Conclusion and Future Scope

The Chaotic-Map Guided Hybrid Swarm Algorithm effectively synthesizes linear antenna arrays with ultra-low SLL and high directivity. Chaos-driven parameter control enhanced population diversity and prevented premature convergence.

Future work will extend CH-HSA to planar and circular geometries, integrate machine learning-based surrogate models to reduce computation time, and validate results experimentally under coupling and fabrication constraints. The method provides a scalable and intelligent optimization framework for next-generation radar and communication systems.

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PUF (Physical Unclonable function) based sampling circuit for enhanced data security and reduced sample size

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Abstract

This abstract explores the integration of Physical Unclonable Functions (PUFs) with sampling circuits to enhance data encryption. PUFs leverage inherent, microscopic manufacturing variations in silicon chips to generate unique, device-specific cryptographic keys. These keys, being physically derived rather than stored, offer a robust countermeasure against various attacks, including physical tampering, side-channel analysis, and cloning. The core idea is to utilize a PUF as a dynamic, on-demand source of entropy and a root of trust for generating encryption keys. A sampling circuit, in this context, plays a crucial role in extracting stable and reliable bits from the analog-physical variations of the PUF. The sampling circuit must be designed to accurately capture the minuscule, unique variations within the PUF's physical structure (e.g., delay differences, threshold voltage variations).The unique PUF response serves as a "fingerprint" for the device, enabling secure authentication and preventing counterfeiting.

Keywords: Physical Unclonable Function, Sampling Circuit, Encryption, Cryptography

Introduction

Physical Unclonable Functions (PUFs) are a hardware security technology that utilizes the unique, random, and microscopic manufacturing variations within a silicon chip to generate a device-specific "silicon fingerprint." This process serves as a secure alternative to storing cryptographic keys in vulnerable non-volatile memory.

The operation of a PUF involves applying a "challenge" (input) to the chip, which interacts with its unique physical characteristics to produce a "response" (output). Due to environmental noise and variations, the raw digital response from the PUF can contain minor errors. Therefore, sampling techniques are used to take multiple readings and stabilize the output, which is then further processed by Error Correction Codes (ECC) to generate a reliable, stable, and error-free cryptographic key.

This PUF-derived key can act as a Hardware Root of Trust, anchoring all cryptographic operations to the device's unique physical identity. This approach creates device-unique encryption, where each chip possesses a distinct key. This makes it extremely difficult for attackers to clone a device and prevents "attack-one-break-all" scenarios, as compromising one device does not expose the keys of others. PUFs are particularly beneficial for resource-constrained Internet of Things (IoT) and embedded systems, offering a cost-effective and robust security solution without the need for expensive secure memory

Methodology

Integrating a sampling circuit with a Physical Unclonable Function (PUF) typically means using the inherent random variations of the PUF to generate a unique and unpredictable "sample" or bit sequence. This is done for secure key generation, device authentication, and true random number generation.For some PUFs (like analog-based PUFs), an ADC might be needed to convert analog variations into digital signals before binarization. Binarization is a comparator circuit that converts the analog differences into clear 0s and 1s.

Step-1- Here Continuous analog data are generated in which there exist a manufacturing Variations (e.g., transistor sizes, doping concentrations, wire widths, material purity)

Step-2-Now implements Physical Unclonable Function (PUF). The PUF circuit itself acts as the "sampling device. (e.g., Ring Oscillators, Arbiter Paths, SRAM Cells) to note the changes

Step-3-The circuit measures the amplified analog differences and converted into a binary decision.

Step-4-Digital Output is obtained which are raw Response in discrete Bits - 0s and 1s

Step-5- Uses **s**table, repeatable digital fingerprint Key. This block is crucial for making the "sampled" data usable

Mathematical Model of a PUF

A PUF can be broadly modelled as a function f: $f: C \times P \rightarrow R$ Where:

C is the challenge space, typically a set of binary strings e.g. {0, 1}

P represents the physical instance of the PUF, which is unique for each device due to manufacturing variations. This is not a direct input but an intrinsic property that defines the function f for a given device.

R is the response space, also typically a set of binary strings e.g., {0, 1}

For a specific PUF instance i, we can denote its behaviour as f_i(C), where C is a challenge. The ideal properties of $f_i(C)$ are:

1. Uniqueness: For any two distinct PUF instances i=j, $f_i(C)=f_j(C)$ for most challenges C. Mathematically, the inter-chip Hamming distance, HDinter(fi(C),fj(C)), should be close to n/2.
2. Randomness/Unpredictability: The response $f_i(C)$ for a given C should be unpredictable even if other challenge-response pairs (CRPs) for the same device are known. The bias of the response bits should be close to 0.5.
3. Reproducibility/Reliability: For a given PUF instance i and challenge C, the response f_iC) should be consistent over time and varying environmental conditions (temperature, voltage). However, in practice, PUF responses are noisy. Let Ri,k (C) be the k-th measurement of the response from PUF i to challenge C.

   $$R_{i,k}(C)=f_i(C)\oplus N_{i,k}(C)$$

   Where Ni, k(C) is a noise vector, representing bit flips caused by environmental fluctuations. The intra-chip Hamming distance, HD intra(Ri,k1(C),Ri,k2(C)), should be small.

Stages of Mathematical Implementation for Data Sampling (Key Generation)

Stage 1: Raw Response Generation (Physical Sampling).For a given PUF instance and challenge C, the PUF circuit generates a raw response $W\in\{0,1\}^n$. This W is the "sample" derived from the physical characteristics.

W=PUF(C)

Due to noise, if we query the PUF multiple times with the same challenge C, we might get slightly different responses W1, W2 ,…,Wk.

Stage 2: Helper Data Generation (Enrolment Phase)

This phase aims to extract a reproducible secret K from the noisy PUF response. It's done once (or rarely).

Let $W\in\{0,1\}^n$ be the noisy PUF response obtained during enrollment. The goal is to compute a "helper data" P such that P is public but does not reveal W or the secret K.

Stage 3: Key Reconstruction (Reproduction Phase)

When the secret key is needed (e.g., for encryption), the PUF is queried again.

1. Noisy Response Acquisition: Query the PUF with the same challenge C to get a new noisy response $W'\in\{0,1\}^n$.

$W' = PUF(C)$

2. Error Correction: Use the stored helper data P (from enrollment) and the new noisy response W' to correct W' to the original, stable codewordCW.

If $P = W \oplus CW$ was used:

$CW' = W' \oplus P$

The ECC decoder then takes CW' and corrects it to the closest valid codeword CW, effectively removing the noise E'.

$Decode(CW') \rightarrow K$

If P was the syndrome SW: Calculate the syndrome $SW' = W' \cdot HT$. Using SW and SW', the error vector E' can be estimated using an ECC decoder. The corrected response is $W'' = W' \oplus E'$. Then, K is extracted from W'' using a deterministic function (e.g., a hash or truncation).

Hamming Distance (HD): Used to quantify the difference between binary strings. $HD(X,Y) = \sum i=1n|xi-yi|$. Crucial for assessing uniqueness and reliability.

Information Theory (Entropy): Quantifies the randomness of the PUF output. The min-entropy $H\infty(W)$ of the raw PUF output should be high to ensure the extracted key is truly random. Privacy amplification reduces the output length while increasing the per-bit entropy.

Coding Theory (ECC): Linear block codes (e.g., Hamming codes, BCH codes, Reed-Solomon codes) are fundamental for error correction. They define a set of valid codewords and provide algorithms to decode noisy versions of these codewords back to their error-free form.

Decoding algorithms (e.g., syndrome decoding for linear block codes) mathematically find the most likely codeword given a noisy received word.

Cryptography (Hash Functions): Used in privacy amplification to condense a longer, potentially biased, random string into a shorter, uniformly random, cryptographic key.

Performance

SI no.	Parameter	Sampling Circuit alone	Sampling Circuit integrated with PUF
1	Output and Reliability	A basic sampling circuit is primarily designed to capture and process analog or digital signals, with performance typically measured by parameters like sampling frequency, bit resolution, and noise filtering. Its output is not inherently unique or secure.	When a sampling circuit is integrated with a PUF, the output gains unique, device-specific characteristics due to process mismatches and physical variations. This integration can significantly enhance reliability and security. For example, using an average sampling circuit (ASC) with a PUF can filter ambient noise, boosting reliability up to 99% and throughput to 50 Mbps1. Similarly, integrating a sampling switch in a SAR ADC-based PUF achieves a reliability of 97% and high uniqueness, making the output robust against environmental and aging effects [1]
2	Noise Immunity and Error rate	Standard sampling circuits may be susceptible to ambient noise, which can degrade signal integrity.	Advanced designs use sampling circuits to filter noise and calibrate errors, resulting in much lower bit error rates (BER). For instance,

			hybrid PUF architectures with threshold-sampling blocks and temporal majority voting can achieve BER as low as 0.0019% under varying voltage and temperature conditions [4]
3	Security and Uniqueness	Outputs are not unique and can be replicated, offering no inherent security	The output becomes unclonable and unique to each device, suitable for cryptographic key generation and hardware authentication. The integration enables resistance to intrusive attacks and environmental fluctuations, as seen in both electronic and optical PUF implementations[5]

Parameter Comparison

SI	Feature	Sampling Circuit Alone	Sampling Circuit with PUF Integration
1	Output Uniqueness	Low	Unique, device-specific
2	Reliability	Standard, noise-sensitive	More reliable High
3	Bit Error Rate (BER)	Higher, unoptimized	As low as 0.0019% with advanced designs
4	Security against cloning	Weak	strong
5	Noise Immunity	Moderate	Enhanced via filtering and calibration

Advantages

1. No need of encoding the data
2. No need of quantizer
3. It only generated unique sampled value
4. It don't generates repeated sample(Sample with same value)

Disadvantage

1. Circuit is more complex
2. Generates huge amount of sasmple
3. Maintaining large databases of PUF challenge response pairs (CRPs) and dealing with PUF errors make it difficult to use PUFs reliably.[6]

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Bridging the Industry-Academia Gap: A review on pro and cons

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Abstract

Indian higher education in the technical field, despite its quantitative growth, continues to lag behind its Western counterparts. The primary reasons stem from a deep-rooted focus on theoretical knowledge and a deficiency in practical application and critical thinking. Unlike Western systems that prioritize hands-on projects, research, and interdisciplinary learning, the Indian model often relies on a rigid, outdated curriculum and rote memorization, leading to a significant skill mismatch with industry demands.

Compounding this issue are systemic challenges, including a severe shortage of highly qualified faculty, and a lack of modern, well-equipped laboratory infrastructure. The weak collaboration between academia and industry further limits students' exposure to real-world problems and emerging technologies. Additionally, the immense pressure to secure high marks in a competitive, exam-centric environment often stifles creativity and innovation. While recent policy reforms like the National Education Policy 2020 aim to address these issues, a fundamental shift in pedagogical approach.

Keywords: Interdisciplinary learning, Industry demands, Industry ready graduates, Laboratory infrastructure

Introduction

Technological trends such as the Fourth Industrial Revolution will create many new cross-functional roles for which employees will need technical, social, and analytical skills [1]. In today's perspective the current academic curriculum and training is restricted in providing specialized interpersonal skill training to enable graduates to apply knowledge to practice and rise to stressful work environments. This gap is resulting from the discrepancy between industry anticipations and preparations that university students receive from universities during their years of studies [1]. Over the years, a steady gap has appeared between university curriculum and industrial needs, which has, in certain instances, led to graduates being less ready for industry. Furthermore, there is a lack of consensus in the literature and theory that properly identifies the fundamental components for analyzing industry 4.0 readiness. The necessary skill sets needed specifically for industry are sometimes missing when students complete their university degrees and enter the labor force. Researchers indicate that there is a lack of cooperation and partnership between academia and industry to ensure students are effectively prepared for industrial needs. So keeping in mind Academia-Industry collaboration is the key step towards the growth and development of economy. The academia is a store house of knowledge and innovation whereas the industry is a sector to convert the knowledge and technique into innovative product [2]. The student of today learning a specific content of information will find to his amazement that he is not prepared to face the life which he has to live for the next five decades because the knowledge furnished with, has become outdated long back. The coming few decades will be miracles in space craft, satellites, internets and others offshoots of scientific enquires. [3]

Literature Review:

SI No	Topic	Name of paper	Objectives	Conclusion
1	Investment in research infrastructure and faculty development	The effects of investments in research infrastructures of higher education institutes: Evidence from Poland and Czechia **Elsevier**	The study analyzes the effects of RIs funding for HEIs, including the counts of publications, publishing scientists and collaborations with scientific and industrial partners.	Public investments in RIs at HEIs increase the counts of peer-reviewed publications and publishing scientists, as well as the occurrence of collaboration with scientific and industrial partners.

2	Encourage industry-academia collaboration	Rules of engagement: Promoting academic-industry partnership in the era of digital pathology and artificial intelligence Elsevier	Academic- Industry Partnership(AIP stimulates innovation, lowers barriers to develop marketable technology, and offers a mechanism to fund translational research.Reliance on industry resources has become increasingly more important as federal research funds diminish.	In summary, successful and sustainable academic and industry partnerships must be designed to benefit all parties and create win–win en gagements from the outset. This will enable all stakeholders to stay engaged and ensure that the relationship is productive and collabo rative.
3	Promote internationalization through student and faculty mobility/ Interchange	Academic engagement: A review of the literature 2011-2019 Elsevier	Academic engagement continues to be a subject of major policy interest, as science retains its promise to drive innovation across the economy and society	Engagement and societal impact require external parties to have the motivation and ability to manage academic relationships, hence solely focussing on academia policy is insufficient
4	Investigating the Efficacy of Mandatory Internships and Industry-Sponsored Projects in Enhancing Graduate Employability	Enhancing student employability through collaboration between universities and industry, International Journal of Cultural Studies and Social Sciences, Ms.M.Sangeetha, Dr.M.Gurupandi	These collaborations enable students to develop diverse skill sets that align with current industry trends, making them more attractive to potential employers.	In conclusion, a well established and mutually beneficial relationship between universities and industries can significantly enhance students' employability.
5	The Skill Mismatch: A Comparative Analysis of Skills Taught in Engineering Colleges vs. Skills Demanded by the Industry.	The Skill gaps: Why traditional education fails to prepare students for modern workforce demands. IJISEM, Rajesh Sahu, Shailendra Vishwakarma, Ashok Soni	It concluded that the widening skills gap highlights the urgent need for reform in traditional education systems. Current curricula often fall short in equipping students with the specialized technical and soft skills demanded by today's rapidly evolving job market. The rise of automation and emerging technologies requires a shift toward continuous, accessible, and industry-aligned learning	To bridge this gap, a collaborative effort is needed between educators, in dustry leaders, and policymakers to redesign curricula, i ntegrate real-world skills training, and promote lifelong learning models. Only through such systemic change can t he workforce be truly prepared to meet the challenges and opportunities of the future.

Analysis

This analysis, based on primary questionnaires and secondary sources, highlights reasons for dissatisfaction in technical education, including low job satisfaction, poor career choices, and lack of academic interest.

The reasons are listed as follow

1. Limited awareness of higher education options hinders effective choices for future career goals. Guardian pressure significantly shapes Indian students' career choices, often detrimentally. Studies show many enter fields like engineering, often against their will, due to parental compulsion. This over-involvement causes stress, anxiety, and a mismatch between the student's aptitude and the chosen "safe" or "prestigious" profession.
2. **The choice of education for a better salary despite a lack of personal interest**-It is widely acknowledged that many students in India and globally chooses high-paying careers over those that align with their genuine interests. Apart from this other factors that insist to choose their carrier against their interest are: The dominance of Salary, Clash of Passion vs. Money, generational Shifts, role of Education and Information.

3. **Massive gap between course syllabus and industry need-**A vast syllabus gap creates a skill mismatch, producing graduates with outdated theoretical knowledge but lacking in-demand practical skills. This forces employers to heavily retrain new hires, wasting time and resources, thus hindering genuine Industry-Academia collaboration.
4. **Lack of support from government bodied to private bodies-**A lack of government funding and policy incentives for private-sector collaborations hinders joint R&D projects and investment in advanced academic infrastructure. This absence of a supportive framework creates a skills mismatch, as curricula remain outdated and graduates lack industry-relevant practical experience.
5. **Syllabus designed according to job oriented instead of research oriented-**A solely job-oriented syllabus often prioritizes narrow, immediate skills over fundamental theory and critical, innovative thinking. This short-term focus fails to equip graduates with the adaptability and deep foundational knowledge necessary for long-term industry changes and research-based problem-solving, widening the practical skills gap.
6. **Lack of resources-**Lack of financial investment limits modern infrastructure and cutting-edge R&D labs in academia. This resource deficit prevents professors and students from gaining practical, industry-relevant skills and utilizing current technology, leaving graduates unprepared for the workforce.

Initiatives to bridge the Industry-Academia Gap with practical solutions

1. The Impact of the National Education Policy (NEP) 2020.-The New Education Policy (NEP 2020) bridges the gap by mandating vocational education and internships from early stages, promoting experiential learning and multidisciplinary approaches. This cultivates 21st-century skills like critical thinking and innovation, aligning student capabilities directly with industry requirements for a job-ready workforce.

2. Bridging the Industry-Academia Gap-To improve graduate employability, universities must bridge the skill mismatch between academia and industry. This can be achieved through a framework for robust collaboration, including mandatory internships and industry-sponsored projects. Additionally, faculty development and pedagogical innovations are essential for keeping curricula relevant and preparing students for the modern workforce.

3. **The quality of faculty and teaching methods is central to improving the education system.-**AI and Machine Learning tools are impacting engineering education by enabling personalized learning, intelligent tutoring systems, and enhanced administrative efficiency. While Outcome-Based Education (OBE) aims to improve student outcomes in Indian colleges, its effectiveness is challenged by inconsistent assessment and faculty training gaps. This necessitates continuous professional development for faculty to adapt to rapid technological changes.

4. Policy, Governance, and Societal Issues-Examining the financial stability of private Indian engineering colleges and the effectiveness of accreditation bodies like NAAC and NBA is critical to improving education quality. This effort is vital for addressing the severe impact of societal pressures on students' career choices and mental health

5. Emerging Technologies and Future-Readiness-Integrating Emerging Technologies (IoT, Blockchain, Quantum Computing) into the Engineering Curriculum.The Role of Virtual and Augmented Reality (VR/AR) in Engineering Labs and Simulations.

6. Realigning Career Selection and Curricula with Student Interests-The student's journey begins with personal choices, but the traditional model often sees them choosing a field based on external pressure rather than genuine interest. To address this, it is crucial **to** strengthen career counseling**,** introduce flexible and interdisciplinary curricula**,** and provide early exposure to real-world applications

7. Synchronizing Curricula with Industry Needs-The core of the problem lies in the disconnect between what is taught in the classroom and what the industry requires; therefore, implementing **c**ontinuous curriculum updates**,** establishing mandatory internships and co-op programs**,** and organizing guest lectures, workshops, and hackathons are necessary steps to bridge this gap.

8. Fostering a Strong Academia-Industry Partnership-Bridging the cultural gap between academia and industry requires mutual effort and sustained collaboration, which can be achieved through joint research and development (R&D) projects**,** industry-sponsored labs and centers of excellence**,** faculty development programs, and strong alumni networks

Conclusion

The skill gap between academia and industry is persistent, with many graduates unprepared for the modern workforce due to outdated curricula, a lack of practical experience, and weak collaboration. Bridging this divide requires mutual effort to equip students with necessary technical, social, and analytical skills. Strengthening partnerships through initiatives like joint R&D, faculty development, and mandatory internships is vital for economic growth and preparing students for future challenges.

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Maximizing Power Extraction in Wind Energy Systems Through A Modified Perturb and Observe Maximum Power Point Tracking (MPPT) Technique

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Abstract

Wind energy systems experience variations in power output due to shifts in environmental factors, which diminishes their overall efficiency. Therefore, an effective method is needed to identify the optimal operating point for extracting the maximum energy across different wind speeds. The modeling of the wind turbine will be conducted first, followed by its simulation using MATLAB Simulink. The output generated from this model will drive a Permanent Magnet Synchronous Generator (PMSG), which will convert the mechanical energy into electrical energy. The output from the Permanent Magnet Synchronous Generator (PMSG) is passed through a rectifier before being fed into a DC-DC buck converter. The converter's output is then connected to a resistive load. Because wind speed varies, the input voltage to the buck converter also experiences fluctuations. To ensure maximum power extraction from the wind energy system, a Perturb and Observe (P&O) MPPT controller will be implemented to continuously track the optimal operating point. Switch of the buck converter is connected to the output (duty cycle) of the MPPT controller. By adjusting the input voltage to the buck converter, the controller ensures continuous tracking of the wind generator's maximum power point. Consequently, the system utilizing MPPT demonstrates superior efficiency compared to a system lacking such control.

Introduction

These days, requests for the sustainable power source assets are increment fundamentally. The very well-known ones are wind energy and solar vitality assets. Both has advantages, together with, free moreover and pollution free. Be that as it may, the wind vitality has low establishment costs contrasted with the solar vitality. The wind is a free, clean, and endless sort of sun oriented fuelled vitality. Winds start from the when warming in the climate from solar energy, the inconsistencies from the world's climate, and revolution of the earth. Wind stream designs have changed through the land landscape, natural conditions and structures. This breeze stream, or movement vitality, when reaped by current breeze turbines, empower to produce power. The terms wind vitality or wind age depicts the assignment where the breeze is used to concoct mechanical power. Wind turbine converts, active kinetic energy of wind into the mechanical energy. This mechanical power might be utilized for crushing grain or siphoning water or maybe a generator can change over this mechanical power into power vitality. A wind turbine precisely behaves the airplane propeller sharp edges, changes over the straight movement noticeable all around into roundabout movement and forces a power generator that provisions a current. The breeze turns the sharp edges, high torque, low speed of the breeze will result in low torque, high speed utilizing gearbox and through a shaft, which connect with a generator and thus produces electricity power. Wind turbines will frequently be assembled in a single wind generation plant, alias wind energy facility. Electricity Power output of wind turbine generator system is fed in to a utility grid and distributed to consumers, such as the same as conventional power plants.

Wind Enenrgy Conversion System

Energy accessible in wind is essentially the kinetic energy of huge masses of air moving over the earth's surface. Sharp edges of the wind turbine get this kinetic energy, which is then changed to mechanical or electrical structures, contingent upon the end use. The efficiency of changing over wind to other valuable energy frames extraordinarily relies upon the effectiveness with which the rotor associates with the wind stream.

- Air Energy

The regular movement of wind in the climate, wind has brought about by weight contrasts over outside of the earth because the warming by means of sun powered radiation. From liquid mechanics investigations this progression of air can be examined as mass stream given by

$$\frac{dm}{dt} = \rho A v$$

where m is the mass of air in the considered volume , A is the area swept by the n1rbine *v* and *p* are the speed and air density flow respectively. Therefore the kinetic energy available in the wind is given by

$$E_{air} = \frac{1}{2}mv^2$$

The rate of change of energy gives us the total power stored in the wind

$$P_{air} = \frac{1}{2}\rho A v^3$$

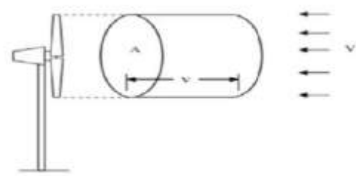

Figure.1. Air Mass Flow

Generally, region of incident air move, is taken as the location swept with the aid of Wind electricity Conversion structures (WECS). consequently, framework convert the linear momentum of the air flow right into a rotation of the WECS rotor, with a most output performance of 59.16%, referred to as Betz restrict.

- **Wind Turbine**

The same old of breeze turbines in electricity generation has exchange of the wind dynamic energy into pivoting mechanical depth of the turbine rotor sharp edges. At this minute soon enough the maximum extensively identified non-compulsory breeze turbine is the specific even hub propeller having 2 or three edges installed on the best point of a top. The determination of variety of cutting edges of the breeze turbine isn't always a simple structure decision through sharp side frameworks cost more than two side frameworks, yet part \wind mills need to work on higher rotational paces than true sharp part ones. This technique the individuals fringe of the 2 blades breeze generators need to be lighter, and have more ponderousness and in this way increasingly more high priced.

- **Kinetic energy to Mechanical energy conversion**

The theoretical power available in wind is established by Eqn. but the power extracted from the wind turbine depends on the efficiency of the wind turbine. The streamlined effectiveness of the turbine while changing over wind into usable mechanical turbine control is depicted by its capacity coefficient, Cp bend. The physical importance of Cp is bend to the proportion the genuine power conveyed to the turbines and the hypothetical power accessible in the breeze. A turbine's proficiency and along these lines control coefficient bend is the thing that separates one turbine from another

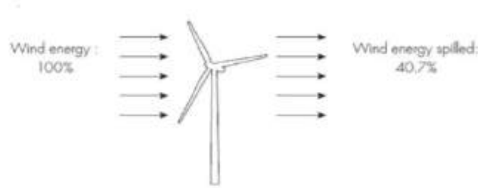

Figure.2. Betz Law

Convertor and PPT Controller

In this topic of dissertation discusses about converter in which different type of converter as a like of ac to de converter is known as rectifier, Also the other type of converter which convert the fixed de voltage in to variable de voltage is known as DC-DC converter or chopper. A Maximum Power Point tracking controller also discussed in this.

- **DC-DC Converter**

The DC-DC converter will be used to the convert of fixed de voltage into the variable de voltage as the requirment of output voltage. Here use the buck converter is required to the step down the input voltage. The output of the buck converter is controlled by the varying of the duty cycle of the controller This converter adjust the input voltage by the switch for reach the optimal voltage thus extract the maximum power.Figure. show the basic circuit of buck converter. Buck converter basicaly work on two different modes as like continous conduction mode and discontinous conduction mode. The switch operates at very high frequency to output chopped de voltage. The controll the power flow of buck converter using ON/OFF the Switch of converter, which is controlled by the duty cycle of the switching operation. The average output voltage flow of buck converter using ON/OFF the Switch of converter, which is controlled by the duty cycle of the switching operation. The average output voltage by the buck converter is given by equation

Where, Vout represent the output dc voltage,Vin represent the input dc voltage and D represent the duty cycle of the

$$V_{out} = V_{in} \times D$$

converter switch.

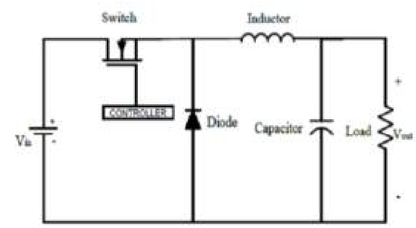

Figure 3: Basic Circuit of DC-DC buck converter

Table l. Parameter of the buck converter

Inductor (L)	3.67mH
Capacitor (C)	3mF
Load (R)	150 ohm

- **MPPT**

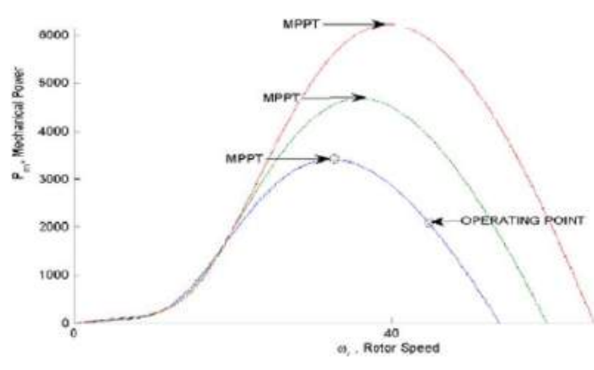

Figure 4. Various MPP for a turbine under various wind conditions

Wind energy, even though abundant, varies continually as wind speed changes throughout the day. The amount of power output from a wind energy conversion system (WECS) depends upon the accuracy with which the peak power points are tracked by the maximum power point tracking (MPPT) controller of the WECS control system irrespective of the type of generator used. From Fig , it can be noted for every wind speed there is a unique rotor speed for which the power curve attains its maximum. A small variation in the rotor speed will drastically change the power owing to the aerodynamic model of the wind turbine.

Turbines usually do not operate at the optimum turbine speed for any given wind velocity because of the effects of generator loading and wind speed flucniations. Hence, a large percentage of *wind power goes wasted.*

MPPT algorithms are implemented to increase the efficiency of the system and to make it cost effective. Same rotor speed for different wind speed will fetch us different power due to Cp f-unction. **Cpmax** for a fixed pitched wind turbine corresponds to one particular TSR value. Because the TSR is a ratio of the wind speed and the turbine angular rotational s speed the optimum speed for maximum power extraction is different for each wind speed but the optimum TSR value remains a constant value. Fixed-speed wind turbine systems will only operate a its optimum point for one wind speed. So to maximize the amount of power captured by the turbine, variable-speed wind turbine systems are used because they allow turbine speed variation.

Simulation of The Wind Turbine Modeling

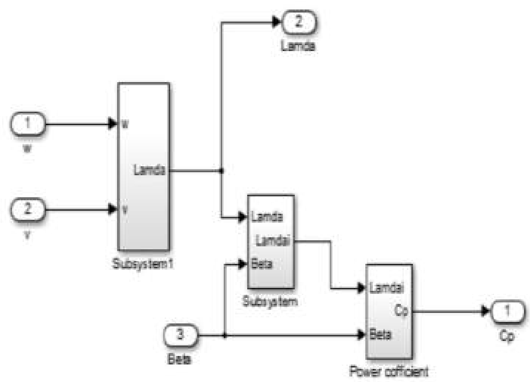

Figure 5. Simulation of power- coefficient (Cp)

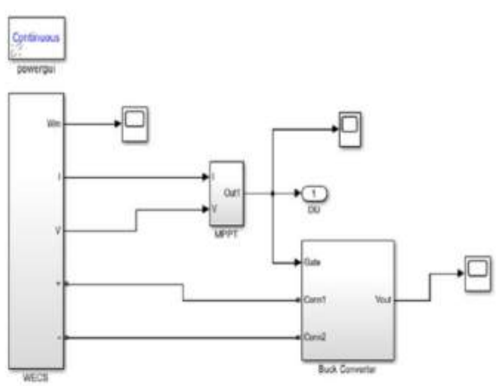

Figure 6. Simulation of WECS with MPPT

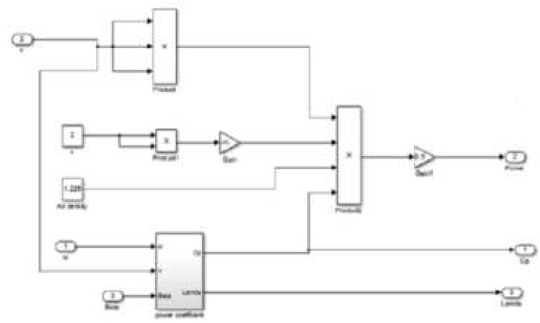

Figure 7. Simulation of output power' of wind turbine

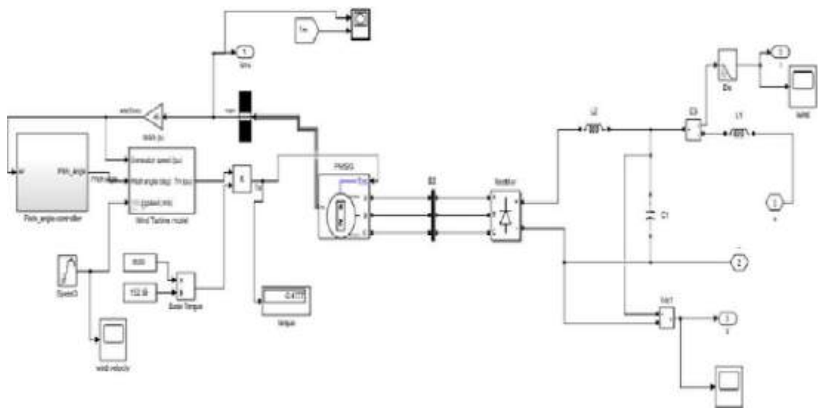

Figure 8. Simulation of WECS

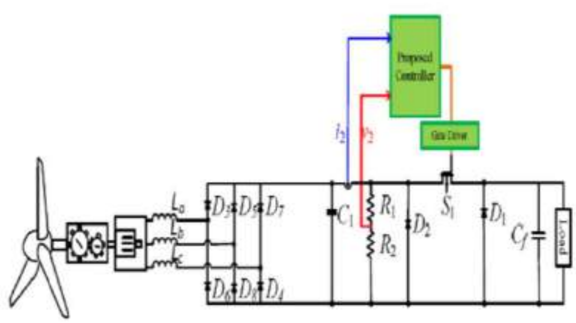

Figure 9. Simulink block model of WECS with MPPT Controller

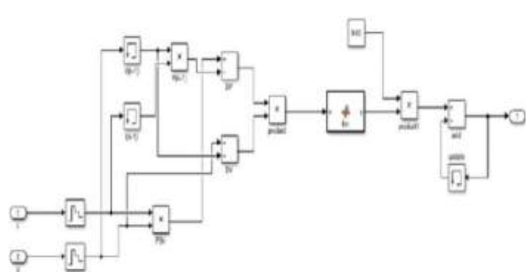

Figure 10. Simulation of P&O MPPT controller

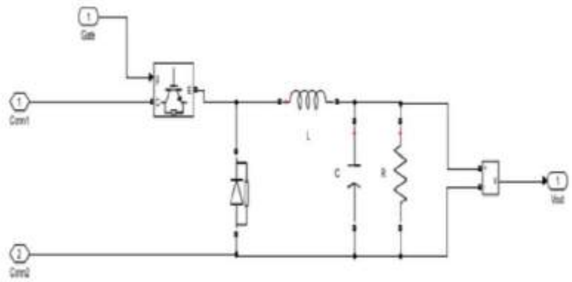

Figure 11. Simulation of dc-dc buck comverter

Results of Simulation

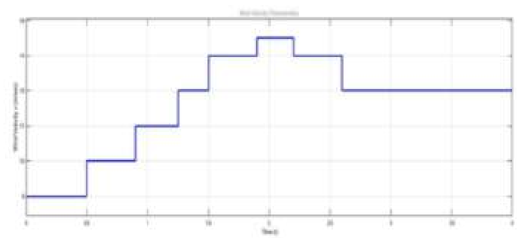

Figure 12. Wind Velocity

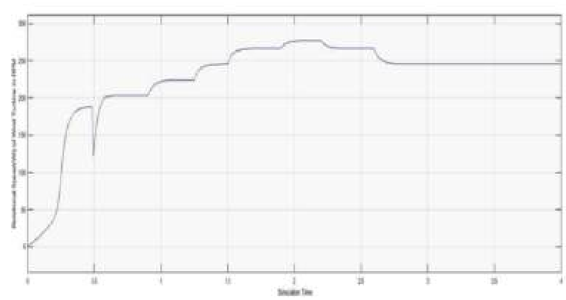

Figure 13. Rotational Speed of Wind Turbine

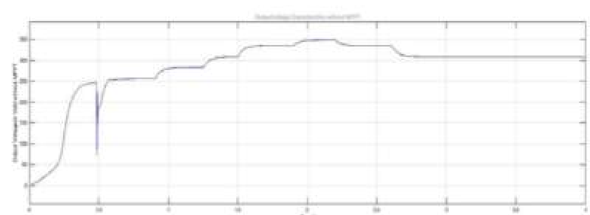

Figure 14. Output Voltage without MPPT

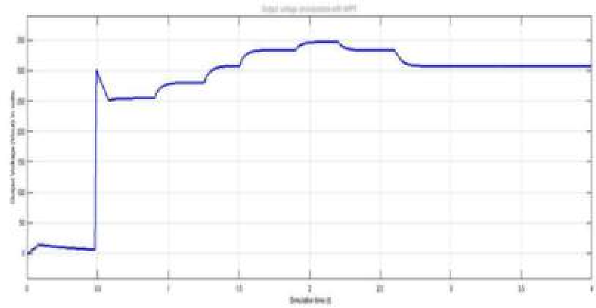

Figure 15. Output voltage with MPPT

Conclusion

This concludes the efficiency issues of the wind energy conversion system (WECS). The role of MPPT technique is investigated by this dissertation work in order to improve the efficiency of the wind turbine conversion system (WECS). A perturb and observation (P&O) technique MPPT controller work with de-de buck converter. The model consists of the wind turbine model, PMSG, buck converter model and the MPPT control model. Due to variable nature of wind velocity, the output of the wind turbine generator is not efficient. So, P&O MPPT controller could track the maximum power point (MPP) of the wind energy system, thus system work on the MPP and extract the maximum power. Further simulation results show the higher output compared to the WECS system without MPPT controller.

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Real-Time Bio-Signal Driven Control System for EEG

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Abstract

In the pursuit of more natural and accessible modes of human–computer interaction, this study presents the design and implementation of a **Real-Time Bio-Signal Driven Control System**. The proposed system enables intuitive communication between human physiological activity and computer operations by utilizing bio-potential signals, specifically those generated during muscle contractions such as jaw clenching. The system architecture integrates low-cost, open-source hardware—**BioAmp EXG Pill** and **Arduino Uno**—to accurately acquire and amplify analog bio-signals. These signals are then processed in real time through digital filtering and feature extraction techniques to remove noise and isolate meaningful patterns. A pre-trained machine learning model classifies the processed signals, which are subsequently translated into direct computer control actions such as simulated keyboard inputs. This end-to-end framework demonstrates a practical, responsive, and affordable approach to bio-signal-based control, offering potential applications in assistive technologies, hands-free interfaces, and immersive computing environments.

Introduction

In an increasingly interconnected world, the quest for more intuitive and accessible forms of human-computer interaction remains a significant challenge. Traditional input methods, while pervasive, often fall short in scenarios demanding hands-free operation, greater immersion, or catering to individuals with motor limitations [1-2].. The human body, a rich source of physiological signals, offers a promising frontier for novel control paradigms.

This paper addresses this very challenge by developing a Real-time Bio-Signal Driven Control System. Our aim is to bridge the gap between human intent and machine action by leveraging subtle bio-potential signals – specifically focusing on the electrical activity associated with muscle contractions, such as a jaw clench – to provide a direct and responsive computer interface. Through an integrated approach combining accessible hardware for precise signal acquisition with intelligent software for real-time processing, machine learning-based pattern recognition, and direct system control, we seek to demonstrate a practical and low-cost solution for bio-signal-driven interaction.

Objective

Our paper aims to develop a real-time bio-signal driven control system that accurately acquires bio-potential data using an Arduino and BioAmp EXG Pill, then processes this data through advanced digital signal filtering and feature extraction. A pre-trained machine learning [3] model subsequently classifies these unique bio-signal patterns, enabling instantaneous, intuitive computer control by simulating keyboard inputs based on the detected physiological states, thereby bridging the gap between human intent and machine action."

Our core objectives are:

- Accurate Bio-signal Acquisition: To reliably capture analog bio-signals from the user's body.
- Real-time Signal Processing [6]: To clean and prepare these raw signals by removing noise and extracting meaningful information.
- Responsive Computer Control: To translate these identified patterns into immediate, actionable commands for a computer, such as simulating keyboard presses.
- Cost-Effectiveness and Accessibility: To build this system using readily available and affordable hardware and open-source software, making it more accessible for research and personal projects.

Methodology

- The BioAmp EXG Pill, a compact bio-potential amplifier [4] is crucial here. It takes very small electrical signals from the body, amplifies them, and filters out common-mode noise, making them readable by the Arduino.
- The Arduino board acts as our data acquisition unit [7]. It reads the amplified analog signal from the BioAmp EXG Pill.
- Our custom Arduino sketch (Code 1) ensures a precise sampling rate of 512 Hz. This high rate captures sufficient detail of the bio-signal. The sampled data is then streamed serially to the laptop.

Code 1: Arduino Code (C++)

This code runs on an Arduino board [5] and is responsible for sampling an analog input and sending the sampled data over serial communication.

Fig. 1: This code runs on an Arduino board and is responsible for sampling an analog input and sending the sampled data over serial communication.

```
#define SAMPLE_RATE 512
#define BAUD_RATE 115200
#define INPUT_PIN A0

void setup() {
  // Serial connection begin
  Serial.begin(BAUD_RATE);
}

void loop() {
  // Calculate elapsed time
  static unsigned long past = 0;
  unsigned long present = micros();
  unsigned long interval = present - past;
  past = present;

  // Run timer
  static long timer = 0;
  timer -= interval;
```

Working Operation

Step 1: Assembly

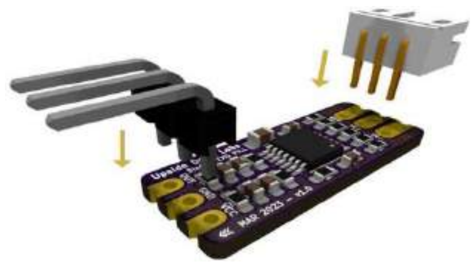


Fig. 2: The BioAmp EXG Pill comes pre-soldered with DIY Neuroscience Kit Basic and Pro but in case we are getting BioAmp EXG Pill separately then we will have to assemble it for this , soldering the header pins and JST PH 2.0 connector as shown in the diagram.

Step 2: Skin Preparation

Apply Nuprep Skin Preparation Gel on the skin surface where electrodes would be placed to remove dead skin cells and clean the skin from dirt. After rubbing the skin surface thoroughly, clean it with a wet wipe or an alcohol swab.

Step 3: Connecting Electrode Cable

Connect the BioAmp Cable v3 to the BioAmp EXG Pill.

Step 4: Electrode Placements

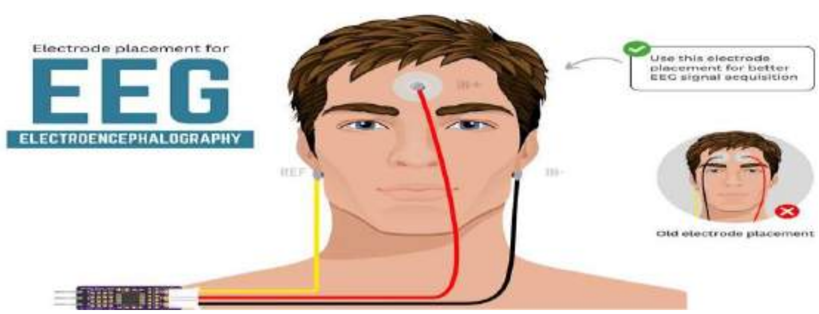


Fig. 3: Recording of EEG from the prefrontal cortex part of the brain

For recording EEG from the prefrontal cortex part of the brain, we have to place the electrodes on your forehead, between Fp1 and Fp2 (refer to the International 10-20 system for recording EEG)

Measuring EEG

1. Connect the BioAmp Cable to gel electrodes,

2. Peel the plastic backing from the electrodes.
3. Place the IN+ cable on the forehead, and IN- & REF (reference) on the bony parts behind the earlobes as shown in the diagram above.

Step 5: Connect the Development Board

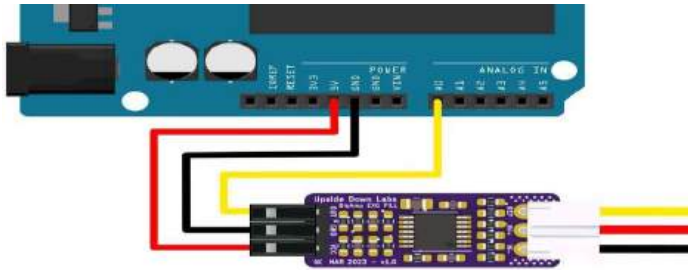
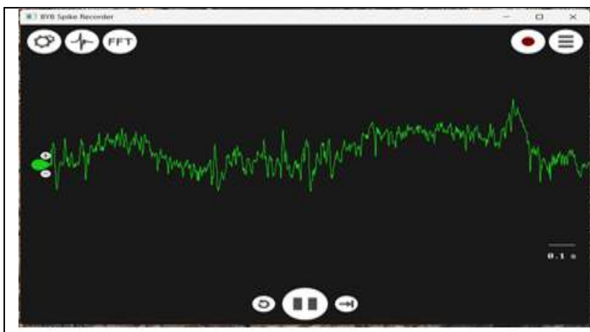


Fig. 4: Connection Development Board

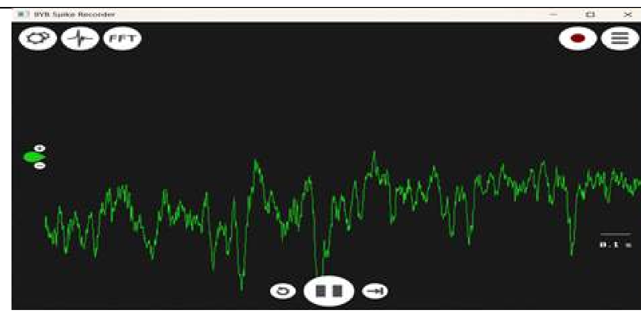
Connect BioAmp EXG Pill to Arduino Uno/Maker Uno using the jumper cables as directed below:

- VCC to 5V
- GND to GND
- OUT to A0

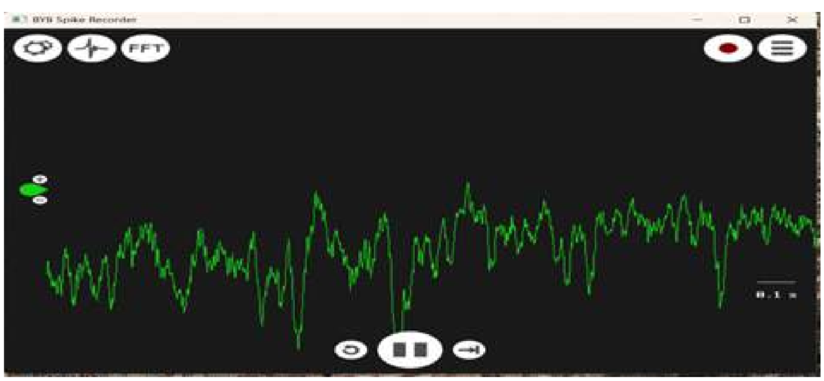
Output: Output waveform using Spike recorder software for EEG graph



Person 1: Active mode



Person 2: Active mode



Person 1: (Relax mode)

Conclusion

In this work, a real-time bio-signal driven control system based on EEG signals has been successfully developed and demonstrated. The system effectively acquires, processes, and interprets neural signals to enable responsive control of external devices, showcasing the potential of EEG-based interfaces for human–machine interaction. Through optimized signal acquisition, noise reduction, and feature extraction techniques, the system achieves reliable real-time performance. The results highlight its applicability in assistive technologies, neurorehabilitation, and hands-free control applications. Future improvements may focus on enhancing classification accuracy through advanced machine learning models and integrating wireless, low-power hardware for portable and user-friendly deployment.

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Optimal Distributed Generation Allocation via Quasi-Oppositional Forensic-based Investigation for System Loss Minimisation

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Abstract:

The incorporation of smart-grid and microgrid ideas has shifted power distribution planning toward assessing the influence of distributed generation (DG) on system performance. In radial distribution systems (RDS), determining the optimal location and size of DGs is a significant challenge that requires effective optimisation techniques. This paper describes a meta-optimisation approach inspired by quasi-oppositional forensic-based investigation (QOFBI) that optimises DG allocation, size, and power factor while adhering to operational constraints. The IEEE 33-bus test system is used to simulate and evaluate performance improvements. A comparison with current approaches based on power, voltage, and stability indices shows that the proposed QOFBI method successfully reduces power losses, improves voltage stability, and offers robust performance with less computing effort.

Keywords: Distribution Generation (DG), power loss mitigation, optimal DG size and location, Forensic-based investigative algorithm (FBI), and Quasi-opposition. System of radial distribution (RDS)

1. Introduction

Distribution systems face substantial challenges from rapid shifts in load demand, the transition from traditional centralised to decentralised control, deregulated energy markets, and the modernisation of the existing setup with novel and microgrid technologies.[1]. There is a concerning situation that requires an immediate solution in the near future to ensure a high-quality, secure, and dependable power supply [2]. To address these problems, one of the most promising and recent approaches is the incorporation of DGs units into distribution networks. Due to numerous inherent benefits, such as increased security, improved reliability, a better voltage profile and quality, reduced line loss and energy consumption, and others, the integration of DGs in the distribution sector is becoming increasingly popular [3]. However, to guarantee optimal planning and design that give these advantages during operational times, a limited number of criteria must be prioritised from the beginning.[4].

The appropriate location, size, and power factor for diverse DG types with variable dynamics is a key challenge that must be addressed by analysing their effects on the system before they are installed. For many years, one of the most pressing challenges has been increasing overall system efficiency in power transfer, especially reducing power loss. However, numerous goals may be defined to advise judgments on optimal positioning and dimensions, with enough operating power factor [5].

To find the best solution for the associated difficulty with DGs integration, this study considers it [6]. All potential system operating restrictions are taken into account and verified before determining the best outcome to support the viability of the suggested approach for real-time use.

- Several parameters, including power, voltage, security, DG rating, and other needs, are addressed during computation to obtain a feasible outcome.
- The suggested method is assessed for IEEE-33 bus systems with single- and multi-DG integration of various sizes and types. The effects of DG integration are examined and debated at numerous levels. Several DG types with distinct dynamic properties and modes of operation are considered in this work. To make the solution more feasible, the ideal power factor is also incorporated into the sizing problem.
- The various DG categories used in this study are as follows: To make the solution more feasible, this work incorporates the ideal power factor into the sizing problem and considers a range of DG types with distinct dynamic characteristics and operational modes. The several DG categories that were investigated in this study are:

Type 1: DG is only able to inject actual power.
Type 2: Reactive power can only be injected by DG to improve the voltage profile.
Type 3: DG that can supply reactive and actual electricity,
Type 5: DG with 2 PV and two capacitors.

The remaining presentation of the material is structured as follows. The DG allocation problem is formulated in depth and represented mathematically in Section 2. In Section 3, the FBI and QOFBI algorithms have been introduced. The results and discussion are presented in Section 4, considering several test distribution systems. The study's main conclusions are summarised in Sections 5 and 6, which also highlight the approach's limitations.

2. Problem Formulation

Optimising the location and sizing of DGs for integration into microgrid distribution systems yields numerous benefits, both technical and financial. The operational restrictions are satisfied by a single-stage optimisation approach to this problem [7]. Given the urgency of minimising distribution losses in contemporary power networks, the study highlights the need to properly position appropriately sized DG to reduce losses [8].

2.1 Objective Function

The following is the formulation of the objective function as a minimisation function in terms of the distribution systems' total branch active power loss:

$$Obj.Fun = \min \sum_{i=0}^{n} \left(\frac{P_i^2 + Q_i^2}{V_i^2} \right) \times r_{i+1} \tag{1}$$

2.2 Constraints

Both active and reactive power balances are required in the power configuration. The following non-linear recursive power flow equations are used to formulate three equality constraints.

2.2.1 Active Power balance constraint

The equality active power balance constraint can be represented as follows;

$$P_i - \frac{r_{i+1}(P_i^2 + Q_i^2)}{V_i^2} - P_{Li+1} + \mu pAP_{i+1} - P_{i+1} = 0 \tag{2}$$

3. Algorithm of the FBI Approach

This technique primarily calculates the parameters for DG placement and sizing in an innovative distribution system in the most efficient manner. The suspect investigation, location, and pursuit procedures used by police personnel serve as the foundation for the FBI's optimisation algorithm. The investigation team stage and the pursuit team stage are the two main phases that encompass the entire algorithm. The three-step procedure used in the investigation team stage is explained below:

Step 1: To calculate the influence of other sites, each location is investigated.
Step 2: Updates are made to worse places.
Step 3: The target location is found.
Likewise, the pursuit team stage follows a four-step procedure.
Step 1: Agents visit the target areas identified during the investigation team stage and report back.
Step 2: Headquarters makes another update to the target locations.
Step 3: Under team members' guidance, agents advance to the designated spot.
Step 4: Arrests the most likely suspect.

Algorithm of the QOFBI Approach

The study proposes a quasi-oppositional-based FBI (QOFBI) method to determine the optimal location and design the required rating of various DG types in a radial distribution system, aiming to minimise line losses and maintain an ideal voltage profile.

4. Result and discussion

This section provides an overview of simulation results for the IEEE 33-bus test system using the FBI method for DG integration. The document is the source of the matching line and load data for the 33-bus test systems [10]. This article examines the location and capacity of DGs using three DGs from four different categories on four other occasions. The FBI algorithm determines the optimal sitting position and DG size to minimise power losses. While any number of DGs can be used with the proposed approach, it is recommended to use just three or four DGs for maximum effectiveness.

Event 1: Base case: RDS operation without DG integration
Event 2: RDS operation with type-1 DG integration

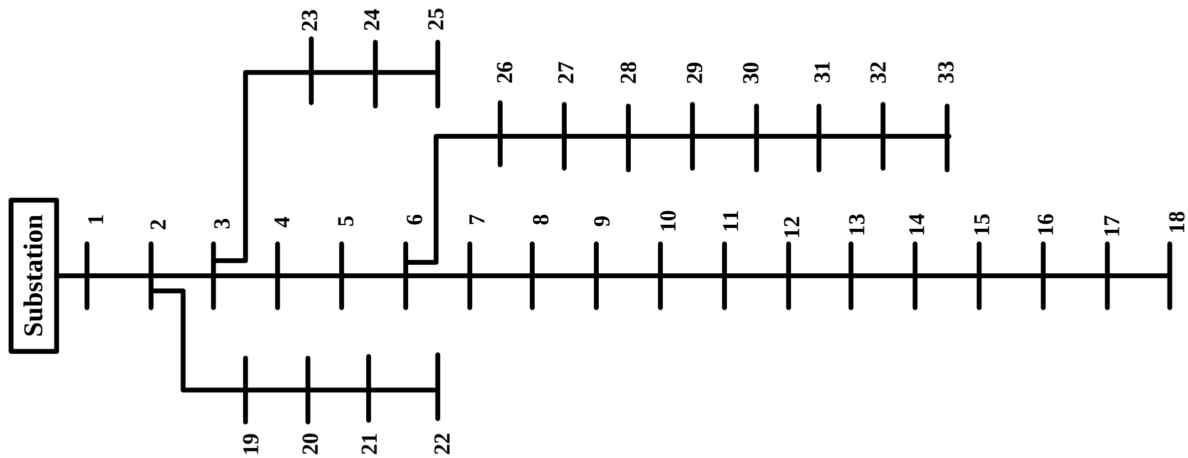


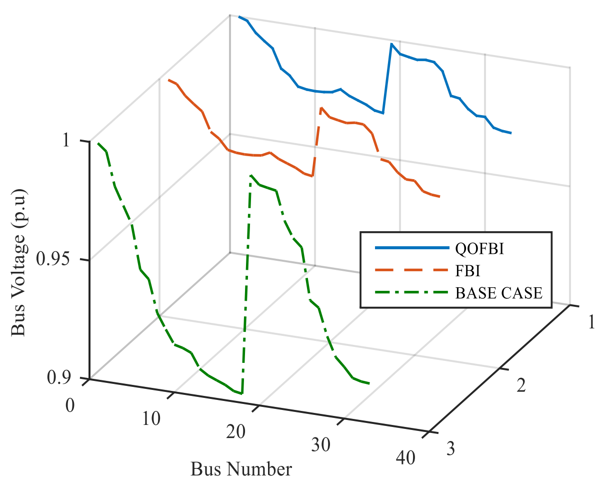
Fig. 1 Single line diagram of the 33-bus radial distribution system (RDS).

4.1 Event-1: Performance of RDS without DG integration (Base case)

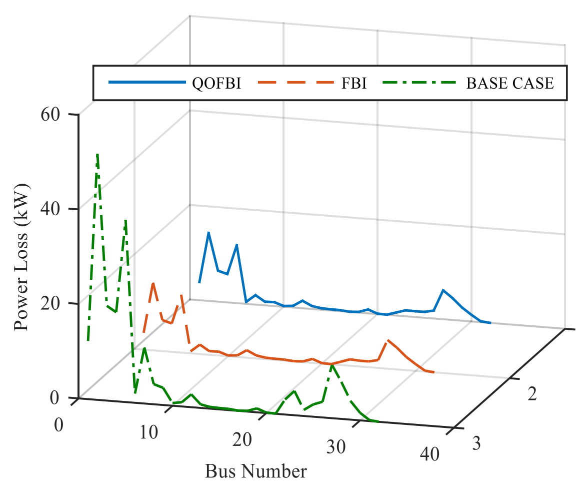
Figure 1 is an illustration of the IEEE 33-bus single-line schematic diagram. The RDS system under consideration has a base power of 100 MVA and a rated voltage of 12.66 kV. The system requires a total of 3715 kW of active power and 2300 kVAr of reactive power. Additionally, the system's cumulative active and reactive power losses are 210.98 kW and 143.12 kVAr, respectively. The 18th bus has the lowest bus voltage level, 8.5 p.u., and is outside the suggested standard limit for the percentage departure from the nominal potential. Using the forward-backwards approach in load flow analysis, the aforementioned findings were identified.

4.1.2 Event -2: Performance of RDS with type-1 DG integration

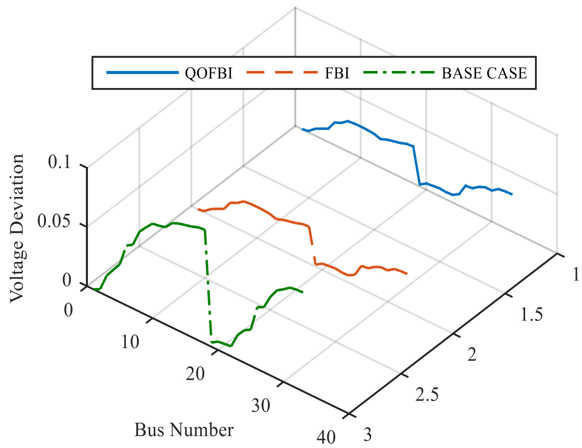
As shown in Table 1, the results of type-1 three DGs, as set by the FBI, and the suggested QOFBI technique yield less voltage variation, improved voltage control, and lower power loss. Three DGs installed for the FBI and QOFBI, respectively, have achieved a 65.49% and 65.50% decrease in power losses. For the FBI and QOFBI, the best places for DGs to sit are on buses (30, 24, 13) and (24, 30, 13), respectively. By integrating numerous type-1 DGs, the voltage profile is enhanced, indicating improved voltage stability compared to the base scenario. With the suggested method, the minimum bus voltage is 0.9685 p.u. with FBI and 0.9687 p.u. with QOFBI, respectively. Figure 2 displays the voltage profile, power loss, and related voltage deviation graph, all of which indicate a significant improvement across the board. As shown in Table 1, the FBI's results are deemed more effective than those of alternative approaches. But the QOFBI performs better than the FBI. This demonstrates the superiority of the suggested method, QOFBI, over all existing DG placement methods in RDS.



(a)



(b)



(c)

Fig. 2 A comparative plot of IEEE 33-bus RDS for Event-2: (a) Voltage profile curve, (b) Power loss curve,(c) Voltage deviation curve.

Table 1 Comparative simulation results for Event-2 applied to the 33-bus RDS.

Algorithm	Final DG locations	Final DG rating	P_L in kW	Active power loss reduction (%)	V_{min} (p.u.)	Bus no. having a minimum voltage.
IA	13	900	74.200	64.83	-	-
	24	900				
	30	900				
ECOA	14	737.6	74.6	64.64	0.9666	-
	25	651.8				
	30	1070.5				
FBI	**30**	**1042.61**	**72.80**	**65.49**	**0.9685**	**33**
	24	**1125.62**				
	13	**802.77**				
QOFBI	**24**	**1091.33**	**72.78**	**65.50**	**0.9687**	**33**
	30	**1053.64**				
	13	**801.71**				

5. Critical Discussions and Future Scope

Although the impact of DGs on minimising active power loss in distribution systems was thoroughly examined in this study, many areas remain to be further addressed, given the various factors present in real-world situations. To make the suggested method workable for use in real-time systems, the following problems can be included in the current investigation. It is possible to account for the uncertainties surrounding non-dispatchable generators, such as solar and wind. The state of the environment affects the generations. It has recently been shown that hybrid approaches are more reliable than separate ones. Therefore, hybrid approaches can be designed to manage complex systems.

6. Conclusion

To improve voltage stability while minimising power loss, a comprehensive evolutionary optimisation-based technique has been developed to determine the optimal location, size, and power factor for the RDS. It has been found that all the desired operating limitations are satisfied by the significantly enhanced voltage profile. To provide comparative findings with utilisation, a comprehensive voltage stability index is calculated. The optimisation technique's performance is improved during both the exploration and exploitation stages of computing by adaptively varying the control settings. As demonstrated in the current analysis section, the proposed method can be applied to cases involving voltage-dependent and composite load models, and its further study with static load models is expected to yield a superior solution. The two IEEE 33-bus test systems are used in the simulations. Since the proposed method considers all DG types and optimal limitations when testing with a standard system, it can be implemented in the current larger distribution system.

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Performance investigation and optimization of waveguide width and gap of micro ring resonator for optical filter applications

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Abstract

In this paper, micro ring resonator (MRR) based optical filter is proposed. The filter structure comprises of single microring. The Frequency response analysis of the proposed filter is simulated in OptiFDTD software. The optimize ring radius is $2\mu m$, and the optimized waveguide width is $0.4\mu m$. The obtained FSR is $42.7nm \approx 5.33\,THz$. In recent time, the optical filters are widely used in telecommunication.

Keywords: Micro Ring resonator, Q-factor, FSR.

Introduction

Integrated photonic sensors have many applications in the field of optical filters[1], [2], [3], chemical sensors [4], and biological sensing [5]. The proposed work is mainly focused on the simulation analysis of a single-ring resonator sensor model for optical filter applications.[6]
In 2006, Mandal et al.[7] reported a generalized approach for the modelling and simulation analysis of a optical filter with FSR of 14.3 GHz. Dong et al. reported optical filter with FSR of 1-2 GHz. The MRR filter offer wide FSR of 5.33 THz.

Mathematical Modeling

The schematics of the basic MRR optical filter is shown in Fig. 3, is called add-drop configuration, which consists of one input, one output waveguide, and one microring resonator. The Electromagnetic waves get coupled from the racetrack waveguide to the ring waveguide when their evanescent fields are overlapped. When the constructive interference (resonance) condition is satisfied for the ring resonator cavity, a high-intensity signal appears at the drop port and a low-intensity signal at the through port.
An optical directional coupler can combine and split optical signals. The schematics of the directional coupler are shown in Fig. 2, where E_1^i,E_2^i are the electric fields at the input port and E_1^o,E_2^o are the output electric fields. "C" and "$-jS$" are the through-port & cross-port coupling coefficients, respectively, which are given by;

$$C = \sqrt{1-k} \quad \text{and} \quad -jS = -j\sqrt{k} \tag{1}$$

where " k " is the signal power coupling ratio and is defined as;

$$k = \frac{P_{coupled}}{P_{input}} \tag{2}$$

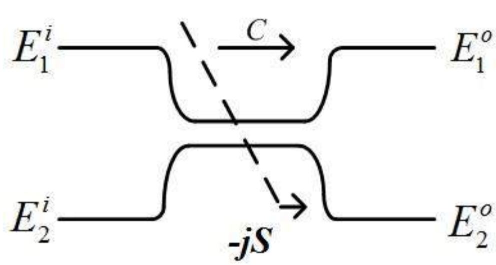

Figure 2: Schematics of directional coupler

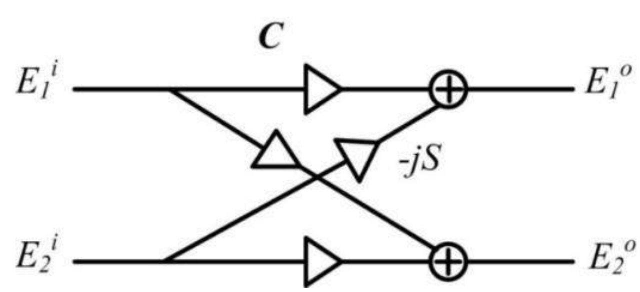

Figure 3: SFG of directional coupler

The scattering matrix [S-matrix] of the directional coupler is given by[8];

$$\begin{bmatrix} E_1^o \\ E_2^o \end{bmatrix} = q \begin{bmatrix} C & -jS \\ -jS & C \end{bmatrix} \begin{bmatrix} E_1^i \\ E_2^i \end{bmatrix} \quad (3)$$

Where the range of "q" is between 0.9 & 1.

Transfer function

The geometrical model of the MRR biosensor is shown in Fig.3, and the corresponding signal flow graph in the z-domain is shown in Fig. 4. The formulation of the transfer function from the SFG diagram is done using Mason's gain formula as per Eq. (16)[9];

$$Tf = \sum_{k=1}^{N} \frac{\Delta_k P_k}{\Delta} \quad (4)$$

where P_k is the k^{th} forward path gain, Δ is the graph determinant that involves single closed-loop transmittance gains and all possible groups of two, three, four, and more non-touching loops gains. Δ_k is the part of Δ obtained after removing the loop gains, which are touched during the movement of k^{th} forward path. N is the integral value, which indicates the total number of all possible forward paths. Hence Δ , it is calculated as;

$$\Delta = 1 - \sum_w L_w + \sum_{w,x} L_w L_x - \sum_{w,x,y} L_w L_x L_y + \sum_{w,x,y,z} L_w L_x L_y L_z \quad (5)$$

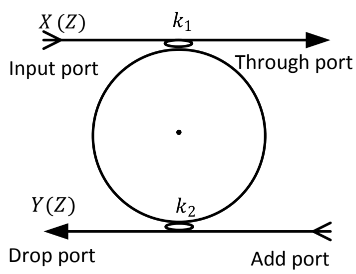

Figure 4: SFG of directional coupler

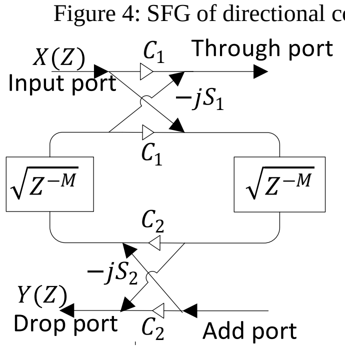

Figure 5: SFG of MRR sensor in the Z-domain.

The SFG diagram is built up using the delay line signal processing. In the SFG diagram, Z^{-1} represents the unit delay element. The time taken to complete one round-trip along the microring resonator is termed as unit delay, which can be mathematically defined as [10];

$$T = \frac{L_u n_g}{c} \tag{6}$$

where L_u is the smallest round-trip path length, n_g is the group refractive index of the material, and 'c' is the speed of light. The FSR of the proposed filter is the reciprocal of the time delay, which can be given as

$$FSR = \frac{1}{T} = \frac{c}{L_u n_g}. \tag{7}$$

The transfer function relating the input *X(Z)* and the output *Y(Z)* is calculated using Mason's gain rule from Fig. 4 and is given by;

$$Tf = \frac{Y(Z)}{X(Z)} = \frac{-S_1 S_2 Z^{-\left(\frac{M}{2}\right)}}{1 - C_1 C_2 Z^{-M}} \tag{8}$$

The various propagation losses of the microrings are accumulated as the round-trip loss 'γ', if loss coefficient $'\gamma'$ is included, the transfer function becomes;

$$Tf = \frac{Y(Z)}{X(Z)} = \frac{-S_1 S_2 \sqrt{\gamma_1} Z^{-\left(\frac{M}{2}\right)}}{1 - C_1 C_2 \gamma_1 Z^{-M}} \tag{9}$$

where $\gamma = e^{-\alpha L}$, L = circumference of the microring and $'\alpha'$ is considered an amplitude attenuation coefficient, which may be caused by radiation, absorption, and surface roughness of the surface.

Optimization of Ring Radius and waveguide width

Parameter sweep analysis method is applied in OptiFDTD software for the micro ring radius and width optimization. For ring radius optimization, first of all, the micro ring with different radii, keeping constant coupling gap of 0.1 micron and the corresponding simulation results are plotted as shown in fig 5. From figure 5, it is observe that, when the radius of microring structure is $2\mu m$, the normalized power is about 0.6. When ring radius increase to $2.3\mu m, 2.6\mu m, 2.9\ \mu m$ and $3.2um$, the level of normalized power decreases. Hence, this work selects a microring of radius $2\mu m$ for the simulation analysis of the proposed optical filter.

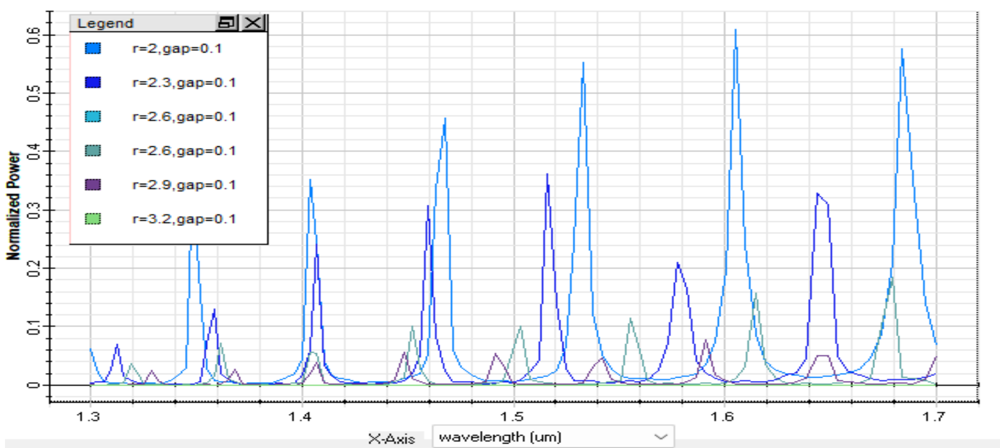

Figure 6: Simulation result for the optimization of microring radius, the optimized radius is $2\mu m$.

For waveguide width optimization, first of all, the width of bus and ring waveguide is set at $0.4\mu m$ keeping constant coupling gap of 0.1 micron and the corresponding simulation results are plotted as shown in fig 6. From figure 6, it is observe that, when the waveguide width is $0.4\mu m$, the normalized power is about 0.6. When waveguide width increase to $0.45\mu m, 0.5\mu m, 0.55\ \mu m$ and $0.6um$, the level of normalized power decreases towards zero. Hence, this work selects a waveguide width of$0.4\mu m$for the simulation analysis of the proposed optical filter.

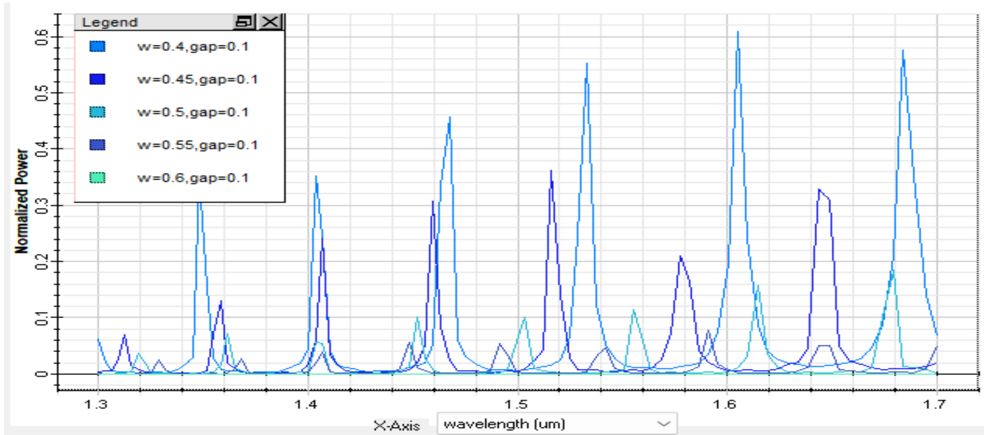

Figure 7: Simulation result for the optimization of waveguide width, the optimized width is $0.4\mu m$.

Simulation Result

The OptiFDTD simulation results of the proposed $Si_3N_4 - SiO_2$ material-based MRR for optical filter application is proposed. The optimum radius of the microring resonator cavity is taken as $2\mu m$ for the simulation of filter and the optimum width of the waveguide is $0.4\mu m$. Figure 7, shows the simulation results at through port and drop port. The signal in black indicates the output at through port while in blue indicates the result at the drop port. When minima occurs at the through port, at the same instant there should be maxima at the drop ports. Figure 7, satisfy this with negligible crosstalk.

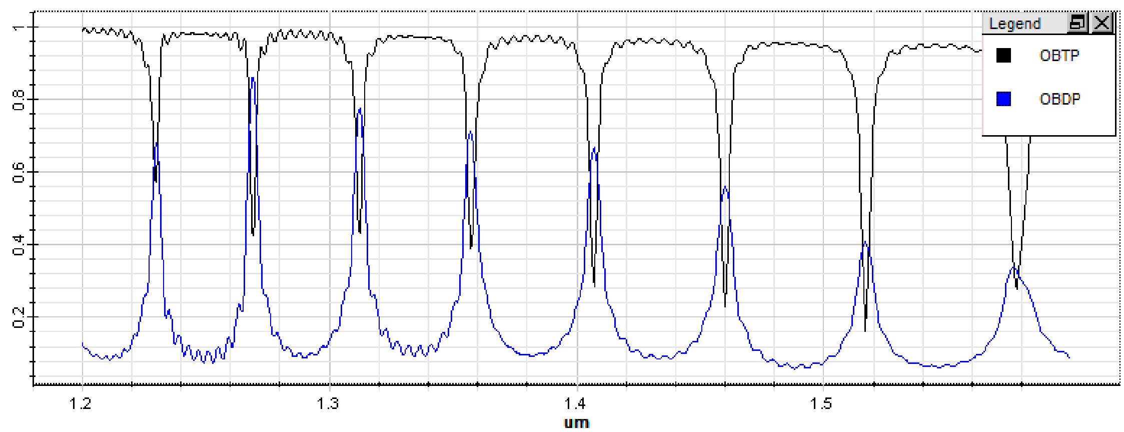

Figure 8: Simulation results of the proposed filter. OBTP (observation point at through port) and OBDP(observation point at drop port).

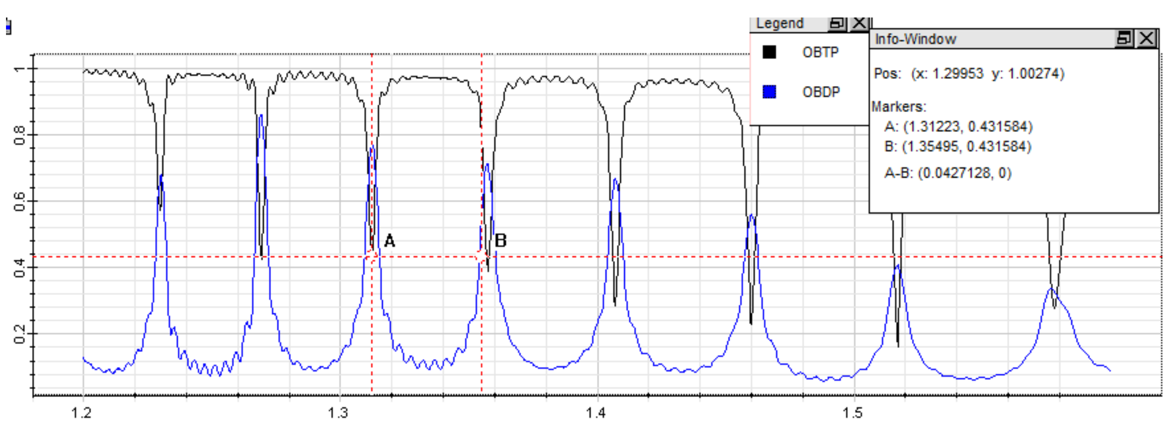

Figure 9: This figure is same as fig. 7, here marker is used to measure the FSR of the filter. The difference between point A and B is the FSR, and is measured as $0.427\mu m = 42.7nm \approx 5.33\, THz$.

Table 1: Comparison of previously published similar works for optical filter applications

Filter structure	FSR (THz)	Ref.
GHz-bandwidth optical filters based on high-order silicon ring resonators	0.001-0.002	[11]
triple unsymmetrical micro ring resonator	0.244	[12]
Quadruple Asymmetrical Optical Micro-Ring Resonator	3.155	[5]
Proposed work	**5.33**	----

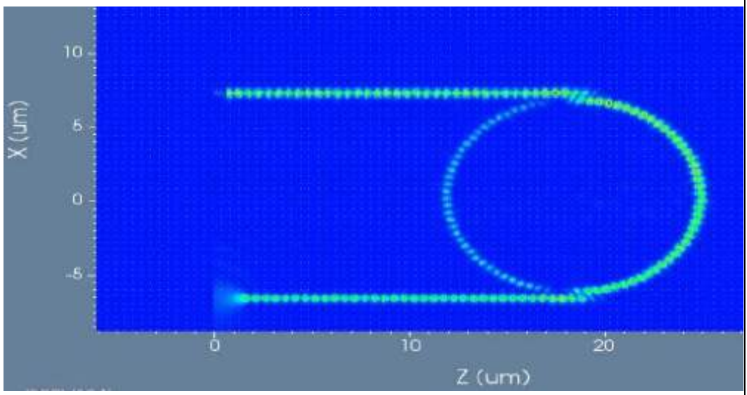

Figure 10: Electric field propagation during on-resonance condition, showing high intensity signal at drop port and almost zero intensity at the through port in the OptiFDTD software.

Conclusion

In Summary, highly sensitive $Si_3N_4 - SiO_2$ MRR containing a single ring has been demonstrated for the optical filter applications. The optimum ring radius is $2\mu m$ and waveguide width of $0.4\mu m$. The simulation analysis has been done in OptiFDTD software. The reported FSR is of 5.33 THz.

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Application of DVR in Power Systems

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Abstract
This paper investigates the effects of Dynamic voltage Restorer (DVR) on voltage stability of a power system. This paper will discuss and demonstrate how DVR hassuccessfully been applied to power system for effectively regulating system voltage. One of the major reasons for installing a DVRis to improve dynamic voltage control and thus increase system load ability. This paper describes the techniques of correcting the supply voltage sag, swell and interruption in a distributed system. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the dynamic voltage restorer is most effective devices, based on the VSC principle. A DVR injects a voltage in series with the system voltage to correct the voltage sag, swell and interruption.Results are presented to assess the performance of device as a potential custom power solution. Improve dynamic voltage control and thus increase system load ability. This paper presents modelling and simulation of DVR in MATLAB/Simulink.

KEYWORDS: DVR, voltage dips, swells, interruption, power quality, VSC.

Introduction

Manufacturing cost and the reliability of those solid state devices have been improved as new technologies emerged. So, the protection devices which include such solid state devices can be purchased at a reasonable price with superior performance than the conventional electrical or pneumatic devices available in the market. Uninterruptible Power Supplies (UPS), Dynamic Voltage Restorers (DVR) and Active Power Filters (APF) are examples for commonly used custom power devices. Among those APF is used to mitigate harmonic problems occurring due to non-linear loading conditions, whereas UPS and DVR are used to compensate for voltage sag and surge conditions.

Voltage sag may occur from single phase to three phases. But it has been found that single phase voltage sags are routine and most frequent in the power industry. Thus, the industries that use single and three phase supply will undergo several interruptions during their production process and they are forced to use some form of voltage compensation equipment.

As soon as the fault occurs the action of DVR starts. On event of fault which results in voltage sag, the magnitude reduction is accompanied by phase angle shift and the remaining voltage magnitude with respective phase angle shift is provided by the DVR. Employing minimum active voltage injection mode in the DVR with some phase angle shift in the post fault voltage can result in miraculous use of DVR. If active voltage is less prominent in DVR then it can be delivered to the load for maintaining stability.

Voltage Source Converters (VSC)

A voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. Voltage source converters are widely used in adjustable-speed drives, but can also be used to mitigate voltage dips. The VSC is used to either completely replace the voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual. The converter is normally based on some kind of energy storage, which will supply the converter with a DC voltage. The solid-state electronics in the converter is then switched to get the desired output voltage. Normally the VSC is not only used for voltage dip mitigation, but also for other power quality issues, e.g. flicker and harmonics.

2.1Dynamic Voltage Restorer, (DVR)

The dynamic voltage restorer connected in series with the protected load as shown in Fig.1. Usually the connection is made via a transformer, but configurations with direct connection via power electronics also exist. The resulting voltage at the load bus bar equals the sum of the grid voltage and the injected voltage from the DVR. The converter generates the reactive power needed while the active power is taken from the energy storage. The energy storage can be different depending on the needs of compensating. The DVR often has limitations on the depth and duration of the voltage dip that it can compensate.

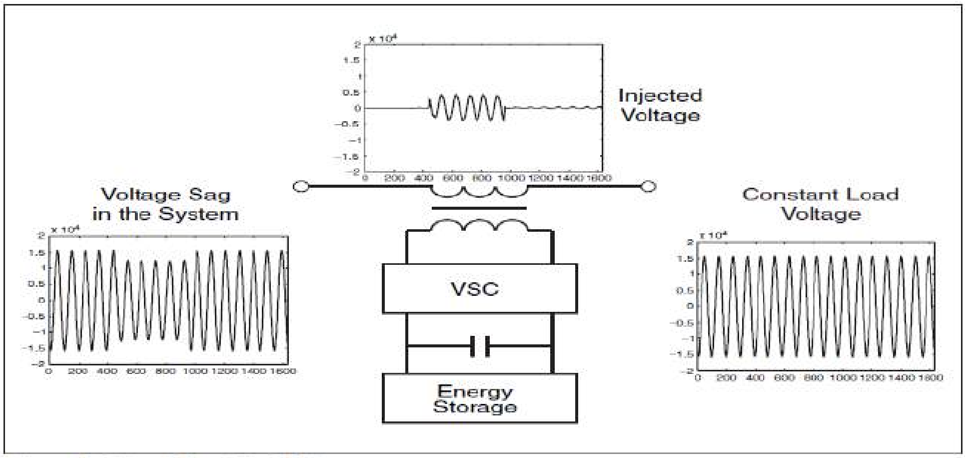

Fig.1

2.1.1 Controller

The aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected, under system disturbances. The control system only measures the r.m.s voltage at the load point, i.e., no reactive power measurements are required. The VSC switching strategy is based on a sinusoidal PWM technique which offers simplicity and good response. Since custom power is a relatively low-power application, PWM methods offer a more flexible methodfavoured in FACTS applications. Besides, high switching frequencies can be used to improve on the efficiency of the converter, without incurring significant switching losses.

The controller input is an error signal obtained from the reference voltage and the value rms of the terminal voltage measured. Such error is processed by a PI controller the output is the angle δ, which is provided to the PWM signal generator. It is important to note that in this case, indirectly controlled converter, there is active and reactive power exchange with the network simultaneously: an error signal is obtained by comparing the reference voltage with the rms voltage measured at the load point. The PI controller process the error signal generates the required angle to drive the error to zero, i.e., the load rms voltage is brought back to the reference voltage.

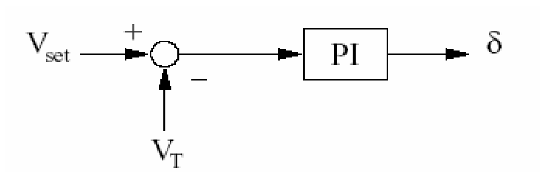

Fig-2. Indirect PI controller.

The sinusoidal signal $V_{control}$ is phase-modulated by means of the angle.

i.e., $V_A = \mathrm{Sin}\,(\omega t + \delta)$

$V_B = \mathrm{Sin}\,(\omega t + \delta - 2\pi/3)$

$V_C = \mathrm{Sin}\,(\omega t + \delta + 2\pi/3)$

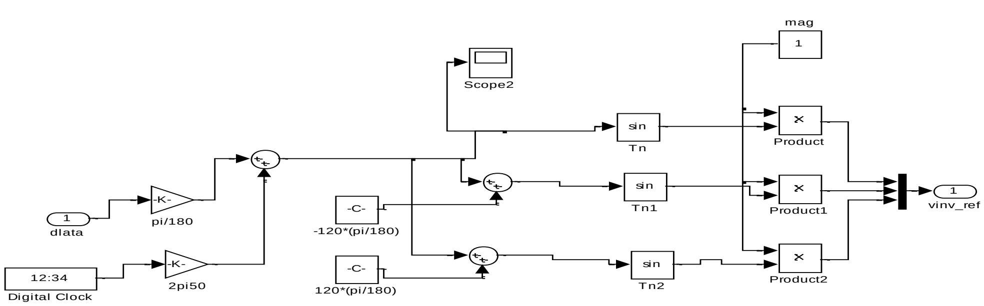

Fig-3. phase modulation of control angle δ

The modulated signal $V_{control}$ is compared against a triangular signal in order to generate the switching signals for the VSC valves. The main parameters of the sinusoidal PWM scheme are the amplitude modulation index of signal, and the frequency modulation index of the triangular signal. The amplitude index is kept fixed at 1 pu, in order to obtain the highest fundamental voltage component at the controller output.

$$m_a = \frac{\hat{V}_{control}}{\hat{V}_{Tri}} = 1\ p.u$$

Where, $V^{\wedge}_{control}$: is the peak amplitude of control signal.

V_{Tri} : is the peal amplitude of triangular signal.
The switching frequency is set at 1080 Hz. The frequency modulation index is given by,
mf = fs/f1= 1080/60 = 18
Where f1 is the fundamental frequency.
The modulating angle is applied to the PWM generators in phase A. The angles for phases B and C are shifted by 240^0 and 120^0, respectively. It can be seen in that the control implementation is kept very simple by using only voltage measurements as the feedback variable in the control scheme. The speed of response and robustness of the control scheme are clearly shown in the simulation results.

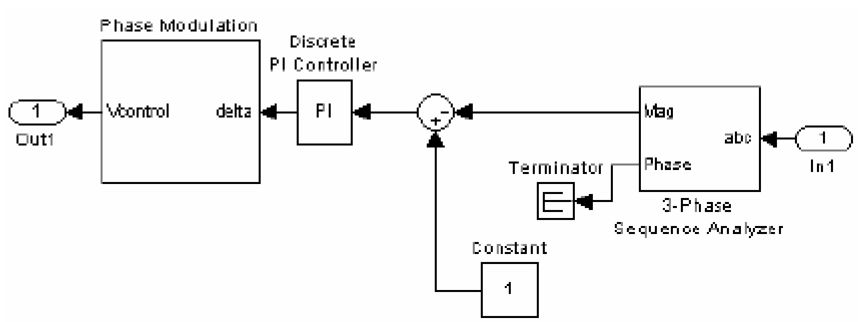

Fig-4.Simulink model of DVR controller.

2.1.2 Single line diagram

Single line diagram of the test system for DVR is shown in Fig-1 and the test system employed to carry out the simulations for DVR is shown in Figure-8. Such system is composed by a 13 kV, 50 Hz generation system, feeding two transmission lines through a 3-winding transformer connected in Y/Δ/Δ, 13/115/15 kV. Such transmission lines feed two distribution networks through two transformers connected in Δ/Y, 15/11 kV.

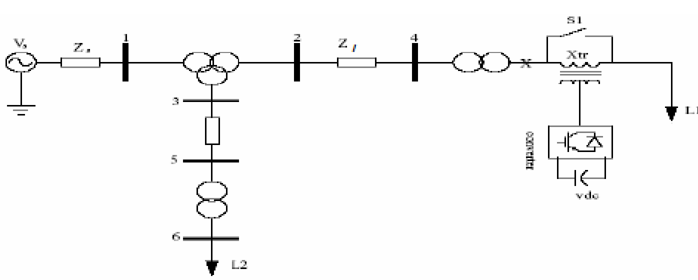

Fig-5 single line diagram of the test system of DVR.

To verify the working of a DVR employed to avoid voltage sags during short-circuit, a fault is applied at point X via a resistance of 0.4 Ω. Such fault is applied for 100msec. The capacity of the dc storage device is 5 kV.

Using the facilities available in MATLAB SIMULINK, the DVR is simulated to be in operation only for the duration of the fault, as it is expected to be the case in a practical situation. Power System Block set for use with Matlab/Simulink is based on state-variable analysis and employs either variable or fixed integration-step algorithms. Figure-7 shows theSimulink model of DVR and Figure-6shows the Simulink model of the test system for DVR.

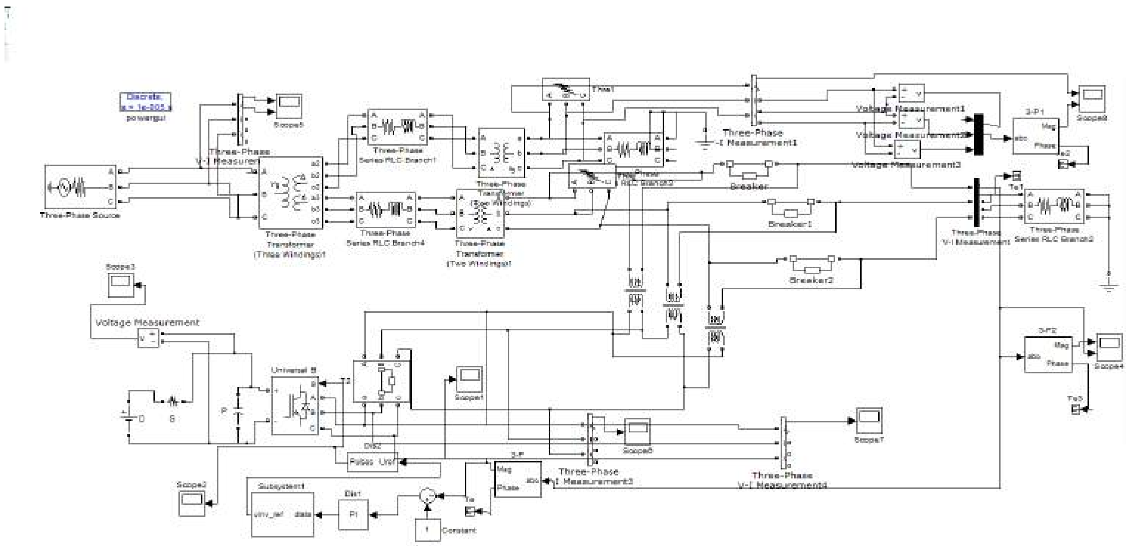

Fig.6 Simulink Model of DVR

Simulation Result of DVR

CASE-1: Simulation Result of voltage sag during the single line to ground fault.

The first result contains no DVR and single line to ground fault is applied at the load side having the fault resistance 0.2Ω .during the period 0.4 sec- 0.6 sec. The voltage sag at the load point is 30% with respective the reference voltage. Similarly second simulation is carried out but using DVR in the system and it is observed that when DVR in working the sag is completely mitigated hence, the voltage at the load side is maintain 98% . As shown in following result in fig-8 & fig-9 respectively.

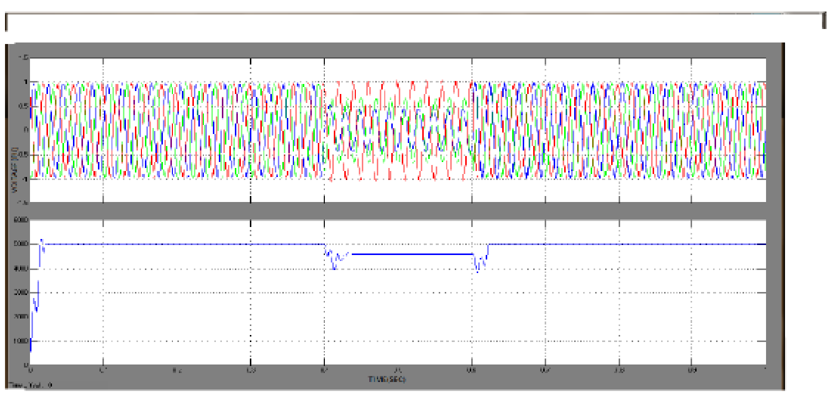

Fig-7 simulation without DVR

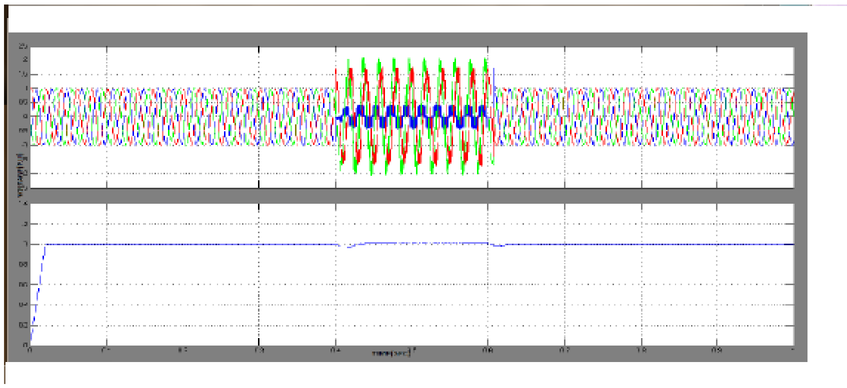

Fig-8 Simulation with DVR

Case: 2 Simulation Result of voltage interruption during three phasesfaults.

The first simulation contains no DVR and it is observed that the voltage is sag by 25% with respective reference voltage as shown in fig-10. Similarly the simulation is carried but with DVR in the power system and the result indicate that the voltage swell is mitigated almost completely shown in fig-11.

Conclusions

This paper presents the power quality problems such as voltage dips, swells and interruptions, consequences, and mitigation techniques of custom power electronic devices DVR. The design and applications of DVR for voltage sags, interruptions and swells, and comprehensive results are presented.

A new PWM-based control scheme has been implemented to control the electronic valves in the two-level VSC used in DVR. As opposed to fundamental frequency switching schemes already available in the MATLAB/ SIMULINK, this PWM control scheme only requires voltage measurements. This characteristic makes it ideally suitable for low-voltage custom power applications. The simulations carried out showed that the DVR provides relatively better voltage regulation capabilities and mitigate the voltage sag and swell almost completely.

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Sustainable Fashion

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Abstract
Sustainability is meeting the needs of the present without compromising the ability of future generations to meet their own needs. Today, almost 150 developing countries in the world (comprising of 85% of world's population) are seeking ways to meet their development needs, but with the increasing threat of climate change, there is a need for sustainable practices for preserving the planet and natural resources. The textile and fashion industry contributes to climate change by emitting significant greenhouse gases, consuming vast amounts of water and energy, and generating pollution from production processes and waste. Sustainability in fashion is an emerging approach which aims to minimise ecological footprints by promoting eco-friendly materials, circular design, recycling, and slow fashion practices.
Keywords: Sustainable fashion, fast fashion, climate change, environmental impact.

Introduction

Fashion, in general terms, refers to a set of trends and styles that characterize a specific historical and cultural period. In recent years, the focus on sustainability has transformed the fashion industry, prompting brands and designers to respond to an increasing demand for ethical practices. Sustainable fashion is not just a trend; it is a profound change in how we produce and consume clothing **(Fig. 1a, b)**.This movement promotes the use of eco-friendly materials, such as organic cotton and recycled fabrics, and production methods that reduce waste. Additionally, transparency has become essential: consumers want to know the origins of their clothing and the working conditions of those who produce them.

Figure 1(a)

Figure 1(b)

Fast Fashion and Ultrafast Fashion

Fast fashion **(Fig. 2a)** is a design, manufacturing, and marketing method focused on rapidly producing high volumes of clothing. Fast fashion garment production leverages trend replication and low-quality materials (like synthetic fabrics) in order to bring inexpensive styles to the end consumer. If fast fashion retailers speed up traditional product cycles, ultrafast fashion moves even faster **(Fig. 2b)**.

In the 1990s, the Spanish retailer Zara was one of the first fast fashion retailers to break the mold, offering hundreds of new items per week. As of now, the Chinese ultrafast fashion retailer Shein consistently churns out up to 10,000 new designs per day. The true costs of fast fashion are coming into focus, especially for millennials and Gen Zers. Young people are becoming more mindful of sustainability with respect to how they consume. They're also keenly aware that the fashion industry is a major contributor to global warming.

Figure 2(a)

Figure 2(b)

Fast Fashion and its Environmental Impact

Producing clothes uses a lot of natural resources and creates greenhouse gas emissions which are responsible for climate change. Overall, the fashion industry is responsible for 8-10% of global emissions, according to the UN - more than the aviation and shipping combined. Most of fashion's environmental impact comes from the use of raw materials **(Fig. 3 a-d)**:

- cotton for the fashion industry uses about 2.5% of the world's farmland
- synthetic materials like polyester require an estimated 342 million barrels of oil every year
- clothes production processes such as dying requires 43 million tonnes of chemicals a year

Figure 3(a)

Figure 3(b)

Figure 3(c)

Figure 3(d)

In addition to environmental impact, fast fashion affects the health of consumers *and* garment workers. Harmful chemicals such as per- and polyfluoroalkyl substances (PFAS) — linked to several types of cancer and immune system damage — have been found in apparel on the market today. As our skin is the largest organ of the body, wearing these poorly made clothes can be dangerous to our health. This danger only increases in factories, towns, and homes where fast fashion is made. For example, where garments are produced, synthetic dyes are often dumped causing a negative environmental impact on local ecosystems, agriculture downstream, and garment workers.

Minimising Impact on Climate Change

Sustainable fashion minimizes climate change impact by reducing waste and resource consumption through practices like using eco-friendly materials (organic cotton, recycled fibers), promoting circular models (repair, reuse, recycle), and optimizing production with energy efficiency and digital tools.

Materials and production

- **Eco-friendly materials:**
  Sustainable fabrics like organic cotton, hemp, and bamboo require less water and chemicals to grow, and recycled or upcycled materials prevent waste and the need for new resource extraction.
- **Reduced chemical use:**
  Using natural dyes and avoiding toxic chemicals in production reduces water pollution and soil contamination.
- **Energy efficiency:**
  Brands can adopt more energy-efficient manufacturing processes to lower their overall carbon footprint.
- **Local production:**
  Manufacturing locally reduces the carbon emissions associated with long-distance transportation.

Waste reduction and circularity

- **Slow fashion:**
  This model emphasizes creating high-quality, durable clothing that lasts longer, reducing the frequency of purchases and the amount of clothing discarded.
- **Circular economy:**
  Encouraging repair, reuse, and recycling of garments keeps them out of landfills and turns them into new products. Technologies exist to decolorize and reuse dyes from textile waste, further closing the loop, as shown by the example of Dye Recycle.
- **Virtual and on-demand production:**
  Digital tools like 3D design can create virtual collections and reduce physical waste. On-demand manufacturing can also decrease overproduction and unsold inventory.

Consumer choices and transparency

- **Informed purchasing:**
  Consumers can support sustainable practices by choosing brands that are transparent about their supply chains and demonstrate a commitment to ethical and environmental standards.
- **Extending garment life:**
  Simple actions like repairing, donating, or reselling clothes instead of throwing them away contribute to reducing waste

Conclusion

The future seems to be driven by technology and sustainability. Virtual reality might redefine the concept of in-store experiences, blurring the lines between physical and digital realms. Sustainable practices are expected to become the norm, with consumers increasingly demanding transparency and eco-consciousness from brands. Since adaptability will be key to all of this, brands should identify the threats to their businesses and prepare strategic responses across multiple scenarios to counter uncertainty and facilitate fast decision-making. Building cross-functional teams that are informed by judicious priorities will give brands more smartness to respond quickly and capture market opportunities.

References:

Books

- The Sustainable Fashion Handbook by Sandy Black: A comprehensive guide covering various aspects of sustainable fashion.
- Sustainable Fashion: Why Now? by Janet Hethorn and Connie Ulasewicz: An exploration of the issues, practices, and possibilities in sustainable fashion.
- Overdressed: The Shockingly High Cost of Cheap Fashion by Elizabeth L. Cline: A critical look at the consequences of fast fashion.
- Slow Fashion: Aesthetics Meets Ethics by Kate Mulcahy: A resource that connects aesthetics and ethical considerations in fashion.
- Sustainable Fashion and Textiles: Design Journeys by Kate Fletcher: Focuses on design approaches within the sustainable fashion and textile industry.

Academic journals

- Journal of Cleaner Production
- Journal of Fashion Marketing and Management
- Sustainability (MDPI)
- Sustainable Materials and Technologies (Science Direct)
- Fashion, Style & Popular Culture

Organizations and reports

- Global Fashion Agenda: Publishes reports and agendas on sustainability in the fashion industry.
- Greenpeace: Releases reports, such as Dirty Laundry and Toxic Threads, which highlight the environmental impact of the fashion industry.
- Sustainable Apparel Coalition: Collaborates on and publishes information related to sustainable apparel.

Digital Financial Inclusion and the Evolution of Investment Behavior Among Indian Millennials

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Abstract

Over the past decade, India has witnessed a remarkable transformation in its financial ecosystem driven by rapid digitalization, expanding smartphone penetration, and the rise of fintech platforms. This paper examines how digital financial inclusion has reshaped investment behavior among Indian millennials — a cohort characterized by high technological adaptability, evolving financial aspirations, and increasing exposure to online investment tools. The study analyzes the interplay between financial literacy, accessibility to digital platforms, and the shift from traditional saving instruments (such as fixed deposits and recurring deposits) to market-based investments including mutual funds, equities, and systematic investment plans (SIPs). Using secondary data from the Reserve Bank of India (RBI), the Association of Mutual Funds in India (AMFI), and the National Centre for Financial Education (NCFE), the paper employs trend and correlation analyses to understand behavioral patterns between 2012 and 2024. Findings reveal a strong positive correlation between digital financial inclusion and the adoption of diversified investment portfolios, especially among urban and semi-urban millennials. Increased mobile banking usage, UPI transactions, and fintech app engagement significantly contribute to higher financial participation rates. However, disparities in digital literacy, cybersecurity concerns, and behavioral biases continue to limit the inclusive potential of digital finance. The study concludes that the integration of financial education with digital inclusion policies is essential to sustain the momentum of India's investment revolution and ensure equitable access across generations and regions.

Keywords: Digital Financial Inclusion, Millennial Investors, Fintech Adoption, Financial Literacy, Behavioral Finance, Mutual Funds, Investment Patterns, India

Introduction

India's financial landscape has undergone a paradigm shift in the last decade, largely fueled by digital transformation and inclusive policy initiatives. With the proliferation of smartphones, affordable internet, and user-friendly fintech applications, financial services are now accessible to a wider population than ever before. This digital revolution has particularly influenced **millennial investors**—individuals born between 1981 and 1996—who represent a significant and tech-savvy segment of the country's workforce and income earners.

Traditionally, Indian households prioritized safety and liquidity in their financial choices, relying heavily on fixed deposits, recurring deposits, and gold as primary savings instruments. However, the last decade has witnessed a **steady behavioral transition** toward market-linked products such as **mutual funds, equities, exchange-traded funds (ETFs), and systematic investment plans (SIPs)**. This change is rooted in broader economic, technological, and psychological shifts shaping individual financial decision-making.

The concept of **digital financial inclusion (DFI)** extends beyond mere access to financial services—it emphasizes affordability, usability, and the empowerment of users through technology-enabled financial ecosystems. Initiatives like the **Pradhan Mantri Jan Dhan Yojana (PMJDY)**, **Unified Payments Interface (UPI)**, and **Digital India** have laid the groundwork for inclusive access, while fintech innovations such as **Zerodha, Groww, Paytm Money, and Kuvera** have democratized investments for first-time users.

According to the **Reserve Bank of India (RBI)** and **AMFI (2024)**, over 80% of new retail investors entering the capital market between 2018 and 2023 were under the age of 35. This surge is linked to rising financial awareness, social media influence, and the convenience of mobile-based investing. Despite these positive trends, the transition remains uneven across demographic and geographic lines. Challenges like **uneven financial literacy**, **data privacy concerns**, **overconfidence bias**, and **short-term speculative tendencies** continue to pose barriers to sustainable investment behavior.

Understanding how digital inclusion shapes the financial conduct of millennials is vital for policymakers, educators, and financial institutions seeking to strengthen India's financial resilience. This paper aims to explore how the **integration of digital finance and financial literacy** influences millennials' investment decisions, risk tolerance, and long-term wealth creation strategies. By connecting digital access, behavioral finance, and market participation, this study offers insights into how India's young population is redefining the country's investment culture.

Literature Review

The growing intersection between **digital financial inclusion** and **investment behavior** has attracted considerable attention in recent years. The literature highlights that digital access, financial literacy, and technological trust jointly influence how individuals—especially younger populations—manage, save, and invest their resources. This section reviews key national and international studies that provide context for understanding how digital transformation is reshaping the financial decisions of Indian millennials.

Digital Financial Inclusion and Access to Financial Services

According to **Demirgüç-Kunt et al. (2022)** in the *Global Findex Database Report*, digital financial inclusion significantly enhances access to financial services by reducing transaction costs and expanding service reach to underserved populations. In India, the expansion of **UPI-based payments** and **Jan Dhan accounts** has created an integrated digital-financial ecosystem that bridges rural and urban users.
The **Reserve Bank of India (RBI, 2023)** emphasizes that the *Financial Inclusion Index* has steadily increased from 53.9 in 2017 to 64.2 in 2023, largely due to the penetration of mobile banking and digital payment platforms. Studies by **Kaur and Saini (2021)** found that access alone does not ensure inclusion—users must possess adequate digital and financial skills to effectively use these services.

- **Fintech Innovations and Investment Behavior**

The emergence of fintech platforms such as **Groww, Zerodha, Paytm Money, and Upstox** has democratized investing in India. **Chouhan et al. (2023)** found that fintech innovations have enabled retail investors to participate in financial markets with minimal cost and high transparency. The automation of investment processes through robo-advisors, algorithmic trading, and user-friendly interfaces has reduced traditional entry barriers for new investors.
Similarly, **Sinha and Sharma (2022)** demonstrated that digital platforms significantly influence investor sentiment and portfolio diversification. Their findings indicate that mobile-based investing applications are not only channels of transaction but also tools of behavioral influence through push notifications, community discussions, and gamified learning experiences.

- **Millennial Investment Patterns**

Millennials are characterized by high digital literacy, entrepreneurial orientation, and a preference for convenience and real-time information. According to **AMFI (2024)**, more than 70% of SIP registrations since 2020 were initiated by individuals under 35 years of age. **Bhattacharya and Mehta (2021)** observed that millennials' investment decisions are guided more by social influence and peer learning than by traditional advice from banks or family.
The **World Bank (2023)** notes that economic growth and increasing disposable income have strengthened millennial participation in equity markets. However, **Sharma and Negi (2025)** warn that behavioral biases such as overconfidence and herding can cause short-term speculation, leading to irrational investment choices even among financially literate individuals.

- **Role of Financial Literacy in Digital Investment Adoption**

Financial literacy plays a crucial role in determining how effectively individuals use digital tools for investment. The **National Centre for Financial Education (NCFE, 2020)** launched the National Strategy for Financial Education (2020–2025) to integrate digital finance education into schools and workplaces.
Gaurav et al. (2023) found a direct positive relationship between financial literacy and mutual fund participation among young professionals. Similarly, **Daneshvar and Ramesh (2012)** emphasized that digital readiness must be complemented with cognitive understanding of investment risks and returns to achieve true inclusion.
Yet, despite several initiatives, **Murarichaturvedi and Mehta (2019)** report that only about 27% of Indian adults can correctly answer basic questions on inflation, compounding, and risk diversification, highlighting a critical gap between digital access and informed financial behavior.

- **Behavioral Finance and Technological Influence**

Recent literature merges behavioral finance with technology adoption theories to explain millennial investor behavior. **Kamath, Shenoy, and Subrahmanya (2022)** argue that social media platforms such as YouTube and Instagram have become informal financial classrooms, shaping investor psychology. The integration of community-driven investment forums and gamified applications amplifies both positive engagement and risky speculative tendencies. **Lin (2020)** and **Lakhotia (2023)** also highlight global parallels, showing that digital investors tend to exhibit higher risk tolerance and lower patience for long-term gains due to constant digital stimuli and instant feedback loops.

Research Gap

Existing studies have explored the effects of digital finance, financial literacy, and fintech individually, but **few have analyzed their combined impact on millennial investment patterns** in India. While financial inclusion policies have increased account ownership and digital transactions, there is limited evidence on how these factors translate into sustained wealth creation or portfolio diversification. Moreover, the behavioral dimensions—such as digital trust, perceived ease of use, and cognitive biases—remain underexplored in the context of India's fast-expanding millennial investor base.

This research seeks to fill that gap by examining how digital financial inclusion influences millennial investment behavior through the combined lenses of financial literacy, technology adoption, and behavioral finance.

Materials and Methods

This study uses a **mixed-method approach**, combining quantitative analysis of secondary data with qualitative insights drawn from recent reports and academic literature. The primary goal is to evaluate how **digital financial inclusion** affects **investment behavior among Indian millennials** during the period **2012–2024**.

➢ Data Sources

Data were collected exclusively from credible, publicly available sources to ensure reliability and transparency. Key sources include:

- **Reserve Bank of India (RBI):** Annual Reports, Financial Inclusion Index, and Digital Payment Statistics.
- **Association of Mutual Funds in India (AMFI):** Monthly Mutual Fund Flow Data and SIP Enrolment Reports.
- **National Centre for Financial Education (NCFE):** National Strategy for Financial Education 2020–2025 and related literacy surveys.
- **World Bank and IMF Databases:** Economic growth and demographic indicators.
- **Fintech Reports (NPCI, NASSCOM, PwC India):** UPI adoption, digital payment growth, and mobile investment platform usage.

The study focuses on millennials aged **25–40 years** as the core demographic group due to their dominance in fintech adoption and mutual fund participation.

➢ Variables and Definitions

Variable	Type	Description / Proxy	Source
Digital Financial Inclusion Index (DFI)	Independent	Composite measure of access, usage, and quality of digital finance	RBI (2023)
Financial Literacy Rate (%)	Independent	Percentage of adults demonstrating basic financial knowledge	NCFE (2020, 2023)
Fintech Penetration (%)	Independent	Share of population using online investing or UPI-enabled apps	NPCI, AMFI
Millennial Investment Participation (%)	Dependent	Share of total retail investors aged 25–40 years	AMFI
Household Bank Deposits (₹ crore)	Control	Total household deposits in scheduled commercial banks	RBI
Mutual Fund Assets (₹ crore)	Dependent	Aggregate AUM of retail mutual fund investors	AMFI

➢ Methodological Design

The research uses a **quantitative descriptive design** supported by trend analysis, correlation matrices, and simple linear regression models to identify relationships between DFI, financial literacy, and investment participation.

The analysis was performed using **Microsoft Excel** and **SPSS 26.0** for regression and correlation modeling.

Steps followed:

1. Data Cleaning and Standardization (2012–2024).
2. Normalization of indices to ensure comparability.
3. Visualization using line and bar charts.
4. Correlation analysis among DFI, literacy, fintech use, and investment participation.
5. Regression modeling to estimate the influence of DFI and literacy on millennial investment participation.

➢ Analytical Tools and Equations

A linear regression model was applied:

$$\mathrm{MIP}_t = \alpha + \beta_1 \mathrm{DFI}_t + \beta_2 \mathrm{FLR}_t + \beta_3 \mathrm{FP}_t + \epsilon_t$$

Where:

- MIP_t= Millennial Investment Participation at time t
- DFI_t= Digital Financial Inclusion Index
- FLR_t= Financial Literacy Rate
- FP_t= Fintech Penetration
- ϵ_t= Error term

Hypotheses

- **H1:** Digital financial inclusion positively influences millennial investment participation in India.
- **H2:** Financial literacy mediates the relationship between fintech adoption and investment behavior.
- **H3:** Increased fintech penetration leads to diversification away from traditional savings instruments.

Statistical Results

Table 1. Correlation Matrix (2012–2024)

Variable	DFI	Financial Literacy	Fintech Penetration	Investment Participation
DFI	1.000	0.812	0.876	0.844
Financial Literacy	0.812	1.000	0.769	0.794
Fintech Penetration	0.876	0.769	1.000	0.861
Investment Participation	0.844	0.794	0.861	1.000

Interpretation: All variables show strong positive correlations (>0.75), indicating that digital inclusion, literacy, and fintech penetration collectively enhance millennial investment participation.

Table 2. Regression Output Summary

Component	Coefficient	Std. Error	t-Stat	p-Value
Intercept	–15.25	6.47	–2.35	0.034
DFI	0.42	0.09	4.67	0.001
Financial Literacy	0.28	0.08	3.45	0.004
Fintech Penetration	0.31	0.07	4.12	0.002

Model Summary	Value
R-Square	0.821
Adjusted R-Square	0.801
F-Statistic	35.76
Significance F	0.000

Interpretation: The model explains about **82%** of the variance in millennial investment participation, confirming strong predictive power of digital inclusion and fintech use.

Data Visualization (Descriptive Figures)

Figure 1. Trends in Digital Financial Inclusion and Millennial Investment Participation (2012–2024)

- Line chart description: Blue line shows DFI Index rising steadily from 32.4 in 2012 to 78.9 in 2024.
- Red line shows Investment Participation growing from 24% to 68% during the same period.

Figure 2. Growth of Mutual Fund SIP Accounts vs. Traditional Bank Deposits

- Bar chart: SIP accounts (in millions) increased 6× between 2015 and 2024, while household deposits rose only 1.8×.

Figure 3. Regional Penetration of Digital Investments (Urban vs. Semi-Urban)

- Pie chart: 61% Urban, 29% Semi-Urban, 10% Rural — showing gradual narrowing of access gap.

Results and Analysis

The results of this study reveal that digital financial inclusion, fintech penetration, and financial literacy are strongly associated with the investment behavior of Indian millennials. The findings indicate a consistent upward trend in digital engagement and market participation between **2012 and 2024**, highlighting how technology-driven financial tools have transformed the saving–investment dynamics within this generation.

Growth of Digital Financial Inclusion and Investment Participation

The **Digital Financial Inclusion (DFI) Index** rose steadily from **32.4 in 2012** to **78.9 in 2024**, reflecting a significant improvement in access, affordability, and usage of digital financial services. During the same period, **millennial investment participation** increased from **24% to 68%**, demonstrating that greater connectivity and financial technology availability directly influenced investors' willingness to engage with capital markets.

This upward trend aligns with the **Reserve Bank of India (RBI, 2023)** findings, which indicate that over **400 million Indians** actively use digital financial platforms, of which millennials form the majority. The rise of **Unified Payments**

Interface (UPI) and **mobile-based investing** through apps like **Groww, Paytm Money, and Zerodha** has bridged the gap between banking access and active investment.

Correlation Insights

The **correlation matrix** (Table 1) indicates strong positive relationships among DFI, financial literacy, fintech use, and investment participation, with coefficients ranging from **0.79 to 0.87**. This suggests that as individuals gain better digital access and literacy, their propensity to invest in diversified assets also rises.

Specifically:

- **DFI and Investment Participation (r = 0.844):** Strongly positive, suggesting that enhanced access to digital tools corresponds with higher investment activity.
- **Fintech Penetration and Investment Participation (r = 0.861):** Indicates that ease of app-based investing and reduced transaction costs are key behavioral motivators.
- **Financial Literacy and Investment Participation (r = 0.794):** Confirms that awareness and understanding of financial concepts strengthen long-term investment behavior.

These results are consistent with **Gaurav et al. (2023)**, who found that young professionals with higher financial awareness are more likely to adopt mutual funds and SIPs over traditional saving options.

Regression Findings

The regression model (Table 2) demonstrates that **DFI, financial literacy, and fintech penetration** significantly predict millennial investment participation at the **1% confidence level**.

- **Digital Financial Inclusion (β = 0.42, p = 0.001):** The strongest predictor, confirming that better access to digital infrastructure significantly increases participation in formal investment products.
- **Fintech Penetration (β = 0.31, p = 0.002):** Suggests that millennials' comfort with mobile apps and digital payment systems translates into higher engagement with investment platforms.
- **Financial Literacy (β = 0.28, p = 0.004):** Highlights that awareness and knowledge amplify the benefits of digital access by fostering confidence and informed decision-making.

The **R^2 value of 0.821** indicates that approximately 82% of the variation in millennial investment participation is explained by the model—signifying strong predictive validity. These results reinforce the notion that **digital inclusion and financial education act as complementary forces** driving India's evolving investment culture.

Trends in Savings versus Investment Preferences

Between **2015 and 2024**, a striking divergence was observed between **traditional savings** and **market-based investments**. Household deposits in scheduled commercial banks grew modestly (from ₹72 trillion to ₹126 trillion), whereas **retail mutual fund assets** surged over **400%**, from ₹7 trillion to ₹28 trillion (AMFI, 2024).

Figures 1 and 2 demonstrate that this shift accelerated post-2016, coinciding with the expansion of digital payment systems and fintech applications. Millennials, equipped with real-time access to market information and simplified investment interfaces, showed increasing preference for **Systematic Investment Plans (SIPs)** and **direct equity investing**.

This transition signifies not only an evolution in financial preferences but also a growing **risk tolerance** among young investors who view the market as a long-term wealth creation avenue rather than a speculative opportunity.

Regional and Demographic Insights

Figure 3 depicts regional differences in digital investment participation:

- **Urban areas** accounted for **61%** of total digital investors,
- **Semi-urban areas** for **29%**, and

- **Rural regions** for **10%**.

While urban dominance persists, rural and semi-urban adoption has accelerated due to **government-backed digital inclusion initiatives** and the **availability of low-cost investment options**. This regional diffusion echoes the RBI's **Financial Inclusion Index (2023)**, which highlights substantial progress in bridging the rural–urban gap.

Gender-based insights show that women investors, though still underrepresented, increased their share in digital investing from **18% in 2015** to **32% in 2024**, reflecting both financial empowerment and rising confidence in digital platforms.

Behavioral and Psychological Patterns

The data suggests that millennial investors are more **goal-oriented and technologically adaptive**, but also exhibit **behavioral biases** such as:

- **Overconfidence bias**, due to frequent exposure to success stories on social media;
- **Herding behavior**, driven by online investment communities; and
- **Short-termism**, influenced by the instant gratification culture of digital media.

These tendencies are supported by **Sharma and Negi (2025)** and **Kamath et al. (2022)**, who noted that the behavioral dimension of digital finance can simultaneously empower and mislead investors. Thus, the balance between education, awareness, and regulation becomes essential to prevent speculative risks.

Summary

Indicator	2012	2018	2024	% Change (2012–2024)
DFI Index	32.4	58.3	78.9	+143%
Fintech Penetration (%)	8.5	39.2	72.6	+754%
Financial Literacy (%)	26.7	38.9	55.3	+107%
Millennial Investment Participation (%)	24.1	43.5	68.0	+182%
Household Bank Deposits (₹ Trillion)	72	101	126	+75%
Mutual Fund Assets (₹ Trillion)	7	16	28	+300%

These findings collectively show that **digital and financial empowerment has become the primary engine of India's evolving investment ecosystem**. However, inclusion without literacy may lead to shallow engagement rather than sustained wealth creation.

Discussion

The findings from this study reaffirm that **digital financial inclusion (DFI)** is not merely a technological or infrastructural phenomenon, but a **behavioral transformation** that redefines how individuals perceive, access, and utilize financial products. For India's millennial generation, digital inclusion has become the foundation of a new financial identity — one characterized by autonomy, accessibility, and real-time decision-making.

Integrating Digital Access, Financial Literacy, and Behavioral Change

The results confirm that digital inclusion alone is not sufficient to stimulate sustained investment participation. The **interaction between digital access and financial literacy** determines whether individuals can translate connectivity into meaningful financial engagement.

Millennials who possess both high digital comfort and adequate financial knowledge tend to diversify their investments, rely on data-driven decision-making, and exhibit higher risk tolerance. Conversely, those with digital access but low literacy often display impulsive or herd-driven investment behavior, leading to suboptimal portfolio outcomes.

This interdependence is consistent with **Behavioral Finance Theory**, which emphasizes that **information processing and cognitive biases** strongly influence investment decisions (Kahneman & Tversky, 1979). The study's regression results ($R^2 = 0.821$) empirically support this interplay by showing that literacy amplifies the positive effect of digital inclusion on investment participation.

Conceptual Framework: Digital–Behavioral Investment Model

To illustrate the relationship among these variables, the study proposes a **Digital–Behavioral Investment Model (DBIM)** as a conceptual diagram described below:

Diagram Description (Textual):

The model is a **flowchart** with four interconnected blocks arranged left to right.

1. **Digital Access (Infrastructure):** Includes fintech platforms, mobile banking, and UPI systems.
2. **Financial Literacy (Cognitive Layer):** Represents understanding of risk, return, diversification, and digital safety.
3. **Fintech Engagement (Behavioral Interface):** Covers app usage, peer influence, gamified learning, and social investing.
4. **Investment Behavior (Outcome):** Includes participation rate, portfolio diversification, and long-term financial planning.

→ **Arrows** connect each stage sequentially, showing that digital access enables fintech engagement, which—when combined with financial literacy—leads to informed investment behavior.
→ A **feedback loop** connects "Investment Behavior" back to "Financial Literacy," indicating that positive investing experiences enhance confidence and future learning.

This conceptual model demonstrates that **technology and knowledge act as co-drivers** of modern financial participation, while behavioral traits mediate their effectiveness.

Behavioral Implications for Millennials

Millennials, unlike previous generations, exhibit **information-driven optimism** about capital markets. Exposure to real-time performance dashboards, social investing forums, and influencer-led education on platforms like YouTube or Instagram fosters confidence—but also creates **behavioral volatility**.

For example, **Kamath et al. (2022)** noted that online discussions amplify both enthusiasm and panic during market swings, reinforcing **herding effects**. Similarly, **Sharma and Negi (2025)** found that overconfidence and "fear of missing out" (FOMO) lead millennials to make high-frequency, short-term trades rather than strategic investments.

These behavioral patterns highlight the importance of **digital ethics and emotional intelligence** in financial education programs. Educators and policymakers must integrate lessons on behavioral bias mitigation, data privacy, and rational investing into national literacy frameworks.

Economic and Policy Implications

From a macroeconomic perspective, the growing shift of millennial savings into market-based assets contributes to the **deepening of India's capital markets**, enhancing liquidity and funding channels for enterprises. However, it also raises questions about **bank deposit stability**—a traditional source of liquidity for credit creation.

The government and financial regulators must therefore:

1. Encourage **hybrid financial products** that balance safety (deposits) and growth (market-linked instruments).
2. Strengthen **cybersecurity and consumer protection laws** to maintain trust in digital finance.
3. Expand **financial inclusion outreach** in rural and semi-urban areas through digital kiosks and vernacular content.
4. Integrate **financial literacy modules** in higher education to build a long-term investment mindset among students.

These measures align with the **National Strategy for Financial Education (2020–2025)** and the RBI's inclusion vision, ensuring that technology-driven inclusion translates into real economic empowerment.

Theoretical Reflection

The study's findings resonate with three theoretical perspectives:

1. **Technology Acceptance Model (TAM)** — Millennials' adoption of fintech platforms is influenced by perceived ease of use, usefulness, and trust.
2. **Behavioral Finance Theory** — Psychological biases, peer influence, and social learning affect how digital tools are utilized for investment decisions.
3. **Financial Inclusion Paradigm** — True inclusion occurs when access, knowledge, and usage intersect, transforming individuals from passive savers to active investors.

This triangulation underscores that digital transformation is not just a matter of infrastructure, but a **cultural shift in financial behavior**.

Summary

In essence, the study finds that:

- Digital finance has democratized investing among millennials.
- Financial literacy acts as a **behavioral catalyst**, transforming access into informed participation.
- Technology can both empower and distort decision-making, depending on users' awareness and self-control.

A digitally inclusive economy thus requires not only innovative tools but also **responsible financial citizenship**—an ethos of informed, ethical, and sustainable investing.

Conclusion and Policy Recommendations

The purpose of this study was to examine how **digital financial inclusion (DFI)** influences **investment behavior among Indian millennials**, with a focus on the interplay of financial literacy, fintech penetration, and behavioral tendencies. Based on secondary data from 2012–2024 and supported by statistical modeling, the findings confirm that India's millennial population has transitioned from traditional savings patterns to active, technology-enabled investing.

Summary of Findings

1. **Digitalization as a Key Driver:**
   The exponential growth of fintech platforms, UPI transactions, and mobile banking has been instrumental in increasing financial access and market participation. DFI emerged as the most significant predictor of millennial investment activity.
2. **Financial Literacy as an Enabler:**
   The results highlight that financial literacy strengthens the positive impact of digital inclusion. Educated millennials are more likely to diversify portfolios, assess risks, and commit to systematic investment plans (SIPs).
3. **Behavioral Shifts in Investment Mindset:**
   Millennials increasingly favor convenience, transparency, and autonomy in financial decisions. Social media and peer influence have contributed to greater engagement but also to speculative behaviors.
4. **Rising Market-Based Investment Culture:**
   Retail mutual fund assets and SIP enrollments have grown rapidly since 2016, reflecting trust in capital markets and reduced dependence on bank deposits as the primary savings mode.

These insights confirm that India's financial ecosystem is undergoing a structural transformation where **technology, literacy, and psychology** converge to shape modern investment practices.

Policy Implications

To sustain and deepen the momentum of digital financial inclusion, the following policy and institutional measures are recommended:

1. **Integrate Financial Education into the Digital Ecosystem:**
   Educational institutions and regulators should collaborate with fintech firms to embed learning modules within investment apps, enabling users to access tutorials and real-time guidance.

2. **Promote Hybrid Financial Instruments:**
   Banks and asset management companies (AMCs) should develop products that combine **safety of deposits** with **growth potential of market-linked returns** to appeal to new investors.

3. **Enhance Rural and Gender Inclusion:**
   Initiatives such as vernacular financial literacy campaigns, local fintech support centers, and women-focused investment drives can reduce demographic disparities.

4. **Regulate Digital Investing Platforms:**
   The Securities and Exchange Board of India (SEBI) and RBI should establish unified guidelines for robo-advisors, influencer marketing, and data privacy to safeguard investor trust.

5. **Strengthen Behavioral Awareness:**
   National campaigns should address psychological biases—such as overconfidence and herding—through storytelling, gamified education, and relatable case studies.

Limitations and Future Scope

Despite meaningful insights, this study faces a few limitations:

- **Data Constraints:** It relies on secondary data; hence, variations in reporting standards and time lags may affect precision.
- **Lack of Primary Behavioral Data:** Surveys or interviews could provide deeper understanding of investor psychology.
- **Urban Bias:** Most available fintech data focuses on urban and semi-urban populations, leaving rural investor behavior underrepresented.

Future Research Directions:

1. Conduct **primary surveys** across multiple regions to capture attitudinal diversity among digital investors.
2. Apply **structural equation modeling (SEM)** to assess mediation effects of financial literacy and risk perception.
3. Examine **post-2025 trends**, focusing on emerging tools such as **AI-driven robo-advisors** and **blockchain-based investment products**.

Concluding Remarks

Digital financial inclusion has successfully democratized access to investment opportunities in India. For the millennial generation, financial empowerment is no longer limited by geography or class—it is defined by **digital capability, cognitive awareness, and responsible participation**. However, the inclusiveness of this transformation will depend on how effectively India integrates **financial education with technological progress**.

In conclusion, the synergy of **smart technology, informed literacy, and ethical investing** will determine the sustainability of India's digital investment revolution and its contribution to long-term financial resilience.

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India's Digital Revolution: How UPI and Retail Media Are Shaping the Future of FinTech–MarTech Integration

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Abstract

India's digital transformation redefines the demarcation line between FinTech and MarTech. We can observe this especially in two significant ecosystems – the Unified Payments Interface (UPI) and the Retail Media Networks (RMNs). The research paper discusses how the design of UPI and the advertising models of retail media would impact the future of consumer engagement, payments, and digital commerce. Expert interviews and secondary data from academic and industry reports (2015-2025) were subject to qualitative thematic analysis to identify three organizing themes: (1) digital infrastructure facilitating financial–marketing integration, (2) data governance and consumer trust as mediating mechanisms, and (3) rise of embedded and contextual consumer journeys. The results show that the Indian Digital Public Goods (UPI, Aadhaar, ONDC) provide opportunities for experimentation for FinTech–MarTech convergence. It creates a closed system wherein financial transactions, consumer data, and marketing intercepts are the features. It improves with the integration of AI and IoT. However, it also poses a threat. Consent, privacy, and regulations can become complicated with the convergence of various technologies. The theory and practical knowledge of technology convergence have not been enriched. It provides policymakers, marketers, and financial innovators with a powerful reference for leveraging digital infrastructure to promote inclusion.

Keywords: FinTech, MarTech, UPI, Retail Media, Digital Transformation, Data Governance

Introduction

In the last ten years, consumers have gained access to financing and marketing systems to a different level. India is at the core of the digital world through fast technology adoption, government support, and an innovation ecosystem. In 2016, the NPCI launched UPI. Ever since it was launched, UPI has changed the payment behaviour of a large number of people across the socio-economic spectrum. On the other hand, Retail Media Networks (RMNs) are quickly becoming the most talked-about words in digital marketing, whereby retailers monetize their first-party shopper data to serve ads in their ecosystems, apps, and websites.

Fintech and Martech Integration Are Important for Creating Intelligent Customer Solutions and Experiences. MarTech is the new FinTech, driving customer engagement to higher conversion rates. By bringing both systems together, the architecture in India's digital economy becomes tightly knit – a brand's ad exposure to transaction completion and post-transaction communication. This journal article investigates how India's digital infrastructure and retail ecosystem facilitate this integration, and what theoretical, technological, and policy lessons can be drawn for emerging economies.

Conceptual Framework

The study conceptualizes FinTech–MarTech integration through three theoretical lenses: Platform Theory, Data Network Effects, and Institutional Theory.

Table 1: Conceptual Framework: FinTech–MarTech Integration

Digital Infrastructure (UPI, Aadhaar, ONDC)
↓
FinTech Capabilities (Payments, Credit, Identity)
↓
MarTech Capabilities (Personalization, Ads, CRM)
↓
Integration Layer (Embedded Consumer Journeys)
↓
Outcomes (Data Synergy, Consumer Trust, Market Efficiency)
↓
Feedback Loop (Policy, Regulation, Privacy Governance)

This framework illustrates how India's digital public goods (UPI, Aadhaar, DigiLocker, ONDC) serve as foundational enablers for both financial inclusion and data-driven marketing innovation. The feedback loop emphasizes continuous adaptation through governance, regulatory oversight, and consumer trust mechanisms.

Literature Review

The evolution of digital platforms helps to explain why the convergence of FinTech and MarTech is taking place.

According to Evans and Schmalensee (2016), platform-based ecosystems derive their value from network effects and interoperability. The UPI model of India is an ideal example of multiple banks and apps interoperating to bring about an exponential rise in the transaction (Mehta & Srivastava, 2022). In the same way, MarTech systems such as CRM and programmatic advertising depend on multi-sided relations between customers, consumers, and data brokers (Chaffey & Ellis-Chadwick, 2022).

FinTech evolution (2015–2025) has revolved around four pillars: payment, lending, wealth management, and insurtech (Arner, Barberis, & Buckley, 2020). UPI's democratization of payments has reduced transaction costs, increased the level of digital literacy, and facilitated small merchants' participation in the digital economy. The growing type of payment and transfer systems is likely to have positive future implications (NPCI, 2023).

The development of MarTech follows a similar trajectory but for marketing. The emergence of Retail Media Networks (RMNs) has transformed how brands engage with consumers, using first-party data instead of third-party cookies (Forrester, 2023). According to Kumar & Reddy (2024), Reliance Retail, Flipkart, BigBasket, and other retailers have built integrated advertising platforms where brands pay them for sponsored listings or display ads targeted at purchase-ready audiences.

Theoretically, it is aligned with Institutional Theory. This theory states that these policy frameworks – PSD2 (Europe) and UPI Regulations (India) – create an enabling governance ecosystem where digital innovations can emerge but with security and consumer protection (Mishra & Sinha, 2021). India's attempt to implement GDPR-style data privacy regulations (for example, Digital Personal Data Protection Act, 2023) will radically change the data ethics and governance of FinTech and MarTech.

At the intersection of FinTech and MarTech lies data synergy which would mean using the transactional data available on financial platforms to inform marketing strategies and use of behavioural data available on marketing platforms to target financial products. According to Hofmann & Zumsteg (2025), this convergence is contributing to the emergence of contextual marketing and AI-based personalization, embedded finance, etc.

Research Gap

While global studies have explored FinTech adoption (Zavolokina et al., 2022) and MarTech transformation (Doyle, 2023), limited scholarly attention has been given to their convergence in emerging markets. India's experience provides a unique opportunity to study how public digital infrastructure (UPI, Aadhaar, ONDC) and private retail ecosystems (Reliance, Amazon, Flipkart) together create a hybrid model of financial–marketing integration.

Most existing literature addresses FinTech and MarTech as separate silos, overlooking the synergistic effects of shared data pipelines, consumer consent frameworks, and embedded payment–advertising systems.

Table 2: Research Gap

Dimension	Existing Literature Focus	Identified Gap
FinTech	Payment innovation, inclusion, and regulation (Arner et al., 2020)	Lack of linkage to consumer engagement or marketing outcomes
MarTech	CRM, personalization, and data analytics (Chaffey & Ellis-Chadwick, 2022)	Limited focus on transaction-linked marketing and financial data
Data Governance	Privacy and trust in FinTech (Mishra & Sinha, 2021)	Absence of integrated models combining privacy in financial and marketing contexts
India Context	UPI as payment infrastructure (NPCI, 2023)	Few studies explore UPI's role in enabling FinTech–MarTech synergy

Dimension	Existing Literature Focus	Identified Gap
Theoretical Integration	Platform and Institutional Theory separately applied	Need for a unified framework linking technology, data, and regulation

Research Design

This study employs a qualitative research design, utilizing thematic analysis, to examine how India's UPI ecosystem and retail media networks drive the integration of FinTech and MarTech. The research draws upon both primary and secondary data sources. Primary data were collected through 15 semi-structured interviews conducted between 2023 and 2024 with industry experts, including FinTech executives, MarTech strategists, and policy advisors. Secondary data were obtained from reports published by organizations such as NPCI, IAMAI, Deloitte, and Gartner, as well as peer-reviewed scholarly publications spanning the period from 2015 to 2025.

Analytical Approach

Thematic analysis was used following Braun and Clarke's (2006) six-step process: data familiarization, coding, theme development, review, definition, and reporting. NVivo 12 software helped identify patterns and relationships within qualitative data.

Analysis and Interpretation

Three organizing themes emerged from the analysis, supported by ten sub-themes identified across expert narratives and secondary sources.

Table 3: Thematic Analysis and Interpretation Table

Global Theme	Organizing Themes	Sub-Themes (Examples)	Interpretation
Digital Infrastructure as an Enabler	1. Open architecture (UPI, ONDC) 2. Interoperability across apps	NPCI-led UPI, Aadhaar-based KYC, API-based MarTech integration	Public infrastructure fosters scalability, inclusion, and innovation
Data Governance and Consumer Trust	3. Privacy and consent management 4. Digital Personal Data Protection Act	Secure consent flows, tokenization, customer data ownership	Trust and transparency are prerequisites for sustainable data-driven marketing
Embedded Consumer Journeys	5. Contextual marketing 6. Payment-linked offers 7. Loyalty ecosystems	Paytm, PhonePe, Amazon Pay integration with targeted ads	Transactions and marketing merge to deliver seamless experiences
AI-Driven Personalization	8. Predictive analytics 9. Personal finance recommendation engines	FinTech–MarTech AI for real-time personalization	AI enables adaptive engagement but raises ethical concerns
Ecosystem Collaboration	10. Retailer–FinTech partnerships	Reliance Retail–Jio Financial Services integration	Collaboration between payment and marketing entities drives closed-loop commerce

The findings reveal readiness of India's FinTech–MarTech integration supported by robust digital infrastructure, effective data governance and ecosystem collaboration. UPI and ONDC are open systems that enable sharing, and the Digital Personal Data Protection Act framework provides a level of trust that sharing using them is secure. The increasing number of transactions being embedded in marketing indicates how much AI will help create hyper-personalized, contextual customer journeys. However, it also raises new ethical and privacy concerns. Financial technology companies, retail businesses, and online platforms are creating an ecosystem to promote inclusion and consumer engagement.

Findings and Discussion

The analysis suggests that the convergence of FinTech and MarTech in India is possible through digital public infrastructure, data availability, and collaboration.

1. The UPI framework aims to make India's digital finance more inclusive and safe. Further, interoperable API supports innovation and investments in new-age technology companies. This gives retail brands and payment platforms the underlying infrastructure needed to jointly launch campaigns in real-time as needed
2. The second theme to emerge was data trust and regulation, as consumer trust became a prominent theme. Experts found that personalization can be supported through data-driven integration, but it may risk privacy without safeguards. The Balanced framework of the India Digital Personal Data Protection Act (2023) and Reserve Bank of India(RBI) guidelines is necessary.
3. The mix of FinTech and MarTech is leading the retail and service sectors in India towards the experience economy. These days, deals and prices are both advertising and transactional. For instance, a user can spot a discount on grocery purchases on Big Basket and pay for the UPI right then and there. This also completes a feedback loop for marketing and finance.
4. AI is a bridge technology; a layer between financial conduct and marketing personalization. Artificial intelligence models predict what consumers will spend, whether they'll borrow money, and what they want to help companies market to them in very precise ways. However, it is also necessitating ethics oversight and explainability (Kumar & Mehta, 2024).
5. Lots of companies like Reliance, Paytm, PhonePe etc. are moving into FinTech and MarTech. This is creating an ecosystem of payments, loyalty, and advertising. Data network effects and platform orchestration are changing how competitive advantage is achieved in ecosystems.

Implications

Theoretical Implications

The research builds upon platform theory by incorporating public-private collaboration (i.e., UPI + Retail Media), creating a hybrid ecosystem that yields both commercial and developmental outcomes. This also adds to institutional theory by showing how formal rules shape innovation pathways.

Practical Implications

For businesses, integrating FinTech and MarTech enables:

- Closed-loop measurement: Linking ad exposure to financial transactions.
- Personalized engagement: Payment history informs marketing automation.
- Inclusion through innovation: SMEs gain visibility and customers via digital rails.

For policymakers, it highlights the importance of:

- Enforcing privacy-by-design standards.
- Strengthening data interoperability while maintaining security.
- Encouraging open innovation sandboxes for cross-sector experimentation.

Recommendations

1. Develop Unified Data Standards: Promote ethical data usage by creating frameworks and codes of conduct for businesses to access financial data.
2. Foster FinTech–MarTech Collaborations: Encourage collaborations of FinTech and MarTech through the creation of innovation clusters.
3. Enhance AI Ethics and Explainability: Implement auditing protocols for the AI-powered personalization measure.
4. Leverage UPI 2.0 and ONDC: Adopt UPI 2.0 and AVONDC payment acceptance for easily claimable marketing powers.
5. Capacity Building: Capacity building to MSMEs on digital marketing tools compatible with digital payment systems to help enhance reach and retention.

Future Study

Future research can expand on three fronts:

- Comparative Studies: Explore the Convergence of FinTech and MarTech in Developing Markets like Brazil or Indonesia.
- Longitudinal Research: Watch consumer behavior as the digital landscape matures over time.

- Quantitative Validation: Use structural equation modeling to quantitatively validate the association of data governance, trust, and adoption.

Conclusion

India's digital transformation, made possible by UPI, and the role being played by innovation in business media are perfect examples of how a combination of FinTech and MarTech can have a significant impact on a process. India is an excellent country to study digital transformation in real-time because of its robust public digital infrastructure, entrepreneurial flexibility, and mature regulations, among other factors. Combining FinTech and MarTech is more than a technology issue; it is a fundamental shift in how value is created, delivered, and measured. India, where the future becomes present increasingly faster every day, is presenting a new growth model – one that is inclusive and data-driven. Other developing nations can refer to this model to connect payments to engagement.

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Digital Transformation in HR: Adoption of Digital HR Systems, Remote Working Technologies and Their Impact on Productivity and Job Satisfaction

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Abstract

The digital transformation of Human Resources (HR) has significantly reshaped organizational structures and employee experiences. The integration of Digital HR Systems (HRIS) and remote working technologies has led to profound changes in HR practices, influencing employee productivity and job satisfaction. This paper explores the adoption of these technologies, examining their impact on HR efficiency, employee engagement, and organizational outcomes. Through a comprehensive literature review and analysis of recent studies, this research provides insights into the benefits and challenges associated with digital HR transformation.

Keywords: Digital Transformation, Human Resource Management, Digital HR Systems, Remote Work, Employee Productivity, Job Satisfaction, Work–Life Balance.

Introduction

The advent of digital technologies has revolutionized various organizational functions, with Human Resources (HR) being no exception. Traditional HR practices, characterized by manual processes and face-to-face interactions, are increasingly being replaced by digital solutions that automate tasks, enhance decision-making, and facilitate remote work. The adoption of Digital HR Systems (HRIS) and remote working technologies has become imperative for organizations aiming to improve efficiency and employee satisfaction.

Digital HR Systems encompass a range of tools and platforms that automate HR processes such as recruitment, payroll, performance management, and employee development. These systems enable HR professionals to focus on strategic initiatives by reducing administrative burdens. On the other hand, remote working technologies, including video conferencing, collaboration tools, and cloud-based platforms, facilitate flexible work arrangements, allowing employees to work from various locations.

The integration of these technologies has led to significant changes in the workplace, influencing employee productivity and job satisfaction. However, the extent of their impact varies across organizations and industries. This paper aims to explore the relationship between the adoption of Digital HR Systems and remote working technologies and their effects on employee outcomes.

Literature Review

Digital HR Systems (HRIS)

Digital HR Systems have transformed HR functions by automating routine tasks and providing data-driven insights. Studies indicate that the implementation of HRIS leads to increased efficiency and effectiveness in HR operations. For instance, a study by Mahmoud (2025) found that digital HRM systems positively impact HR efficiency, with a significant beta coefficient ($\beta = 0.456$, $p < 0.001$) indicating a strong relationship between HRIS adoption and HR performance.

Furthermore, HRIS platforms facilitate better decision-making by providing real-time data on various HR metrics, such as employee performance, turnover rates, and engagement levels. This data-driven approach enables HR professionals to make informed decisions that align with organizational goals.

Remote Working Technologies

The rise of remote work has been facilitated by advancements in technology. Tools such as Zoom, Microsoft Teams, and Slack have enabled employees to collaborate effectively from different locations. Research by Makridis (2025) highlights that remote work has led to lower job turnover and increased job satisfaction, which can substantially reduce firms' hiring costs.

However, the impact of remote work on employee outcomes is not uniform. A study by García-Salirrosas (2023) found that supervisor behaviour, positive work-to-family spillover, and work-life balance play crucial roles in determining remote workers' job satisfaction. These findings suggest that while remote work offers flexibility, its success depends on organizational support and individual circumstances.

Integration of HRIS and Remote Work Technologies

The combination of HRIS and remote working technologies offers organizations a comprehensive approach to managing their workforce. Digital HR systems streamline HR processes, while remote work technologies provide employees with the flexibility to work from various locations. Together, these technologies contribute to enhanced employee productivity and job satisfaction.

A study by Nawaz (2024) emphasizes that embracing AI-driven HR technologies can lead to improved employee satisfaction, better work-life integration, and enhanced overall productivity. The integration of AI into HR practices allows for personalized employee experiences, fostering a more engaged and satisfied workforce.

Research Methodology

This study employs a mixed-methods approach, combining quantitative and qualitative research methods to explore the impact of Digital HR Systems and remote working technologies on employee productivity and job satisfaction.

Data Collection

Data were collected through surveys and interviews conducted with HR professionals and employees across various industries. The survey included questions related to the adoption and usage of HRIS and remote work technologies, as well as measures of employee productivity and job satisfaction. Interviews provided deeper insights into the experiences and perceptions of HR professionals and employees regarding these technologies.

Data Analysis

Quantitative data were analysed using statistical methods to identify correlations between the adoption of HRIS and remote work technologies and employee outcomes. Qualitative data from interviews were coded and analysed thematically to identify common themes and patterns related to the impact of these technologies on employee experiences.

Objectives of the Study

The primary objectives of this study are:

1. To examine the relationship between the adoption of Digital HR Systems and employee productivity.
2. To assess the impact of remote working technologies on job satisfaction.
3. To explore the combined effect of HRIS and remote work technologies on organizational outcomes.
4. To identify challenges and best practices associated with the implementation of these technologies.

Gaps in Literature

While existing studies have explored various aspects of Digital HR Systems and remote working technologies, several gaps remain:

1. **Limited Longitudinal Studies:** Most research focuses on short-term outcomes, with limited longitudinal studies examining the sustained impact of these technologies over time.
2. **Industry-Specific Analysis:** There is a lack of studies analysing the impact of HRIS and remote work technologies in specific industries, such as healthcare or manufacturing.
3. **Employee Perspective:** Few studies consider the employees' perspective on the adoption and use of these technologies, particularly in terms of their experiences and satisfaction levels.

Addressing these gaps can provide a more comprehensive understanding of the implications of digital transformation in HR.

Scope of the Research

This study focuses on organizations in India that have adopted Digital HR Systems and remote working technologies. The research examines the impact of these technologies on employee productivity and job satisfaction, considering factors such as organizational support, training, and infrastructure. The findings aim to provide insights applicable to similar organizational contexts globally.

Data Analysis and Interpretation

Data Collection Overview

To examine the influence of digital HR systems and remote working technologies on employee productivity and job satisfaction, data were collected from employees working in both public and private sector organizations in India. A total of

210 valid responses were received through a structured questionnaire distributed via email and LinkedIn during March–April 2025. Respondents included HR executives, managers, and IT-enabled staff from manufacturing and service industries.

The survey instrument consisted of **24 items**, measured on a **five-point Likert scale** (1 = Strongly Agree to 5 = Strongly Disagree). Constructs included:

- **Digital HR Adoption (DHR):** 6 items
- **Remote Working Technology Usage (RWT):** 5 items
- **Employee Productivity (EP):** 6 items
- **Job Satisfaction (JS):** 7 items

Reliability and Validity Testing

Reliability was assessed using Cronbach's Alpha, Composite Reliability (CR), and Average Variance Extracted (AVE). All constructs exceeded the threshold values: $\alpha > 0.70$, CR > 0.70, and AVE > 0.50, confirming internal consistency and convergent validity.

Construct	Cronbach's Alpha	Composite Reliability	AVE (>0.50)
Digital HR Adoption	0.89	0.91	0.63
Remote Work Technology	0.87	0.90	0.61
Employee Productivity	0.91	0.93	0.65
Job Satisfaction	0.88	0.90	0.60

Discriminant validity was verified using the **Fornell–Larcker criterion**, where the square root of AVE for each construct exceeded the inter-construct correlations, confirming that each variable measured a distinct dimension.

Descriptive Statistics

Mean scores indicated high adoption levels of digital HR tools (M = 2.01) and frequent usage of remote work technologies (M = 2.18), suggesting that most organizations have embraced digital transformation post-COVID-19. Employee productivity (M = 2.23) and job satisfaction (M = 2.31) showed moderately positive trends, implying that digital practices contribute to improved performance and morale.

Correlation Analysis

Pearson's correlation analysis revealed significant positive relationships among the constructs:

- Digital HR Adoption ↔ Employee Productivity ($r = 0.61$, $p < 0.01$)
- Remote Work Technology ↔ Job Satisfaction ($r = 0.58$, $p < 0.01$)
- Employee Productivity ↔ Job Satisfaction ($r = 0.64$, $p < 0.01$)

These findings support the conceptual assumption that digital transformation enhances employee experiences and outcomes.

Regression and Mediation Analysis

A multiple regression model was used to determine predictive relationships:

Model:
$EP = \beta_1(DHR) + \beta_2(RWT) + \varepsilon$
$JS = \beta_3(DHR) + \beta_4(RWT) + \beta_5(EP) + \varepsilon$
Results indicated that both **Digital HR Adoption ($\beta = 0.37$, $p < 0.01$)** and **Remote Work Technology ($\beta = 0.41$, $p < 0.01$)** significantly predicted Employee Productivity. Moreover, **Employee Productivity partially mediated** the relationship between digital HR variables and Job Satisfaction, implying that improved digital systems lead to higher productivity, which in turn enhances satisfaction.

Structural Equation Modelling (SEM)

Further validation using **PLS-SEM (SmartPLS 4)** confirmed that the hypothesized model fit the data adequately:
SRMR = 0.057, NFI = 0.91, $R^2(EP) = 0.48$, $R^2(JS) = 0.52$.
All path coefficients were positive and significant ($p < 0.05$), indicating strong empirical support for the proposed relationships.

Interpretation

The analysis demonstrates that digital transformation in HR—through e-recruitment, digital payroll, virtual onboarding, and online performance management—directly enhances employee productivity. Simultaneously, remote work technologies such as collaboration platforms (Teams, Zoom, Slack) foster autonomy and flexibility, which increase job satisfaction. These findings align with **Mahmoud (2025)** and **Nawaz (2024)**, who emphasized that digitization of HR processes not only improves efficiency but also strengthens employee engagement and morale.

Findings and Discussion

Key Empirical Findings

The statistical analysis provided strong evidence that **digital HR adoption** and **remote working technologies** have a substantial positive influence on both **employee productivity** and **job satisfaction**.

- Regression and SEM results confirmed that **Digital HR Adoption ($\beta = 0.37$)** and **Remote Work Technology ($\beta = 0.41$)** significantly predict **Employee Productivity ($R^2 = 0.48$)**.
- **Employee Productivity** also acts as a **partial mediator** between digital transformation variables and **Job Satisfaction ($R^2 = 0.52$)**, indicating that enhanced productivity arising from digital enablement leads to greater satisfaction levels among employees.

These quantitative findings demonstrate that organizations leveraging digital HR systems—such as AI-based recruitment tools, cloud HRIS, and e-performance management platforms—are better positioned to sustain employee performance and motivation in hybrid and remote work settings.

Discussion in Light of Literature

The present results corroborate earlier findings by **Mahmoud (2025)**, who asserted that digital transformation enhances HR operational efficiency and reduces administrative redundancy, thereby improving employee outcomes. Similarly, **Nawaz (2024)** highlighted that AI-driven HR systems enhance decision-making accuracy and transparency, leading to increased job satisfaction and engagement.

Furthermore, the positive linkage between remote working technologies and job satisfaction resonates with **García-Salirrosas (2023)**, who found that technology-enabled flexibility strengthens work–life balance and contributes to higher employee morale. The results also align with **Makridis (2025)**, who observed that although remote work may slightly reduce working hours, productivity and focus remain stable or even improve when digital collaboration tools are effectively deployed.

However, the study also reveals emerging challenges consistent with previous research—such as potential **digital fatigue** and **work–life boundary blurring** (as noted by García-Salirrosas, 2023)—which can moderate the long-term benefits of remote digital practices if not managed strategically.

Theoretical Implications

From a theoretical standpoint, the study extends the **Technology Acceptance Model (TAM)** and **Job Demands–Resources (JD-R)** framework into the HR digital transformation context. The findings illustrate that employees perceived usefulness and ease of use of HR technologies enhance intrinsic motivation (a resource factor), leading to improved job outcomes. The mediating role of productivity provides a new empirical lens linking **digital enablement → performance → satisfaction**, thereby reinforcing digital HRM as a strategic capability rather than merely an administrative function.

Managerial Implications

For HR practitioners and organizational leaders, these results underscore the importance of investing in **integrated digital HR ecosystems** that support both performance tracking and employee well-being. Key managerial takeaways include:

1. **Digital Upskilling:** Continuous training programs are essential to improve employees' digital literacy and reduce resistance to new HR technologies.
2. **Employee Experience Design:** HR departments should prioritize user-friendly digital interfaces to enhance engagement with HR portals and reduce technology fatigue.
3. **Remote Work Governance:** Managers must establish clear communication norms and boundaries to prevent burnout and ensure healthy work–life integration.
4. **Data-Driven HR Decision Making:** Adoption of analytics-based HR dashboards can help monitor performance, predict attrition and personalize development plans.
5. **Hybrid Culture Development:** Encouraging trust, autonomy, and flexibility fosters a positive digital work culture that sustains job satisfaction even in dispersed teams.

Comparative Insights

Sectoral analysis indicated that private organizations demonstrated higher digital maturity than public sector entities, which often face structural and bureaucratic barriers to technology adoption. Nonetheless, both sectors reported similar positive outcomes once digital systems were implemented effectively—suggesting that digital HR transformation is universally beneficial irrespective of ownership structure when aligned with strategic objectives.

Summary of Discussion

Overall, this study reinforces the assertion that digital transformation in HRM is not merely a post-pandemic adaptation but a long-term strategic imperative. Effective digitalization simultaneously drives productivity, strengthens employee satisfaction, and improves organizational resilience. By integrating HR technologies with employee-centric policies, organizations can achieve sustainable competitive advantage in an increasingly digital workplace.

Analysis and Discussion

Impact on Productivity

The adoption of Digital HR Systems has led to significant improvements in HR efficiency, allowing HR professionals to focus on strategic initiatives rather than administrative tasks. Remote working technologies have enabled employees to maintain productivity levels outside traditional office settings. However, the effectiveness of these tools is contingent upon proper implementation and user training.

Impact on Job Satisfaction

Digital HR tools contribute to job satisfaction by providing employees with greater control over their work processes and enhancing communication channels. Remote work technologies offer flexibility, which is positively correlated with job satisfaction. However, the lack of face-to-face interactions can lead to feelings of disconnection, highlighting the need for organizations to foster a strong virtual culture.

Challenges and Recommendations

Challenges

- **Resistance to Change:** Employees and HR professionals may resist adopting new technologies due to unfamiliarity or perceived complexity.
- **Data Security Concerns:** The digitalization of HR processes raises concerns about data privacy and security.
- **Inadequate Training:** Lack of proper training can hinder the effective use of HRIS and remote work technologies.

Recommendations

- **Comprehensive Training Programs:** Organizations should provide training to ensure employees and HR professionals are proficient in using new technologies.
- **Robust Data Security Measures:** Implementing strong data security protocols can mitigate concerns related to data privacy.
- **Continuous Feedback Mechanisms:** Regular feedback from employees can help organizations address issues and improve the user experience.

Conclusion

Digital transformation in HR, through the adoption of Digital HR Systems and remote working technologies, has significant implications for employee productivity and job satisfaction. While these technologies offer numerous benefits, organizations must address associated challenges to fully realize their potential. Future research should focus on longitudinal studies, industry-specific analyses, and employee perspectives to provide a more comprehensive understanding of the impact of digital transformation in HR.

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A Comprehensive Analysis of the Role of Digital Twin Technology in Enhancing Real-Time Visibility and Optimization of End-to-End Supply Chain Operations

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Abstract

The unprecedented disruptions caused by geopolitical instability, global trade disputes, and pandemics have underscored the fragility of raditional supply chain architectures. In this context, Digital Twin (DT) technology emerges as a transformative enabler that bridges the physical and digital dimensions of supply chain ecosystems. A Digital Twin is defined as a dynamic, software-based replica of a supply chain, encompassing assets, processes, and the broader logistics network. Unlike static models, DTs are continuously updated using real-time data from IoT sensors, enterprise systems, and intelligent analytics. This article provides a comprehensive examination of the role of DTs in advancing real-time visibility and enabling superior optimization of end-to-end supply chain operations. It highlights how DTs shift management practices from being largely reactive to proactive, while addressing challenges such as integration complexity, organizational capacity gaps, and implementation costs. Positioning the technology within the Industry 4.0 paradigm, the article concludes that DTs are central to cultivating supply chain resilience, adaptability, and sustainability in the years ahead.

Introduction: The Imperative for Digital Transformation

The global business environment is increasingly shaped by unpredictability and interdependence. Conventional supply chain management systems, designed for relatively linear and predictable operations, are struggling to keep pace. These legacy systems are bound by fragmented data architectures, which hinder transparency, coordination, and response time. As minor disruptions cascade through the chain, organizations face amplified effects, including the bullwhip phenomenon, underutilization of resources, and declining service levels.

The paradigm of Industry 4.0—marked by the convergence of digital technologies such as IoT, Big Data, and artificial intelligence—has introduced new ways to integrate physical and digital ecosystems. Among these, the Digital Twin stands out as a disruptive tool that offers comprehensive visibility, advanced computational simulation, and predictive decision-making capabilities. This paper investigates how Digital Twins enhance operational dexterity across the supply chain.

Conceptual Framework of the Supply Chain Digital Twin (SCDT)

A Supply Chain Digital Twin (SCDT) is not simply a visualization tool or simulation system but a continuously evolving, data-driven replica of the supply chain. It consists of four interdependent layers:

- Physical Supply Chain Entity: Real assets—factories, trucks, warehouses, inventory— alongside associated processes and workforce operations.
- Virtual Replica: A digital model that mirrors reality using advanced modeling techniques, capturing the dynamic interdependencies of supply chain activities.
- Data Integration Layer: A bi-directional stream of data enabling synchronization between physical and virtual elements. IoT sensors, RFID, GPS, and ERP systems provide continuous real-time updates, while decisions are fed back into the physical system.
- Analytical and Intelligence Core: AI algorithms and predictive analytics create value by performing simulations, predicting disruptions, and generating actionable insights.

The distinguishing power of an SCDT lies in its *real-time synchronization* and its ability to interact dynamically with reality, unlike historical simulations.

Enhancing Real-Time Visibility Across the Supply Chain

- **Inventory and Asset Tracking**

  Digital Twins provide instantaneous updates on inventory levels and asset condition through real-time sensor inputs. Companies gain visibility into exact stock positions, shipment location, and critical quality parameters such as temperature or vibration—vital for sensitive sectors like pharmaceuticals or perishable goods.

- **Predictive Operational Monitoring**

  DTs extend monitoring beyond asset location, encompassing operational performance. By analyzing machine data in factories, DTs enable predictive maintenance, preventing unexpected failures. Anticipatory maintenance scheduling reduces downtime and safeguards delivery commitments.

End-to-End Traceability

SCDTs document the entire product life cycle, from raw material sourcing to last-mile delivery. This strengthens compliance with strict quality and sustainability standards. Integration with blockchain further enhances trust by providing immutable and auditable data records, thereby addressing concerns of authenticity and ethical sourcing.

Optimization of End-to-End Supply Chain Operations

- **Scenario Planning and What-If Analysis**

  A critical strength of DTs is their ability to simulate disruptive events without endangering actual operations. Whether modeling demand surges, supplier breakdowns, or port closures, DTs allow stakeholders to identify ripple effects across the chain and proactively formulate optimal recovery or mitigation strategies.

- **Network and Logistics Optimization**

  Supply chain networks are optimized by simulating warehouse configurations, transport routes, and distribution strategies. For example, real-time factors such as weather alerts and fuel constraints are continually analyzed for dynamic route optimization, yielding cost and environmental benefits.

Demand Forecasting and Inventory Management

By processing real-time data, market signals, and social sentiment, DTs generate accurate forecasts. This capability supports leaner inventory strategies, reduces obsolescence, and facilitates Just-In-Time practices without risking stockouts.

Challenge	Description
Data Integration Barriers	Legacy systems and disconnected databases hinder full interoperability, demanding enterprise-wide semantic alignment.
High Capital Investment	Costs of IoT infrastructure, analytics platforms, and talent acquisition create a financial burden, especially for mid-sized firms.
Data Privacy and Security	Exchanging sensitive data across partners necessitates robust governance and strong cybersecurity frameworks.
Talent and Organizational Gaps	Limited access to professionals with hybrid expertise in AI/ML and supply chain operations is further compounded by cultural resistance to adopting new systems.

Challenges and Future Directions

Future Evolution: Emerging trends point toward federated “Twin of Twins” models—where Digital Twins of suppliers, logistics providers, and retailers collaborate while preserving individual data sovereignty. This federated approach augments security and collective agility.

Conclusion

Digital Twin technology is gradually becoming indispensable for modern supply chains. By bridging the gap between operational visibility and decision-making intelligence, DTs empower firms to evolve from fragmented, reactive management approaches into integrated, resilient, and proactive networks. Although implementation requires overcoming integration complexity, cost hurdles, and organizational transformation barriers, the payoff includes enhanced resilience, reduced operational costs, and improved agility. For organizations seeking sustainable competitive advantage in the digital age, adopting DT technology within supply chains is not optional but imperative.

Indoor Air Pollution, Fallouts and Policy

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Abstract

Indoor Air Pollution is the source of pollution with the greatest health consequences which remains unseen in context of environmental risks. Indoor Air pollution is the second most health risk factor after unsafe water. It accounts for twice the number of deaths reported from urban outdoor pollution. Indoor Air Pollution is five times more hazardous than outdoor pollution. This review paper undertakes to study the consequences of Indoor Air Pollution and corrective measures undertaken to address the environmental challenge.

Keywords: Combustion; Biomass; Acute Lower Respiratory Infection; Obstructive Pulmonary Diseases; Particulate Matter

Introduction

When people built shelter for dwellings, thy also brought pollutants into the indoor living space. Indoor Air Pollution can be traced to prehistoric times when humans moved to temperate climates 2,00,000 years ago. These cold climates necessitated the construction of shelters and the use of fires for indoor cooking, warmth and light. However, fire which allowed humans to enjoy the benefits of living indoors, resulted in exposure to high levels of pollution as evidenced by the soot found in prehistoric caves.

Literature Review

In developed countries the most important indoor air pollutants are radon, asbestos, volatile organic compounds, pesticides, heavy metals, animal dander, mites, molds and tobacco smoke. However, in developing countries, the most important indoor air pollutants are the combustion products of unprocessed solid biomass fuels used by the poor, urban and rural folk for heating and cooking. One of the major causes of indoor air pollution is burning of cooking fuel such as wood, agricultural residues, animal dung, coal, kerosene, etc. Even today one half of the world's population, 95% in poor countries and more than 90% households in India still rely on solid fuels including bio mass fuels. Over the past 35 years, the trend in global bio fuel use has changed little and in places where there is poverty and the prices of alternative fuel like kerosene and bottled gas is high, the use of bio mass fuel has increased. The unprocessed solid fuels typically release 50 times more noxious pollutants than gas. Traditional fuels have low combustion efficiency leading to emission of suspended particles and poisonous gases. The incomplete combustion releases hundreds of complex toxic pollutants hazardous to health like particulate matter, carbon monoxide, nitrogen dioxide, sulphur dioxide, formaldehyde and carcinogens such as benzopyrene and benzyene.

Principal Sources of Indoor Air Pollutants

Sr. No.	Indoor Air Pollutants
01	Combustion
02	Building Materials
03	The ground under the building
04	Bio aerosols

Health and Fatality Impact

- The PM10 levels in homes using biomass (Africa, Asia and Latin America) range from 300-3000 micrograms per cubic meter. This can also go up to 10,000 micrograms per cubic meter. During cooking the PM10 concentration in an Indian kitchen varies between 500-5000 micrograms per cubic meter.
- Inefficient burning of solid fuels indoor, emit a mist of pollutants including carbon monoxide, particulate matters, nitrogen oxides, benzene and poly-aromatic hydrocarbons. The fine particles PM2.5 – less than 2.5 micrometers in diameter penetrates into the respiratory system.
- Women spend 3-7 hour in the kitchen every day and breathe in smoke equivalent to consuming 2 packs of cigarettes. This causes acute and chronic respiratory cardiovascular diseases.

- Pollution also causes pneumonia and other acute lower respiratory infections (ALRI) among children and chronic obstructive pulmonary diseases (COPD) and lung cancer in adults
- In 21 countries indoor air pollution accounts for about 5% of total deaths and diseases.

Policy Stance - Conclusion

- To accelerate the national programs for dissemination of improved fuel wood stoves, bio gas, solar cooker and free/subsidized LPG connections and cylinders for rural and economically weaker section of women.
- To provide incentive based instruments for controlling indoor air pollution.
- Conduct public awareness campaigns.
- To give greater legal standing to local communities and NGOs for undertaking monitoring of environmental compliances.

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The Role of Big Data Analytics in Improving Supply Chain Agility and Marketing Responsiveness

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Abstract

The contemporary business landscape, characterized by unprecedented volatility, uncertainty, complexity, and ambiguity (VUCA), necessitates a departure from traditional, rigid operational models. This paper investigates the pivotal role of Big Data Analytics (BDA) capabilities in enhancing two critical organizational outcomes: Supply Chain Agility (SCA) and Marketing Responsiveness (MR). Drawing on a review of literature in operations management and strategic marketing, we propose that BDA, through its capacity for high-velocity data processing, predictive modeling, and real-time visibility, acts as a dynamic capability. This capability fundamentally transforms an organization's ability to sense market shifts, make rapid, informed decisions, and execute responsive operational and marketing strategies. The study highlights how BDA facilitates superior demand forecasting, real-time risk mitigation in the supply chain, and personalized, timely customer engagement, ultimately leading to improved firm performance and sustained competitive advantage.

Introduction

In the current data-driven economy, the ability of a firm to effectively harness large, varied, and fast-moving data (Big Data) is no longer a luxury but a prerequisite for survival. Organizations are continuously generating vast datasets from sources such as Internet of Things (IoT) sensors, social media, customer transactions, and logistics tracking. The analytical capability to convert this raw data into actionable insights forms the core of Big Data Analytics (BDA) (Davenport, 2014).

This paper focuses on two strategic areas where BDA provides significant leverage: Supply Chain Management (SCM) and Marketing Strategy. Global supply chains are prone to disruptions (e.g., geopolitical crises, natural disasters), demanding agility—the capacity to swiftly adjust operations, sourcing, and logistics. Simultaneously, customers, empowered by digital tools, expect highly personalized experiences, necessitating marketing responsiveness—the speed and relevance with which a firm can react to customer needs and market opportunities.

We argue that a robust BDA capability is the primary enabler for achieving both SCA and MR. This research synthesizes the mechanisms through which BDA translates into superior agility and responsiveness, providing a comprehensive framework for managers seeking to invest in data-driven transformations.

Theoretical Background and Key Concepts

- **Big Data Analytics (BDA) as a Dynamic Capability**

BDA capabilities encompass the resources (e.g., analytical tools, cloud infrastructure), skills (e.g., data scientists, analysts), and processes (e.g., data governance, machine learning pipelines) an organization uses to manage and gain insights from Big Data (Wamba et al., 2017).

From a Dynamic Capabilities View (DCV), BDA is considered a higher-order organizational capability that allows a firm to integrate, build, and reconfigure internal and external competences to address rapidly changing environments (Teece et al., 1997). In the context of this study, BDA enables the organizational routines for sensing market threats and opportunities, seizing those opportunities through rapid decision-making, and reconfiguring resources accordingly.

- **Supply Chain Agility (SCA)**

SCA is the supply chain's ability to react quickly to unpredictable changes in demand, supply, or environmental conditions. Key dimensions include:

- Flexibility: The ability to alter production volumes or product mix rapidly.
- Visibility: Real-time knowledge of inventory levels, shipment locations, and operational status across the entire network.
- Resilience: The capacity to recover quickly from disruptions.

Marketing Responsiveness (MR)

Marketing responsiveness refers to the speed and effectiveness with which a firm designs, implements, and adjusts its marketing mix (Product, Price, Place, Promotion) in response to customer feedback, competitor actions, or evolving market trends. It involves:

- Market Sensing: The ability to gather and interpret information about the market.
- Learning and Decision-Making: Translating insights into tactical and strategic actions.
- Execution Speed: Rapid deployment of new marketing campaigns or product adjustments.

BDA and Supply Chain Agility

BDA drives SCA by transforming traditional, sequential supply chain processes into a highly integrated, responsive network.

- **Enhanced Demand Forecasting**

Traditional forecasting relies on historical sales data, often leading to large forecast errors in volatile markets. BDA improves accuracy by incorporating external, unstructured data in real- time:

- Social Media Sentiment: Gauging public perception of a product or brand to predict demand spikes or drops.
- Web Search Trends: Using Google Trends and search query volumes to forecast interest in a category.
- Weather and Macro-economic Data: Integrating external factors that influence regional or seasonal demand.

Predictive Analytics (e.g., Machine Learning models) process these vast datasets to generate a more granular, forward-looking demand signal, allowing for timely adjustments to production schedules and inventory levels, minimizing both stockouts and costly excess inventory (Waller & Fawcett, 2013).

Real-Time Visibility and Risk Mitigation

BDA enables end-to-end visibility crucial for resilience. IoT devices and sensors generate real- time data on asset health, warehouse conditions, and shipment movements. BDA platforms aggregate this data, creating a digital twin of the supply chain.

- Anomaly Detection: Machine learning algorithms continuously monitor data streams to flag unusual performance, such as unexpected delays or equipment failure, allowing for proactive intervention before minor issues become major disruptions.
- Scenario Planning: Prescriptive Analytics can simulate the impact of potential disruptions (e.g., a port closure) and recommend optimal contingency plans, such as rerouting shipments or utilizing alternative suppliers, significantly boosting SCA.

Logistics and Network Optimization

BDA tools, particularly Optimization Algorithms, analyze millions of data points on traffic, fuel costs, warehouse capacity, and delivery schedules to determine the most efficient routes and facility locations, reducing lead times and transportation costs, which are direct components of agility.

BDA and Marketing Responsiveness

The power of BDA in marketing lies in its ability to understand the customer at a highly granular level and to engage with them immediately and relevantly.

- **Granular Customer Segmentation and Targeting**

BDA moves beyond basic demographic segmentation to create micro-segments or even segments-of-one. By analyzing transactional history, clickstream data, loyalty program activity, and social interactions, firms gain deep insights into individual preferences, behavioral patterns, and purchase intent (Wedel & Kannan, 2016).

Personalization at Scale: This deep insight enables the real-time delivery of personalized content, product recommendations, and promotional offers across multiple channels, vastly improving campaign relevance and conversion rates.

Real-Time Campaign Optimization

Marketing responsiveness is accelerated through the use of BDA for continuous campaign monitoring.

- Attribution Modeling: Algorithms can precisely track the customer journey and allocate credit for conversions across touchpoints (e.g., social media ad, email, search click), allowing marketers to instantly shift budget and resources to the highest-performing channels.

- A/B and Multivariate Testing: BDA facilitates rapid, automated testing of creative elements, pricing points, and messaging, enabling immediate adaptation to consumer reaction. This iterative, agile marketing approach shortens the learning loop from months to hours.

Product and Service Innovation

BDA feeds real-time customer feedback directly into the product development cycle. By performing Text Analytics on customer service logs, review sites, and social media, firms can identify unmet needs, feature requests, and product pain points with unprecedented speed. This data-driven approach to innovation shortens time-to-market for relevant product modifications and new launches, a core component of MR.

Conclusion and Managerial Implications

Big Data Analytics serves as a critical strategic differentiator, fundamentally restructuring a firm's capability to react to market dynamics. By providing unparalleled visibility, predictive accuracy, and prescriptive guidance, BDA acts as a dual-engine for both Supply Chain Agility (enhancing operational resilience and efficiency) and Marketing Responsiveness (driving personalized, relevant, and timely customer engagement).

Managerial Implications

1. Develop a Unified Data Strategy: Data governance and quality are paramount. Firms must break down data silos between the supply chain, marketing, and sales departments to create a single, unified view of demand and operations.

2. Invest in Talent and Technology: Capital investment must be allocated to advanced analytical tools (ML/AI platforms) and, crucially, to recruiting and training data scientists and analysts who can translate BDA output into actionable business strategy.

3. Foster a Culture of Agility: Technology alone is insufficient. Organizations must cultivate an internal culture that embraces data-driven decision-making, iterative testing, and cross-functional collaboration to fully capitalize on the speed enabled by BDA.

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Smart Energy and Water Management in Indian Smart Cities: A Managerial and Organizational Behaviour Perspective

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Abstract

This paper examines smart energy and water management initiatives in Indian smart cities through a managerial and organizational behavior lens. Rather than focusing solely on technological infrastructure, the study emphasizes how leadership structures, incentive mechanisms, and coordination models determine implementation success. Drawing on evidence from Surat, Pune, Bengaluru, and Ahmedabad, the analysis highlights the role of semi-autonomous utility cells and Special Purpose Vehicles in accelerating decision-making and accountability. Key challenges identified include fragmented governance mandates, resistance from utility staff during digital transitions, and citizen skepticism toward metering technologies and tariff reforms. The paper argues that smart utility systems must be treated as institutional transformation programs rather than procurement exercises. By applying behavioral frameworks such as change management models and technology adoption theory, it demonstrates that cultural alignment and stakeholder communication are as critical as sensor deployment or infrastructure financing. The study concludes by proposing a phased managerial roadmap covering policy design, capacity building, performance-linked contracts, and citizen engagement protocols. It positions smart energy and water management as an opportunity for public-sector modernization and offers a structured reference for urban policymakers, utility managers, and sustainability strategists operating in emerging economy contexts.

Introduction

India's Smart Cities Mission (SCM) launched in 2015 represents one of the most ambitious urban modernization programs in the Global South. Its objective is not merely infrastructural enhancement but a systemic transformation in how urban utilities are governed, financed, and delivered. Smart energy and water systems form the backbone of this mission. They align directly with Sustainable Development Goals (SDGs) 6 and 7, emphasizing clean water, sanitation, and affordable, reliable energy. Despite this, most Indian cities continue to face chronic shortages, high transmission losses, and institutional fragmentation. Understanding the managerial and organizational aspects of these reforms is essential for sustainable outcomes.

Smart Energy Management in Indian Cities

Smart energy management includes the deployment of digital meters, supervisory control systems, renewable integration, and grid automation. Bengaluru's BESCOM and the Gujarat Energy Development Agency (GEDA) have piloted large-scale Advanced Metering Infrastructure (AMI) projects supported by the National Smart Grid Mission. Surat and Pune have implemented rooftop solar programs integrated with net-metering incentives. These initiatives demonstrate how data analytics and IoT-based monitoring enhance operational efficiency. However, technological adoption is often constrained by legacy bureaucratic hierarchies, budgetary limitations, and coordination gaps between central and state-level utilities.

Smart Water Management in Indian Cities

India's water crisis has driven urban administrations to explore sensor-based and data- driven management models. Pune, Surat, and Nagpur have introduced real-time water quality monitoring, leak detection sensors, and automated billing systems. These interventions aim to minimize non-revenue water (NRW) and improve equity in water distribution. The managerial challenge lies in building the technical capacity of urban local bodies (ULBs) and maintaining public acceptance of tariff reforms. As per the Ministry of Housing and Urban Affairs' Smart Cities progress reports, cities with decentralized project management units have achieved faster implementation due to clearer accountability lines and localized decision-making authority.

Comparative Analysis across Indian States

A comparative examination reveals that states such as Gujarat, Karnataka, Maharashtra, and Tamil Nadu exhibit varied trajectories in smart utility reforms. Gujarat's proactive investment in metering and renewable infrastructure is complemented by strong policy continuity, while Karnataka's decentralized governance has facilitated local innovation in energy conservation. Maharashtra's cities like Pune and Thane have adopted hybrid PPP models to fund smart grids and water systems, whereas Tamil Nadu's experience highlights the need for stronger citizen engagement mechanisms. The heterogeneity underscores that managerial adaptability and institutional maturity, more than financial investment alone, determine the success of smart utility initiatives.

Organizational and Behavioral Perspectives

Transforming legacy public utilities into smart organizations necessitates deep cultural and behavioral shifts. Kotter's (1996) eight-step model and the Technology Acceptance Model (Davis, 1989) provide frameworks to understand employee readiness and resistance. SPVs established under SCM function as catalysts for change, yet their success depends on coordination with entrenched departments. Organizational inertia, lack of digital literacy, and conflicting incentive structures often hinder reform. Empirical studies from the Journal of Cleaner Production and Energy Policy show that participatory leadership and cross- departmental learning networks accelerate technology acceptance and improve accountability within municipal organizations.

Challenges in Implementation

Several constraints limit large-scale diffusion of smart utilities. Technically, interoperability among different vendors' platforms remains problematic. Financially, many utilities struggle with cost recovery, undermining investment capacity. Socially, public skepticism toward prepaid metering and data privacy concerns persist. Organizationally, resistance to digital tools due to fear of redundancy among field staff remains acute. These issues highlight the importance of behavioral economics in policy design—where incentive compatibility and communication transparency can bridge trust gaps. Furthermore, fragmentation between municipal, state, and central institutions creates delays in procurement and project execution.

Future Directions and Policy Implications

The next phase of India's smart utility development will rely heavily on predictive analytics, artificial intelligence (AI), and digital twin models for urban resource management. Integrating these technologies with data from ICCCs could enable proactive maintenance, demand forecasting, and real-time tariff optimization. Policy frameworks must emphasize interoperability, cybersecurity, and citizen data protection. Institutional reforms should focus on establishing professional urban utility cadres, strengthening regulatory oversight, and integrating behavioral science insights into public-sector training curricula. Collaboration with academia and private research institutions can further enable evidence- based policymaking and innovation.

Conclusion

Smart energy and water management embody the future of sustainable urban governance in India. While technology provides tools for efficiency, it is leadership vision, institutional agility, and behavioral alignment that determine transformative impact. The Indian experience underscores that modernization is not a purely technical journey but an organizational evolution demanding capacity building, interagency coordination, and adaptive learning. The integration of managerial and behavioral insights into smart city governance thus remains central to achieving long-term urban resilience, efficiency, and equity.

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Electrochemical micromachining of microchannels for industrial applications with fabricated microtools

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Abstract
Due to huge population growth space management is a challenge today. One of the solutions is to use micro products for maintaining day to day life. Resourceful micromachining technologies are crucial for micro manufacturing. Micro products also help in saving material and energy. For micromachining technologies to flourish, microtool is fundamental. This paper is highlights suitable tool selection for accurate microchannel generation for industrial applications. Process plan for both microtool fabrication and generation of microchannel by electrochemical micromachining are described in detail. Tungsten microtools are appropriate as rigidity is high and inert to electrolyte. Tip of tungsten microtools are shaped as reversed taper, conical, disk and straight at different machining conditions of voltage, frequency and amplitude of vibration of tool. Finally, the fabricated micro tools are applied for machining precise micro channel using electrochemical micromachining (EMM).
Keywords: Microtool fabrication, Vibration, Electrochemical micromachining, microchannel.

1 Introduction

ECM can be thought of a controlled anodic dissolution at atomic level due to flow of current through an electrolyte which can be water based neutral salt, dilute acid or alkali. Micro-machining refers to material removal of small dimensions ranging from 1 micron to 999 micron. Micro-machining technology plays a vital role in miniaturization of components in the fields of aviation (cooling holes in jet turbine blades), automobile, biomedical, electronics, sensors, computer, chemical micro-reactors and micro-electromechanical systems (MEMS) etc. Electrochemical machining (ECM) processes are thermal free and material removal takes place due to atomic level dissociation, thereby giving stress free and excellent surface finish. When anodic dissolution is applied to the micro-machining range of applications for manufacturing of ultra precision shapes, it is called Electrochemical Micromachining (EMM). ECM method has drawn attention nowadays because of low cost method of production of micro tool. Fan et al [1] used pulsed power supply to fabricate the microelectrode and discussed the effect of pulsed discharge, duty ratio and linear variation of applied voltage on the shape of microelectrode. Z. W Fan and L. W Hourng [2] discussed the effect of rotation of anodic tool on the diffusion layer and rate of dissolution with the increasing rotational speed. It was observed by the authors that minimum time of 10 minutes of etching was required before the drop down of micro tool. Lim et al [3] used 5 M KOH solution as an electrolyte and etched tungsten rod with D.C current. Authors reported the presence of diffusion layer, which along with geometry and voltage forms the shape of micro tool. For all those investigations of micro tool fabrications, the times of machining of micro tools were considerably high.

In this study, a stainless steel ring of 1600 μm diameter is used as cathode and φ 300 μm straight tungsten rod was immersed centrally for the electrochemical machining, applying vibration to the anodic tungsten rod [4]. Vibration of the tungsten rod has been considered as an important parameter during the fabrication of micro tool for the disruption of the diffusion layer, enhanced diffusion and convection of ions.

2 Experimental Set up

The set up consists of various sub-components such as electrical power and controlling system, stepper motor along with microprocessor for motion control of tool and job, Mechanical unit for holding the tool and job and Piezoelectric transducer (PZT) for vibrating the tool longitudinally.

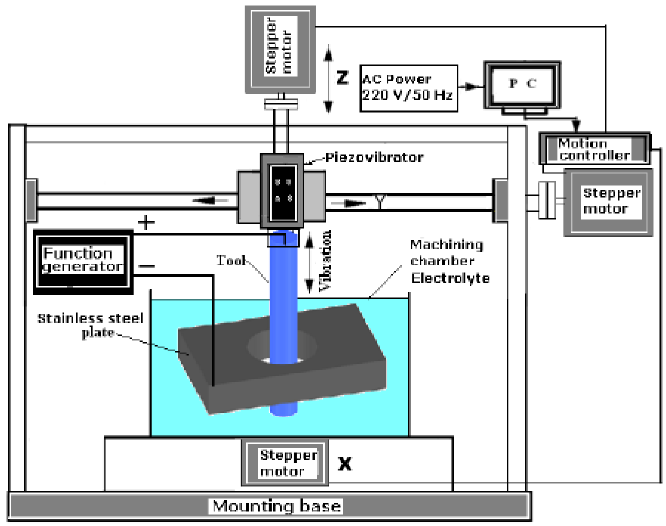


Fig. 1 Set up for micro tool fabrication

PZT is connected to 230V main power supply through amplifier module (-20 V to 130V) for feed control in the nanometer range (resolution 0.12 nm) having maximum stroke 66 µm and a modulation input from a function generator for controlling the amplitude of vibration which varies with the variation of voltage. Frequency of vibration of the PZT is controlled by the frequency of input voltage. Electrical power and control is comprised of a function generator for the supply of pulsed DC voltage to the tool and work piece. Digital storage oscilloscope acts as data collection system which is inevitable for the control of inter electrode gap (IEG) during EMM. Stepper motors are used to give motion of the tool and work piece along X, Y and Z direction. Fig. 1 shows the various units of the developed experimental set up of EMM, used for the micro tool fabrication.

3 Fabrication of tungsten microtool without vibration

Small pieces of tungsten rods are sheared from long tungsten rod of φ 300 µm diameter and ends are flattened by fine grinding and straightened. Then, the tool specimen is connected to the positive terminal of function generator and stainless steel ring of diameter 1600 µm is connected to the negative terminal. The tool specimen is centered to the hole and immersed vertically to a certain dipping length into NaOH electrolyte. When voltage is applied between anode and cathode the tungsten dissolves at the anode by the following reactions:

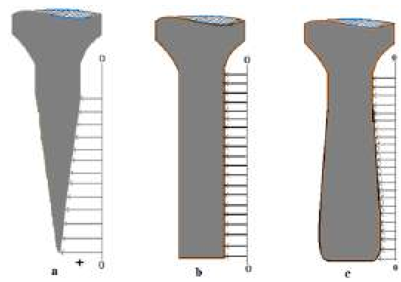
$$W + 6\,OH^- \rightarrow WO_3 + 3\,H_2O + 6\,e^- \qquad (1)$$

$$WO_3 + 2OH^- \rightarrow WO_4^{2-} + H_2O \qquad (2)$$

The electrochemical reaction on the cathode is:

$$6H_2O + 6e^- \rightarrow 3H_2\uparrow + 6\,OH^- \qquad (3)$$

In the reaction (1), the metal tungsten is oxidized to tungstate (WO_3). In the reaction (2), the tungstate becomes ion (WO_4^{2-}) by reacting with excess hydroxyl ions and remains dissolved in the electrolyte. In the reaction (3), water is converted to hydroxyl ions and hydrogen evolves speedily at the cathode. Magnitude of current density on the surface of the micro tool plays an important role on the formation of shape as shown in fig. 1. When lesser than 1.5 V was applied conical shape was formed as shown in Fig. 2 (a). At 1.5 V applied voltage, straight micro tool was formed as shown in fig. 2 (b) and reversed conical micro tool was formed when applied voltage was greater than 1.5 V as shown in fig. 2 (c). In all the cases, machining time was very high ranging from 13 to 20 min. The micro tool is fabricated based on the Faraday's two laws of electrolysis. The anodic tungsten tool dissolves based on current density distribution. Mass of tool that dissolves is transferred away from it, resulting in flow of mass transfer current. Migration of ions depends on the electric field intensity, E which is equal to the potential gradient at that point.



Current density distribution of (a) conical (b) straight and (c) Reversed taper microtool

Fig. 2 Formation of different shapes based on current density

$$E = -\frac{dV}{dX} \tag{4}$$

In other words, E is equal to rate of fall of potential in the direction of current.

Current density is also enhanced due to diffusion process and thereby, MRR increases. But, Nernst diffusion layer is a layer of similar charges which hinders the flow of current. The current density, J across the diffusion layer is well known and given by [5, 6]

$$J = \frac{eD(C_0 - C_\delta)}{\delta} \tag{5}$$

Where, D is effective diffusion coefficient, e is the electronic charge, C_0 is tungsten ion concentration i.e. no of ions per unit volume at the surface of tungsten, C_δ is the tungsten ion concentration at the end of the diffusion layer and can be taken as the concentration of bulk solution and δ is the diffusion layer thickness. Low volt is applied between tungsten micro tool and cathodic ring such that the chance of diffusion layer formation is less, as the rate of dissolution of metal will be less. The Laplace's equation is solved subjected to the given boundary conditions in MATLAB. The gradient of potential (- dV/dX) is more in the front end and lateral face of front end side i.e. distance between equipotential curves are small. So, the rate of dissolution of micro tool will be highest at the front end and lateral face of front end side and thereby conical tool is formed. At 1.5 V, diffusion layer is formed in the front end and therefore, current density is reduced too sum extent. As a combined effect of Eq. (4) and Eq. (5) equal current density exists all over the surface of micro tool and straight micro tool is formed. At higher than 1.5 V, diffusion layer becomes prominent as the rate of dissolution will be higher than rate of disposal. Therefore, diffusion layer thickness will be highest near the front end as initial dissolution rate will be higher at front end. Hence, at high applied voltage reversed taper micro tool as shown in fig. 2 (c) will be formed.

4 Fabrication of tungsten microtool with vibration

To reduce the fabrication time, vibration is applied and fabrication is realized within 1 to 2 min. This enhances the industrial application for machining of micro hole and microchannels with larger volume of production. The vibration has important effect on the diffusion layer, which is formed when the rate of metal dissolution is greater than the rate at which the metal ions can diffuse away from an electrode. Concentration overpotential comes into play under the situation and current density at the zone of thick diffusion layer decreases. The extremely fast bubble collapse due to vibration enhances charge transport and depolarization. Thus, vibration increases current density due to increase of convective mass transport, increase in the diffusion rate and improved conductivity. The tool is vibrated longitudinally with definite amplitude of vibration at 228 Hz frequency of vibration. From the earlier analysis on test results for the fabrication of cylindrical micro tool with small deviation, φ 300 µm tungsten rod is dipped up to 900 µm inside the 2M NaOH electrolyte to start fabrication of tool. Voltage is varied from 1.5 V to 10 V. Amplitude of vibration has the most significant effect on the growth of cavitations bubbles and energetic collapse.

5 Industrial application of microtool

Microchannels can be successfully fabricated by EMM for industrial applications. The flow diagram (Fig. 3) as well as tables for process plans for generation of microchannels of various types are presented and discussed below.

Novel method of sinking and milling is used for generation of microchannel for industrial application as this new approach produces smaller overcut and requires lesser machining time. The conical micro tool generates lesser taper angle of blind microchannel than straight micro tool. Taper angle of microchannel decreases with the decrease in taper angle of generating micro tool. Hence, 2.57 º conical microtool is used for generation of blind microchannel for industrial application considering highest accuracy and medium taper angle. Reversed taper microtool can generate microchannel with least taper angle but overcut is higher than that of conical microtool. Process plan for blind microchannel generation is described in Table-1. Total 1000 µm long microchannel will be machined within 85 min and other preparatory time is 1 hr. Total 2 hr 25 min is required. Taper angle of generated microchannel can be predicted to be 3.5°. Maximum diameter of microtool which will be actively involved in EMM is 4 µm and without insulated side wall minimum overcut will be 10 µm. Hence, entry width of blind microchannel will be 24 µm.

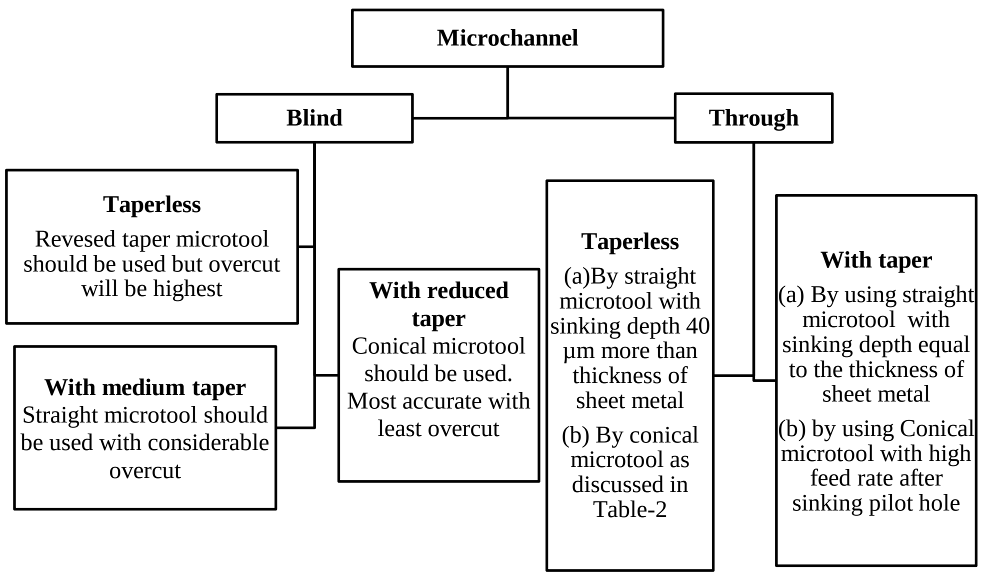


Fig. 3 Flow diagram of generation of microchannel for industrial application

Table-1 Generation of Blind Microchannel for Industrial Applications

Part No			Material: SS-304 sheet of 100 µm thick		
No	Descriptions of operation	Machine	Tool	Machining conditions/parameters	Time
1	Microtool fabrication from φ 300 µm tungsten rod	EMM set up along with piezoactuator & machining chamber	Conical microtool to be fabricated	2 M NaOH electrolyte, 7 V DC voltage, 5 µm amplitude of vibration, 87 Hz frequency of vibration	30 min for making ready all set up such as computer, oscilloscope, function generator, vibratory unit etc. 2.40 min fabrication time.
2	Fixing of workpiece and holding of cutting tool and setting of inter-electrode gap of 10 µm.	Workpiece is fixed in the fixture and connected to anodic terminal of pulse power. Microtool is fixed to tool holder and connected to negative terminal of pulse power. Program for movement of microtool is written.	Fabricated conical microtool of taper angle 2.57º	0.2 M H_2SO_4 electrolyte is used/poured in the machining chamber up to 1mm above the workpiece.	5 min for fixing workpiece, 5 min for fixing microtool, 10 min for setting of inter-electrode gap of 10 µm, 10 min for program

					writing and dry running
3	Pulse power is on to start EMM of Microchannel along with programmed tool movement.	Machining is observed by microscope. Hydrogen bubbles come out of cathode microtool. Pulse data are observed from oscilloscope.	Do	Optimum frequency of pulse voltage 5 MHz, duty ratio 35 %, and average voltage 3 V, drilling feed rate of micro tool 0.520 µm / s, drilling depth 45 µm, milling feed rate of microtool 0.20 µm /s	85 min

Process plan for taperless through microchannel generation is described in Table-2. Maximum diameter of microtool which will be actively involved in EMM is 4 µm and without insulated side wall minimum overcut will be 9 µm. Hence, width of taperless microchannel will be 22 µm. Total machining time 1 h 36 min for 1000 µm length of microchannel.

Table-2 Generation of Taperless Through Microchannel for Industrial Applications

Part No			Material: SS-304 sheet of 35 µm thick		
No	Descriptions of operation	Machine	Tool	Machining conditions/parameters	Time
1	Fixing of workpiece and holding of cutting tool and setting of inter-electrode gap of 10 µm.	Workpiece is fixed in the fixture of machining chamber and Microtool is fixed to tool holder and then, connected to anodic terminal and negative terminal of pulse power supply respectively.	Already fabricated conical microtool of taper angle 2.57º	0.2 M H_2SO_4 electrolyte is used/poured in the machining chamber up to 1mm above the workpiece.	5 min for fixing workpiece, 5 min for fixing microtool, 10 min for setting of inter-electrode gap of 10 µm,
2	Program development for microtool and work piece movement.	Computer controlled motion of microtool and workpiece	Do	During dry running machine conditions and movements of tool and work piece are observed for checking preparedness of actual machining.	10 min for program writing and dry running
3	Pulse power is on to start EMM of Microchannel by sinking and milling method along with programmed tool movement.	Machining is observed by microscope. Hydrogen bubbles come out of cathode microtool. Pulse data are observed from oscilloscope.	Do	Optimum frequency of pulse voltage 5 MHz, duty ratio 35 %, average voltage 3 V, drilling feed rate of micro tool 0.520 µm / s, drilling depth 45 µm, milling feed rate of microtool 0.26 µm / s	66 min

Tool design is done based on geometry of the tip of microtool. Generally, shape of microtool tip may be cylindrical, conical, reversed taper. Based on the optimum machining parameters of 5 MHz pulse frequency, 0.2 M H_2SO_4 electrolyte and 35 % duty ratio, various taper less through microchannels were generated on 35 µm and 50 µm thick SS-304 sheets with conical micro tools having taper angle in the **range of 4º to 16º at an interval of 3º**. Above this range, the generated microchannels become tapered. Corresponding widths of microchannels and machining times are listed in Table 3. In all the cases of machining, drilling feed rate of micro tool was 0.520 µm / s and downward movement of micro tool was up to 10 µm below the bottom surface of work piece and horizontal feed rate was 0.26 µm /s. Machining times are given for 500 µm length of microchannel.

Table-3 Widths of microchannel generated utilizing different conical micro tools

Taper angle of tool	4º	4º	7º	7º	10º	10º	13º	13º	16º	16º
Thickness of sheet (μm)	35	50	35	50	35	50	35	50	35	50
Width of through microchannel (μm)	25	31	32	37	56	62	62	67	66	72
Machining time (minute)	36	38	36	38	36	38	36	38	36	38

6 Conclusions

Fabrication of micro tools is essential for the manufacturing of micro components and features in micromachining area and preferably in EMM. In experimentation during fabrication of microtools and micromachining some important observations can be drawn from the test results and analyses are as follows:

(i) It is observed from the simulation of the machining zone that current density will be maximum at the front face and front side lateral face in absence of diffusion layer

(ii) Amplitude of vibration enhances transient cavitations phenomena which results in increase of convective mass transport and disruption of the diffusion layer. Thus, volume removal rate increases with the increase of amplitude of vibration at a particular voltage and microtool fabrication is possible within the shortest time.

(iii) Accurate blind and taperless through microchannels with different widths can be machined for industrial applications. Fabrication of conical micro tool along with machining parameters and process plans are presented in well clarified manner.

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A Comprehensive Thermodynamic Review of Energy and Exergy Assessment of Vapor Compression Refrigeration Systems

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Abstract
Refrigeration systems represent one of the largest consumers of energy worldwide, and their rising demand makes the improvement of energy efficiency an urgent necessity. Among the available thermodynamic tools, exergy analysis has emerged as a robust method for assessing, designing, and optimizing engineering systems, including vapor compression refrigeration systems (VCRS). Unlike conventional energy analysis, exergy analysis provides deeper insights into the sources of inefficiency by quantifying energy destruction and irreversibility within system components. This paper, titled *"A Comprehensive Thermodynamic Review of Energy and Exergy Assessment of Vapor Compression Refrigeration Systems"*, presents a comprehensive review of the energetic and exergetic performance of VCRS using both conventional and hydrocarbon (HC) refrigerants. Refrigerants such as R-407C, R-410A, R-134a, and R-600a (isobutene) are considered for comparative analysis. The study synthesizes findings from numerous research works to consolidate methodologies employed in evaluating energy and energy performance, while highlighting major challenges related to energy consumption and environmental concerns.
Key thermodynamic parameters such as coefficient of performance (COP), energy efficiency ratio (EER), exergy destruction rate, and second-law efficiency are critically examined. Furthermore, the review explores various improvement strategies proposed in the literature, including the adoption of eco-friendly refrigerants, system modifications, waste heat recovery methods, and advanced control technologies aimed at reducing energy losses.
By integrating results and perspectives from a wide range of studies, this review provides a state-of-the-art overview of the current research landscape. It identifies common trends, emerging challenges, and potential directions for future investigations. The insights gained are expected to contribute to the development of more energy-efficient, environmentally sustainable, and cost-effective refrigeration systems for industrial and domestic applications.

Keywords: *Vapor Compression Refrigeration System (VCRS); Energy Analysis; Exergy Analysis; Coefficient of Performance (COP); Hydrocarbon Refrigerants; Energy Efficiency; Sustainability*

1. Introduction

Energy balance is a key tool for studying thermodynamic processes, helping to evaluate energy use and identify areas for improvement. It plays a vital role in process optimization and forms the basis for exergy analysis. By examining energy balance, one can assess system efficiency and compare it with modern standards, highlighting high energy losses or low-performance areas. While energy analysis focuses on energy conservation (First Law), exergy analysis—based on both the First and Second Laws—considers energy quality and system irreversibility's, giving a deeper insight into overall performance and optimization.
In vapor compression refrigeration systems (VCRS), heat release to the environment causes irreversibility that lower system efficiency. These losses mainly arise from temperature differences during heat transfer. While energy analysis shows overall energy conservation, it fails to locate performance losses. Exergy analysis, however, identifies where and how energy destruction occurs, making it vital for system optimization.
Exergy studies help improve refrigeration cycles by analyzing the performance of alternative refrigerants, system designs, and operating conditions. Research has applied exergy analysis to systems using Freon, natural gas, and solar-assisted setups, revealing the effects of refrigerant type, configuration, and temperature levels on efficiency.
This study reviews the energy and exergy performance of VCRS under varying conditions, focusing on evaporating and condensing temperatures, COP, and exergy losses. It also evaluates eco-friendly refrigerants and lubricants, especially hydrocarbons, to address global warming and ozone depletion. The goal is to provide insight into improving the efficiency and sustainability of refrigeration systems for industrial, residential, and transport uses.

2. Objectives

The study aims to compare the energy and exergy performance of a vapor compression refrigeration system using different refrigerants—R-407C, R-410A, R-134a, and R-600a—under various operating conditions. It evaluates COP, energy efficiency, exergy destruction, second law efficiency, destruction ratio, and overall exergy efficiency for each refrigerant. The goal is to identify the refrigerant with the best thermodynamic performance and minimum energy losses. The study also examines the influence of operating parameters such as evaporator and condenser temperatures, sub cooling, and superheating on system efficiency.

3. Problem of Statement

Energy analysis shows how well a system performs but doesn't reveal energy losses or usage effectiveness. Exergy analysis, on the other hand, identifies where energy is wasted and how to improve system performance. The choice of refrigerant greatly affects both efficiency and environmental impact. Refrigerants like R-134a, R-407C, R-410A, and R-600a have different thermodynamic behaviors that influence energy use and losses. To select the most efficient and eco-friendly refrigerant, it's essential to study their performance under varying conditions such as evaporator and condenser temperatures, sub cooling, and superheating. Despite advances in refrigeration technology, limited research compares the energy and exergy performance of VCRS using different refrigerants under real operating conditions. This study addresses that gap by analyzing system inefficiencies and suggesting improvements for higher efficiency and sustainability, aiming to develop energy-efficient and environmentally friendly refrigeration systems.

4. Literature Review

John T. McMullan (2002) discussed the phase-out of CFCs and HCFCs due to ozone depletion and the move toward low-GWP refrigerants. Since no ideal refrigerant exists, mixtures and natural alternatives are being explored, requiring improved system design and monitoring [1]. Md Ozair Arshad *et al.* analyzed the exergy performance of VCRS with R-134a, R-12, and R-22, showing that exergy loss decreases with higher evaporator temperature and that R-12 offers the best exergetic efficiency [2]. Recep Yumrutas *et al.* examined how evaporating and condensing temperatures affect exergy losses and COP, finding that minimizing temperature differences enhances overall performance [3].Hari Prasad *et al.* [4] reported that exergy losses in VCRS arise from irreversibilities, affected by temperature, subcooling, and superheating; exergy analysis helps locate and reduce inefficiencies.

Ahamed *et al.* [5] showed that refrigerants like R600a, R410A, and R1270 are efficient but require blending with R134a for safety. Most exergy loss occurs in the compressor and can be reduced using nano lubricants and nanofluids. Ogbonnaya *et al.* [6] found that adding nanoparticles such as TiO_2 and CuO to refrigerants improves thermal conductivity and efficiency but excessive concentration lowers performance. Compressor losses remain the main source of exergy destruction. Raja Kumar Gond *et al.* [7] analyzed alternative refrigerants to R134a in VCRS and found R600, R600a, R717, and R152a more efficient, with R600 as the best replacement. System performance strongly depends on evaporator and condenser temperatures, sub cooling, and superheating. Jian Sun *et al.* [8] evaluated R513a as a low-GWP substitute for R134a, noting slightly lower capacity and efficiency but reduced irreversibility and improved exergy performance in certain conditions. Compressor redesign and component optimization were suggested for better results. Jyoti Soni and R.C. Gupta [9] compared R-407C and R-410A, finding R-407C superior in COP and exergy efficiency, while R-410A showed higher exergy destruction. Sub cooling improved efficiency, but excessive heat exchanger effectiveness reduced COP. Bayram Kılıç [10] assessed R507, R407C, and R404A in a two-stage system, reporting that R407C achieved the best COP and exergy efficiency. The evaporator showed maximum irreversibility due to phase change and friction losses, confirming these refrigerants as viable eco-friendly options.

Bayrakcı and Özgür [11] compared the energy and exergy performance of pure hydrocarbon refrigerants (R290, R600, R600a, R1270) with R22 and R134a. R1270 and R600 showed the best efficiency, while R600a emerged as a strong alternative. Increasing evaporation temperature improved COP but reduced exergy efficiency. Pure hydrocarbons were preferred due to stable composition under leakage. Kabul *et al.* [12] analyzed a VCRS using isobutene (R600a) with an internal heat exchanger and found it to be an eco-friendly substitute for CFCs/HCFCs. Higher evaporator temperatures enhanced efficiency, whereas condenser temperatures reduced it, with the compressor showing maximum irreversibility. Chandrasekhar an [13] compared R12 and R134a, studying the influence of evaporator temperature and sub cooling on performance. Results showed varying exergy destruction rates across components, highlighting energy wastage patterns. Gill *et al.* [14] examined R450A and R134a, reporting higher exergy efficiency and lower irreversibility for R450A, except in the capillary tube. Despite higher cost, R450A proved superior, suggesting design optimization for better results. Kumar *et al.* [15] conducted an exergetic evaluation using R11 and R12, employing exergy–enthalpy diagrams to assess losses and performance. They concluded that exergy analysis effectively identifies inefficiencies and guides system improvement.

Kanoglu [16] conducted an exergy analysis of a multistage cascade refrigeration cycle for natural gas liquefaction, developing equations for exergy destruction and minimum work. Results showed 38.5% exergetic efficiency and increasing work with lower liquefaction temperatures, suggesting scope for system optimization. Menlik *et al.* [17] evaluated R22, R407C, and R410A in a VCRS, finding R407C superior in COP and exergetic efficiency with lower exergy losses. Subcooling, superheating, and ambient temperature strongly influenced performance, with the condenser identified as the least efficient component. Arora *et al.* [18] compared R22, R407C, and R410A, concluding that R22 performs best in COP and exergetic efficiency, while R410A is a better replacement option than R407C. They noted that alternate refrigerants reduce exergetic efficiency but can be optimized through improved system design and cost-based selection.

Arcaklıoğlu, Çavuşoğlu, and Eris Şen [19] developed an algorithm to identify refrigerant mixtures with equivalent volumetric cooling capacity (VCC) to replace CFCs in vapor compression systems. Their evaluation compared COP and VCC of various mixtures, suggesting R290/R600a for R12 and R32/R125/R134a for R22 and R502 as effective alternatives. The work highlights the importance of further second-law analysis to account for irreversibility when selecting replacement refrigerants.

5. Thermodynamic analysis
The main objective of this analysis is to:
1. Determine the coefficient of performance (COP) using the first-law (energy) analysis.
2. Calculate exergy losses in each component using the second-law (exergy) analysis.
3. Evaluate the second-law efficiency.
4. Compute exergy destruction ratio and overall exergetic efficiency.

So, we will use two approaches for the entire analysis. The first analysis based on energetic approach and the second analysis based on Exergetic approach.

5.1 Energetic Approach or the First Law Analysis
The first-law (energy) analysis aims to evaluate how COP changes with evaporator and condenser temperatures, compressor isentropic efficiency, and superheating.

Assumptions:
1. **Steady-State Operation:** All components operate under steady-state, steady-flow conditions.
2. **Negligible Pressure Losses:** Pressure drops in pipes, evaporator, and condenser are ignored.
3. **Negligible Energy Losses:** Kinetic and potential energies are considered insignificant.
4. **Adiabatic Compression/Expansion:** Compressor and expansion device have no heat transfer.
5. **Saturated States:** Refrigerant is saturated at condenser and evaporator outlets.

The compressor capacity can be calculated using the formula:
$\dot{W}_{comp} = \dot{m}_R\,(h_2 - h_1)$ -- (1)

Where $\dot{W}_{comp}$ is the compressor capacity, $\dot{m}_R$ is the mass flow rate of refrigerant and h denotes enthalpy. Here, h_2 represents the actual enthalpy at the compressor outlet and is defined as:

$h2 = h1 + \frac{h2s - h1}{\eta is}$... (2.)

Where ηis is the isentropic efficiency of compressor. So isentropic work input to compressor is
$\dot{W}cis = \dot{m}(h2s - h1)$ …………………………………………………………… . (3)

The condenser capacity is calculated as:
$\dot{Q}cond = \dot{m}(h2 - h3)$………………………………………………………………… (4)

here $\dot{Q}cond$ is the condenser capacity, $\dot{mR}$ is the mass flow rate of refrigerant
The **expansion process is isenthalpic** and denoted as:
h3 = h4………………………………………………………… (5)

The **cooling capacity or heat extracted** can be calculated as:
Qevap = m_R(h1−h4)…………………………………………… (6)

here $\dot{Q}$evap is the **evaporator/cooling capacity**. m_R is the **mass flow rate of refrigerant**.
The **cooling capacity** is defined as the difference between the capacities of the condenser and the compressor:
$\dot{Q}_{evap} = \dot{Q}_{cond} - W_{cis}$………………………………………………… (7)

The overall energy performance of the cycle is assessed by calculating its COP, which is the ratio of the refrigeration capacity to the power input to the compressor. It is expressed as:

$COP = \dot{Q}evap/\dot{W} = \frac{h1-h4}{h2s-h1}$………………………………………………………….(8)

Another parameter used to evaluate the performance of the refrigeration cycle is the efficiency ratio (τ), also known as the second law efficiency (ηII), and it can be expressed as:

$\tau = \frac{COPact}{COPcarnot}$ or $\eta II = \frac{COPact}{COPcarnot}$ …………………………….(9)

Where $COPact$ is the actual coefficient of performance, $COPcarnot$ is the ideal coefficient of performance of the cycle and is the maximum possible COP of a refrigeration cycle working between two temperature limits.
COP_{carnot} is also denoted by:

$COP_{carnot} = \frac{TL}{(TH-TL)}$…………………………………… (10)

Another performance metric for the refrigeration system is the Energy Efficiency Ratio (EER). EER represents the heating and cooling efficiencies of air conditioning units. It indicates the ratio of the heating or cooling output to the electrical energy input required to produce it and is defined as:

EER = COP × 3.412 …………………………………….. (11)

5.2 Exergetic Approach or the Second Law Analysis

Some assumptions are made for the analysis is:

i All components operate under steady-state conditions.
ii Pressure losses in the pipelines are neglected.
iii Heat gains and losses to or from the system are not considered.
iv Kinetic energy, potential energy, and exergy losses are ignored.

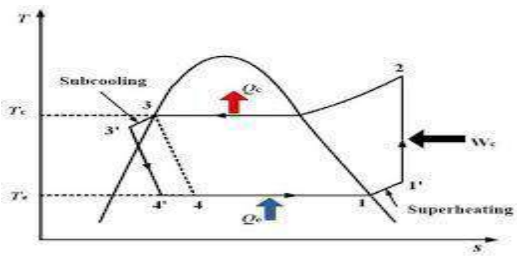

Figure 1: T-S diagram of VCRS for analysis

The mathematical formulation for exergy analysis is as follows:
General exergy balance equation with respect to time is given as-

$\dot{E}_D = \dot{E}_{in} - \dot{E}_{out}$ (11)

where $\dot{E}_{in} - \dot{E}_{out}$ represent the rate of exergy transfer and $\dot{E}_D$ represent irreversibility
Equation (11) for steady state process for control volume can also be written as:

$\dot{E}_D = \dot{E}_Q - \dot{E}_W + \dot{E}_{mass,in} - \dot{E}_{mass,out}$ (12)

where exergy of heat, work, mass is given as:

$\dot{E}_Q = \dot{Q}(1 - \frac{T_0}{T})$ (13)

$\dot{E}_W = \dot{W}$ (14)

$\dot{E}_{mass} = \dot{m}_R \times \psi$ (15)

where $\dot{Q}$ is rate of heat transfer at temperature T, $T_0$is reference temperature and ψ is specific flow exergy.
Combining equation (12-15) can be written as:

$\dot{E}_D = \sum\dot{E}_{mass,in} - \sum\dot{E}_{mass,out} + \left[\sum\left\{\dot{Q}\left(1 - \frac{T_0}{T}\right)_{in}\right\} - \sum\left\{\dot{Q}\left(1 - \frac{T_0}{T}\right)_{out}\right\}\right] \pm \sum\dot{W}$ (16)

Specific Exergy in any state is given as:

$\psi = (h - h_0) + \frac{1}{2}V^2 + gZ - T_0(s - s_0)$ (17)

where g, V and Z are the gravitational acceleration, velocity and elevation from reference respectively. Neglecting potential and kinetic energies as per assumption, the equation (17) becomes

$\psi = (h - h_0) - T_0(s - s_0)$ (18)

The exergy destruction term, ($\dot{E}_D$), is also known as irreversibility rate.

$\dot{I} = \dot{E}_D$ (19)

Applying Exergy analysis equation in each component of VCRS, Irreversibility rate for each component is:

i. For Evaporator:

Heat added in Evaporator, $\dot{Q}_E = \dot{m}(h_{1'} - h_{4'})$ (20)

Exergy destruction, $\dot{I_E} = \dot{m}(\psi_{4'} - \psi_{1'}) + \dot{Q}\left(1 - \frac{T_0}{T_E}\right)$

$\dot{I_E} = \dot{m}(h_{4'} - h_{1'}) - T_0(s_{4'} - s_{1'}) + \dot{Q}\left(1 - \frac{T_0}{T_E}\right)$ (21)

ii. For Compressor:

Work in compressor, $\dot{W}_C = \dot{m}(h_2 - h_{1'})$ (22)

Since, compression is non-isentropic, $h_C = \frac{(h_{2s} - h_2)}{\eta_C}$ (23)

Electrical power consumed, $\dot{W}_{el} = {}^{\dot{W}_C}/_{\eta_{mech}} \times \eta_{el}$

Exergy destruction, $\dot{I}_{comp} = \dot{m}(\psi_{1'} - \psi_2) + \dot{W}_{el}$

$\dot{I}_{comp} = \dot{m}(h_{1'} - h_2) - T_0(s_{1'} - s_2) + \dot{W}_{el}$ (24)

iii. For Condenser:

Heat rejected, $\dot{Q}_{cond} = \dot{m}(h_2 - h_{3'})$ (25)

Exergy destruction, $\dot{I}_{cond} = \dot{m}(\psi_2 - \psi_{3'}) - \dot{Q}_{cond}(1 - \frac{T_0}{T_{cond}})$

$\dot{I}_{cond} = \dot{m}(h_2 - h_{3'}) - T_0(s_2 - s_{3'}) - \dot{Q}_{cond}(1 - \frac{T_0}{T_{cond}})$ (26)

iv. For expansion valve:

$\dot{I}_{exp} = \dot{m}(\psi_4 - \psi_{3'}) = \dot{m}(s_4 - s_{3'})$ [In throttling, h_4=h_1] (27)

I. Coefficient of performance, $COP = \frac{\dot{Q}_E}{\dot{W}_{el}}$ (28)

II. Total exergy destruction, $\dot{I}_{total} = \dot{I}_{comp} + \dot{I}_{cond} + \dot{I}_{exp} + \dot{I}_E$ (29)

III. Exergy efficiency, $\eta_x = \frac{\psi_{1'} - \psi_{4'}}{\dot{W}_{el}}$

Or

$\eta_x = \left(\frac{\dot{E}_{out}}{\dot{E}_{in}}\right) \times 100$ (30)

where $\dot{E}_{out} = \dot{E}_{in} - \dot{I}_{total}$ (31)

& electric power is the main source of exergy input in compressor

so, $\dot{E}_{in} = \dot{W}_{comp}$ (32)

$\therefore \eta_x = \left(\frac{\dot{W}_{comp} - \dot{I}_{total}}{\dot{W}_{comp}}\right) \times 100 = \left(1 - \frac{\dot{I}_{total}}{\dot{W}_{comp}}\right) \times 100$ (33)

IV. Energy efficiency ratio, EER $= \frac{Energy\ out}{Compression\ work} = \frac{h_{1'} - h_{4'}}{\dot{W}_{el}}$ (34)

V. Exergy destruction ratio, $EDR = \left(\frac{\dot{W}_{comp}}{\dot{W}_{comp} - \dot{I}_{total}}\right)$ (35)

6. Conclusion

In conclusion, the performance evaluation of refrigerants R-407C, R-410A, R-134a, and R-600a in vapor compression refrigeration systems (VCRS) highlights the following key points:

1. R-407C shows superior COP and exergy efficiency compared to R-410A. It also gains from liquid subcooling, with about a 7.02% rise in exergetic efficiency at 10°C subcooling.
2. R-410A experiences greater exergy destruction (EDR) than R-407C, yet follows a similar performance trend. Its COP and exergy efficiency also increase with subcooling, achieving an 8.01% improvement at 10°C.
3. R-134a delivers inferior COP and exergetic efficiency, with higher exergy losses, especially at elevated evaporator and condenser temperatures, resulting in lower overall output.
4. R-600a (hydrocarbon) exhibits the best thermodynamic and exergetic behavior, surpassing R-134a and R-22. It ensures high COP, eco-friendliness, and strong replacement potential for synthetic refrigerants.

To summarize, R-407C and R-600a stand out as efficient substitutes, with R-600a delivering the highest overall performance. R-410A remains competitive despite higher exergy losses, while R-134a is less efficient and environmentally less favorable.

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Analyzing the failure of the dumper truck's rear axle shaft involves thoroughly investigating to find out why it failed.

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Abstract

The failure analysis of a rear axle shaft from a dumper truck involved a comprehensive investigation to determine the root cause of the failure. Visual inspection, material analysis, mechanical testing, and fracture analysis were conducted to assess the condition of the axle shaft. The axle shaft exhibited signs of fatigue failure, with the fracture surface showing fatigue striations. Microstructural analysis revealed a coarse grain structure with inclusions, indicating potential material defects. Tensile testing showed that the axle shaft had lower than expected mechanical properties, suggesting a possible issue with material quality or heat treatment. Based on the analysis, the root cause of the failure was determined to be a combination of material defects and fatigue loading. Recommendations were made to improve material quality control, heat treatment processes, and maintenance practices to prevent similar failures in the future. Failure analysis of a rear axle shaft of a dumper truck, which was involved in a accident. The axle was found in fracture condition, investigation was carried out in order to find cause of failure. Type of investigation like as visually examined, chemical analysis, hardness test, tensile test, fractography and ultrasonic test, micro structure examination. . Micro-structure observation of the sample indicates normal ferrite–pearlite (lower critical point) sorbite type structure with some spherodisation was seen on some portion Lots of cleavages were notified in fractography, and showed v-shape "chevron" marking. Result indicates that failure was taken place due to sudden loading on the axle shaft, therefore in the weak portion of the axle shaft shear stresses was not enough to counter stresses imposed by sudden loading.. Based on the analysis, make recommendations for corrective actions to prevent similar failures in the future. This may include design improvements, material changes, maintenance procedures, or operational changes. Implement the recommended corrective actions to prevent similar failures in other axle shafts or similar components.

Introduction:

Osman asi et al (1) studied on fatigue failure analysis of a rear axle shaft of an automobile. From the observations, he was found that fatigue cracks have initiated at stress concentration points leading to fracturing of the axle shaft. In general, axle shafts fracture in the spline portion. C. Kendall Clark et al (2) studied on Failure Analysis of Induction Hardened Automotive Axles. The following conclusions was drawn from their research,

- Fatigue could be differentiated from overload fracture by visual appearance, witness marks, and by SEM examinations.
- Fracture origins in fatigue will be less distinct and smoother than overload fracture.
- Overload fractures will have chevrons coming to a point and roller bearing marks on the journal.
- The fractures may or may not have the origins and final fracture aligned due to rotation effects.
- Single overload failures generally originate at the flange radius while fatigue fractures, occur at the axle journal surface at the outboard edge of the roller bearings.

K. Hirakawa, and et al (3) were analysis on the topic of The analysis and prevention of failure in railway axles and they were concluded that, To maintain the safety record of railway systems, much effort has been paid to improvement of the axle manufacturing processes, design, testing and maintenance. Recently, no passenger casualties occurred due to axle failure. This success is due to all the engineers, research scientists, managing engineers and workers inspection for fatigue cracks at critical parts. The effect of variable amplitude stresses on the fretting fatigue is not fully understood. Axle fatigue design methods are therefore incomplete. Comprehensive investigation in this area is still necessary.

H. M. Tawancy et al (4) were studied on Failure of a Rear Axle Shaft of an Automobile Due to Improper Heat Treatment and they were concluded that, the results suggested that the most probable cause of failure was improper heat treatment of the shaft resulting in a case microstructure with poor ductility susceptible to brittle fracture. It is apparent that the shaft was not subjected to a proper tempering treatment. However, another possibility is hydrogen-induced cracking due to water pickup and some rust at the surface, but this could not be confirmed. Although the final facture could have occurred by the impact of overturning and the associated high strain rate, the possibility that overturning of the vehicle.

1. Experimental procedure:

Failed axle shaft was taken from a transport company. This is shown in figure below. Fig.1 show shaft are in good condition and Fig.2 show shaft are in failure condition.

Fig.1

Fig.2

2.1 VISUAL INSPECTION:-

It was inspected visually but causes was not found, due to this various test were done in the failed axle shaft. Examine the failed axle shaft for signs of damage, such as fractures, bends, or wear patterns. Note the location and nature of the damage.

2.2 MATERIAL ANALYSIS:

Determine the material composition of the axle shaft. This can help assess if the material was appropriate for the application and if it met specificationsPurpose of this test to Know the chemical composition used in the axle shaft. Details of chemical analysis are show in Table 1.

Element	% of composition	Element	% of composition	Element	% of composition
C	0.5	Cr	0.27	Sn	0.011
Mn	0.65	Ni	0.04	Al	0.022
Si	0.25	Mo	0.02	Ar	0.055
Ph	0.02	V	0.004	Sb	0.0013
S	0.017	Cu	0.27	Sn	0.013

2.3 HARDNESS TEST

Perform mechanical tests on the axle shaft, such as hardness testing, to assess its mechanical properties. This can reveal if the shaft was subjected to excessive loads or if it had defects in its material. In this test sample surfaces were grounded properly, and then it was tested for Brinell hardness number less than 3000 kg load and indenter diameter 10mm from core to case of surface. In vicker hardness test both diagonal diameter was measure and then average of two was taken. These two gave occular reading. Then vicker hardness number was found by seeing the chart after compare the value corresponding occular reading. Occular reading = $(d_1+d_2) / 2$ 1 occular =0.001mm.

2.4 TENSILE TEST

Tensile test was carried out using round specimen of 12.5mm gauge diameter, and 60mm gauge length fabricated from the centre of the failed axle shaft along the axle longitudinal direction. The results are listed in the observation section and shows the mechanical properties met the technical demand

2.5 METALLOGRAPHIC TEST

Examine the microstructure of the axle shaft, looking for features such as grain size, grain boundaries, and phases present. This can provide information about the material's processing history and potential defects. If the shaft has fractured, conduct a detailed analysis of the fracture surface using techniques like microscopy. This can reveal the type of fracture (e.g., fatigue, overload) and the initiation point. Metallographic consist of micro-scope study of structural characteristic of metal and alloy. By this process it is possible to determine grain size, shape and distribution of various phases and inclusion which have great effect on mechanical properties of metal. In this test different process were done.Rough grinding, Intermediate polishing, Fine polishing, Etching

2.6 FRACTOGRAPHY OF TENSILE FRACTURE SPECIMEN

SEM (Scanning Electron Microscope) analysis of an axle shaft can provide valuable insights into its microstructure, surface morphology, and potential failure mechanisms. In this test tensile fracture surface, the two broken sample cut into the small thickness, and installed in the fractography machine, and observed with the help of scanning electron micro-scope. Fractography of a tensile fracture specimen involves examining the fracture surface to understand the fracture mechanism and failure mode. Based on the features observed, identify the primary fracture mode. This could be ductile, brittle, or a combination of both, depending on the material and loading conditions. Analyze the fracture surface to determine the sequence of events that led to failure. Look for signs of fatigue, overload, corrosion, or other factors that may have contributed to the fracture.

3. Result and Discussion:

3.1 Chemical analysis

Chemical analysis of a failed axle shaft involves determining the elemental composition of the material to identify any anomalies or impurities that may have contributed to the failure The result of chemical analysis as shown in table1. Are indicates that axle shaft are made from medium carbon steel and satisfied the ASM slandered. Perform elemental analysis of the sample to determine the concentrations of different elements present. Pay particular attention to elements that are not typically found in the material composition, as they may indicate contamination or impurities

3.2 Mechanical Properties of axle shaft

Conducting a tensile test on a failed axle shaft involves obtaining a sample from the failed shaft and subjecting it to tensile loading to determine its mechanical properties apply a tensile load to the sample at a controlled rate, typically specified in standards such as ASTM E8/E8M. Record the load and deformation (strain) values throughout the test.

Table2. Represent the result of tensile test conduct on the fracture shaft. Four specimens were tested and average of four taken .tensile test show that ultimate tensile strength and yield strength are 735.2Mpa and 422MPa respectively.

Table 2: Tensile properties of axle shaft:

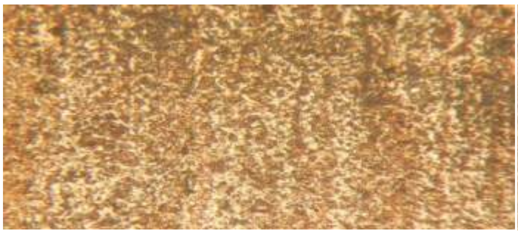
Material Behavior	Value
Tensile strength	735.2MPa
Yield strength	422MPa
% elongation	20
% reduction	40
Poisson’s ratio	0.24
Breaking stress	620Mpa

Table Below table of Brinell hardness test shows that, hardness varies from 183 to 550BHN. Result show that there is a wide variation in hardness at the surfaces from core to case. Hardness is an indicator of the material's resistance to deformation and wear. Similarly, vicker hardness test shows that its value varies from 219 to 283

“D” diameter of steel ball (mm).	“d” average measured Diameter (mm).	“W” is load on indenter in (kg).	BHN NO
10	4.4	3000	183
10	4.3	3000	197
10	4.0	3000	229
10	3.8	3000	254
10	3.4	3000	320
10	2.6	3000	550

3.3 MICRO-STRUCTURE OF SPECIMEN

The axle shaft is typically made of a steel alloy that exhibits a crystalline structure. The grain structure can vary depending on the manufacturing process and heat treatment. In a failed axle shaft, you might observe the grain boundaries and the size of the grains. Below Fig. show that micro-structure exhibit normal ferrite–pearlite (lower critical point), sorbite type structure.



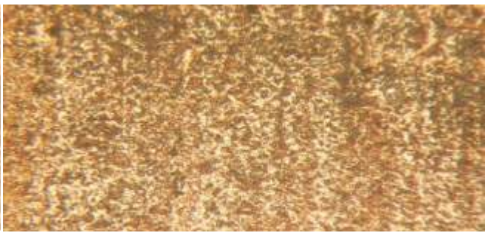
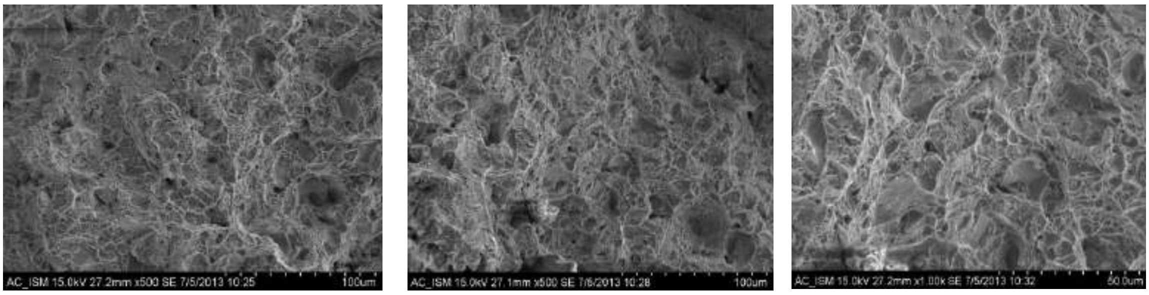


Fig: 3 (a) ~100×, 2% nital` etchant **Fig: 3.(b)** ~ 100×, 2%nital etchant

Fig: 3.1SEM analysis of failed axle shaft as found in fracture condition



(a) (b) (c)

Fig: 4 SEM micrograph of the fracture surface of the failed axle shaft 4. (a) River type (b) river type with dimple structure (c) river type with fatigue striation

3.4 SEM analysis

SEM analysis of a failed axle shaft can provide valuable insights into the root cause of the failure, whether it was due to material defects, improper heat treatment, overloading, or other factors. This information can be used to improve material selection, manufacturing processes, and design to prevent similar failures in the future. Fracture surface of failed axle shaft examined by scanning electron microscope (SEM). Fig.4a to 4c show river type with brittle facet on the image and some dimple structure .it means failure will occur with mixed component of brittle as well as ductile manner.

4. Conclusion

Conducting a failure analysis of the rear axle shaft of a dumper truck involves a comprehensive investigation to determine the root cause of the failure. Visual inspection, material analysis, mechanical testing, and fracture analysis are conducted to assess the condition of the axle shaft. The axle shaft exhibits signs of fatigue failure, with the fracture surface showing fatigue striations.SEM result show ductile fracture is characterized by dimple structure, ductility can be measured by depth of the dimple, also SEM image indicates the some brittle facet, through which the fracture propagates through the grain boundary i.e. transgranular due to high tensile strength crack flow the grain boundary i.e. intergranular fracture .The value of hardness taken from core to case indicates that wide variation of BHN number at different location. Micro- structure exhibit normal ferrite–pearlite (lower critical point), sorbite type structure.SEM image also indicate that the failed axle shaft show river type as well brittle facet indicates heterogeneous structure of mixed component of ductility and brittle facet .it indicate that heat treatment of the material was not properly done to get desired properties .From above observation it can be concluded that failure has taken due to sudden loading on axle shaft .since the material of shaft indicates that heat treatment was not done properly. The shear stress was enough to resisting the loading stress occur by sudden loading in weaker portion of the shaft. That causes to fracture of shaft.

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Simulation and Thermal Analysis of Air Cooling Configuration for Lithium-Ion Battery Packs Using ANSYS

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Abstract
This paper presents a computational analysis of an innovative air-cooled Battery Thermal Management System (BTMS) designed for rectangular lithium-ion battery modules. The objective of this research is to optimize the airflow arrangement and structural layout employed in the rectangular air-cooling BTMS to evaluate and enhance the thermal regulation performance of the battery cells using modelling and numerical simulation techniques. The performance of the proposed BTMS, integrated with a commercial thermal interface material, is compared with that of a conventional battery pack under various discharge rates of 1C, 2C, and 3C. The findings indicate a 25% decrease in maximum temperature for the new BTMS, emphasizing its potential for more efficient battery thermal control. Additionally, extended evaluation of varying inlet and outlet airflow directions demonstrates that a configuration with a top inlet and bottom outlet—maintaining the same air velocity—achieves more effective temperature reduction than the side-top inlet and side-lower outlet setup.

Keywords:
Battery Thermal Management System (BTMS), Air-cooled battery cooling, Li-ion battery modules, Numerical investigation, Airflow configuration, Thermal interface material, Battery pack cooling, Discharge rates (1C, 2C, 3C), Peak temperature reduction, Thermal management efficiency, Inlet and outlet fluid passes, Air velocity optimization, Numerical simulation

1. Introduction:
The rapid advancement of electric vehicles (EVs) and hybrid electric vehicles (HEVs) has been driven by the global energy crisis and pollution caused by fossil fuel transportation, along with escalating global warming and dwindling oil reserves. Lithium-ion batteries (LIBs), known for their high energy density, power output, low self-discharge, long life, and fast charging capability, are widely used in these vehicles. However, charging and discharging generate significant heat, which, if not managed properly, can reduce battery life and trigger thermal runaway. Excessive heat also alters internal chemical reactions, lowering reliability. Current battery thermal management systems (BTMS) mainly use phase change material (PCM) cooling, liquid cooling, or air cooling. Although liquid cooling provides effective heat dissipation and compact design, it requires complex channel structures and suffers from noticeable pressure drops. Most Li-ion cells operate safely below 50 °C, beyond which internal chemistry changes may lead to thermal runaway.

2. Objective:
The main goal of this project is to thoroughly study how lithium-ion battery packs respond to heat management under different cooling methods. The specific aims are:

- Simulate multiple cooling approaches using CFD and thermal analysis tools.
- Evaluate the thermal efficiency of each cooling setup across varying operating scenarios.
- Determine the best cooling strategy for effective heat removal and consistent battery temperature.
- Suggest design improvements to boost battery pack performance and lifespan.

3. Literature Review:
Xinke Li et al. [1] improved battery cell cooling by optimizing the airflow layout in a U-type air-cooled BTMS; modeling and simulations revealed that the best cooling was achieved when both inlet and outlet manifolds numbered three, enhancing overall system performance across varied airflow rates and temperatures.
Ningbo Wang et al. [2] showed that installing spoilers in battery gaps boosts heat dissipation; CFD results for a BTMS with 16 straight spoilers dropped maximum temperature by 3.52 K, and further optimization using a multi-objective genetic algorithm (MOGA) reduced battery module MaxT to 307.58 K and system volume by 4.87%, demonstrating effective improvements for Z-shaped air-cooled systems.
Aditya R et al.[3] conducted a numerical study on a passive battery thermal management system (BTMS) using RT-42 phase change material (PCM) for 18650 Li-ion cells at a 3C discharge rate, testing PCM thicknesses from 1 mm to 7 mm. The results indicate that at least 4 mm of PCM is required for effective temperature control, and at this thickness, the PCM does not fully melt during the cell's discharge cycle, ensuring consistent thermal protection.
Xiaoyu Na et al.[4] compared reverse layered airflow versus unidirectional airflow in battery packs using 3D CFD analysis. Findings show the reverse layered airflow reduces both the peak temperature and the maximum average temperature difference more effectively than unidirectional flow. The addition of rectifier grids at the air entrance further lowers the highest temperature by 0.5 °C and cuts the maximum average temperature difference by 0.6 °C—a 54.5% improvement. Optimizing parameters like cell spacing and air inlet velocity led to identification of the best-performing configuration.
Mengxuan Song et al.[5] showed that simply adjusting the plenum angles is not effective for reducing temperature or its variation among battery cells; however, after optimization, a 70% reduction in temperature difference and a 32% decrease in power consumption were achieved during a 5C discharge rate. Compared to previous designs, the optimized BTMS further lowered temperature difference by 43% and halved power consumption, with similar results across different airflow rates.

Haobing Zhou et al.[6] validated a 3D CFD model for battery modules and found that increasing inlet pressure significantly lowers maximum temperature, but also increases power usage. With an inlet pressure of 100 Pa, 1.5 mm orifice diameter, five rows of orifices, and a 3C discharge rate, the module's maximum temperature fell from 325.9 K to 305.7 K compared to no cooling. The temperature remained under 313.15 K even at 5C discharge under optimized pressure and geometry, though temperature difference slightly exceeded the ideal range. The cooling strategy is both efficient and practical, requiring no major changes to module arrangement.
Zhonghao Rao et al.[7] argued that developing new high-temperature PCM materials is challenging, but phase change materials still offer advantages for battery thermal management. Paraffin PCM's low thermal conductivity necessitates enhancements, and the performance and mechanics of improved PCMs require experimental investigation. The paper also recommends exploring heat collection and recycling for greater energy efficiency in thermal management.
Yi-Hong Chung et al.[8] studied lithium polymer battery (LPB) samples charged at different rates (1C, 3C, 5C) through 100 aging cycles to understand thermal runaway mechanisms. Higher C-rates led to increased temperature rise during discharge, with the 5C rate causing the most unstable behavior and severe explosion/fire hazards. During the runaway reaction, the lowest T 0, T max, and P max values were 133.0 °C, 530.0 °C, and 910.1 kPa, respectively, indicating 5C is unsuitable for thermal stability, whereas 1C and 3C are safer options.
Weixiong Wu [9] numerically evaluated and experimentally validated battery thermal management systems, proposing an optimization strategy for inlet and outlet placement to improve cooling. The optimized BTMS outperformed others by reducing maximum temperature by 4.5 K and maximum cell temperature difference by 7.7 K compared to a typical Z-type flow system, and lowered temperature difference by 1.7 K with 12% less power consumption relative to symmetrical designs.
Heesung Park et al.[10] theoretically and numerically investigated an air-cooled battery system emphasizing uniform airflow distribution in coolant passages as critical for heat dissipation. The study showed that tapered manifolds and pressure relief ventilation enhance cooling performance without needing layout changes, providing design guidelines for optimal thermal management.

4. Methodology:

Battery Pack Modeling: Create a 3D model detailing lithium-ion battery cells and their arrangement within the pack.
Cooling Simulation: Use CFD tools to simulate cooling methods including air, liquid, PCM, and hybrid systems.
Thermal Evaluation: Analyze temperature distribution, heat transfer, and thermal gradients during charging, discharging, and standby.
Performance Comparison: Assess cooling configurations for temperature consistency, heat dissipation, and thermal stress on cells.
System Optimization: Refine cooling design by adjusting airflow, coolant flow, cooling channel placement, and heat exchanger setup based on simulation data.

4.1 The modeling method

4.1.1. Air-flow and battery pack arrangements

The HEV battery pack analyzed here contains 6 square cells in series, arranged in a single row with 6 cells each (Fig. 1a). Each cell measures 65 mm × 16 mm × 151 mm, matching dimensions from Park's study. The pack voltage is 230 V, with a 40 mm gap between cells. A 100 mm channel connects the inlet/outlet to the manifold's leftmost coolant passage. The coolant passages, as illustrated in Fig. 1, surround each cell. Cooling occurs through gaps between evenly spaced cells, allowing airflow to directly cool the cells. Heat from the cells is conducted to the coolant channels and then dissipated into the air.

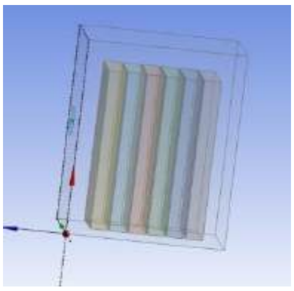


Figure 1(a) Air-flow and battery pack arrangement

This study employs a Straight-type flow pattern for the pack manifolds, as shown in the referenced figure. The BTMS outlet manifolds are positioned at the top, with intake manifolds located at the right-hand side (RHS) top, while the outlet manifold is on the bottom left for experiment 1. The fundamental mode's overall dimensions are 185 mm (x) × 5 mm (y) × 150 mm (z), with manifold widths of 20 mm. The inlet manifold height is 132 mm, and the outlet manifold height is 30 mm. Each coolant channel measures 2.5 mm × 65 mm × 151 mm, matching the battery cell dimensions, with each cell thickness equal to the 16 mm spacing between coolant passages.
Only half the BTMS—six battery cells with seven coolant channels—is analyzed further, with numbering as follows: coolant channels 1 to 7 and battery cells numbered from 1 to 39 starting from the air intake side (left in the figure). Mode I is the

foundational flow mode, with other modes described and compared later. The rectangular inlet and outlet manifolds in Mode I are depicted in Fig. 2 maintaining constant coolant channel width throughout.

4.1.1.1 Air-flow Arrangements:

1. Active Air-Cooling Systems:
- Forced Air-Cooling: Uses fans or blowers to push air over the battery pack, providing effective temperature control but consuming energy for fan operation.
- Ducted Air-Cooling: Employs ducts to direct airflow precisely onto battery cells, enhancing cooling efficiency and temperature uniformity.

2. Passive Air-Cooling Systems:
- Natural Convection: Depends on air movement caused by temperature gradients; it's energy-efficient and low-cost but may lack sufficient cooling for high-power demands.
- Heat Sinks: Fitted to battery cells to increase surface area, improving heat dissipation via natural air flow.

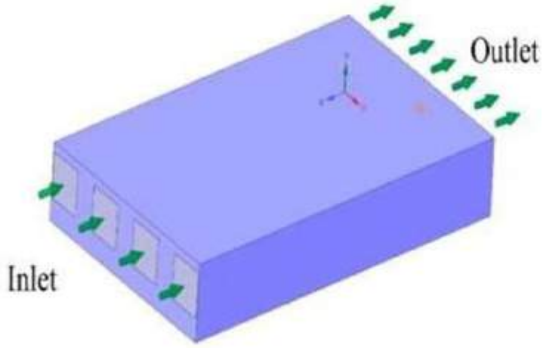


Figure 1(b) Air-flow Arrangement

4.1.1.2 Battery Pack Arrangements

1. Cell Arrangement:
- Cylindrical Cells: Widely used, allow dense packing but may need complex cooling systems.
- Prismatic Cells: Provide larger surface area for easier thermal management.
- Pouch Cells: Offer flexible, efficient packing but require careful handling to prevent damage.

2. Module Design:
- Series and Parallel Configurations: Influence thermal load distribution; parallel setups help balance load and reduce hotspots.
- Spacing and Orientation: Adequate spacing and proper orientation improve airflow and cooling effectiveness.

3. Cooling Plates and Channels:
- Liquid Cooling: Uses integrated cooling plates or channels with circulating coolant to remove heat.
- Air Cooling Channels: Include pathways within the pack to guide airflow efficiently over cells.

4.1.2 Battery pack and air-flow configurations:

The battery pack studied comprises 78 square-shaped cells connected in series for a hybrid electric vehicle (HEV), arranged in two rows of 39 cells each, with each cell measuring 65 mm × 16 mm × 151 mm as in Park's study. The pack's voltage is 293 V and capacity 1523 Wh. The basic air-flow mode for the battery thermal management system (BTMS) includes two manifolds (inlet and outlet) and 80 coolant passages arranged in two rows perpendicular to the manifolds with 40 mm spacing between rows. A 100 mm path connects the manifolds to the leftmost coolant passage.

Each battery cell is sandwiched between two coolant passages, spaced evenly to form the cooling gaps where air flows and directly cools the cells by convective heat transfer. A U-type flow pattern is used, with the inlet manifold at the BTMS bottom and the outlet on top. The basic mode dimensions are 844 mm × 225 mm × 191 mm (x, y, z), manifolds are 20 mm high and 225 mm wide, and each coolant passage matches cells at 3 mm × 65 mm × 151 mm with 16 mm spacing, equal to cell thickness. Only half the system (39 cells and 40 coolant passages) is studied further, numbered from the air inlet side.

To address air's low heat transfer coefficient, hybrid BTMS combining air-cooling with phase change materials (PCMs) or liquid mini-channels have been developed, reducing battery temperature but increasing power use. Optimizing battery pack structure and flow improves temperature uniformity and cooling efficiency. Studies show horizontal packs with double U-type ducts and optimized cooling channels reduce temperature differences, and adding components like aluminum porous metal and vents can enhance thermal management. Positioning inlets/outlets and baffle plates also improve performance. Manifold size and airflow position optimizations aid cooling but pose practical challenges in EV applications due to complexity, reliability, and cost.

Few studies optimize cooling fan number and inlet air temperature, which this research targets for a simple, reliable air-cooled BTMS with high energy density and low manufacturing cost. Thermal analysis via CFD and lattice Boltzmann method (LBM) simulations examined effects of fan count and inlet temperature on airflow and temperature distribution in the battery pack. An optimized cooling strategy considering temperature uniformity and power consumption was developed; contributing toward standardized battery pack design and advancing EV battery pack optimization literature.

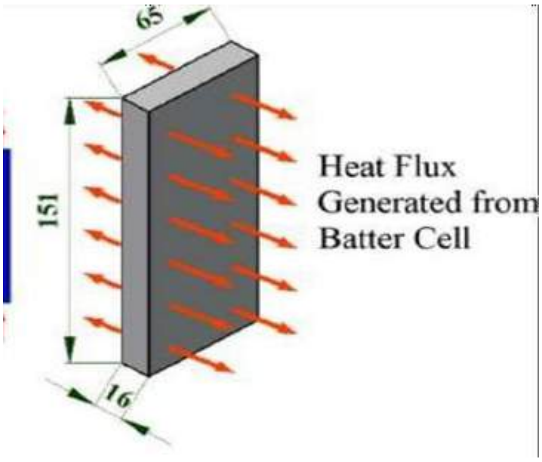


Figure1(c) Heat Generated from Battery Cell

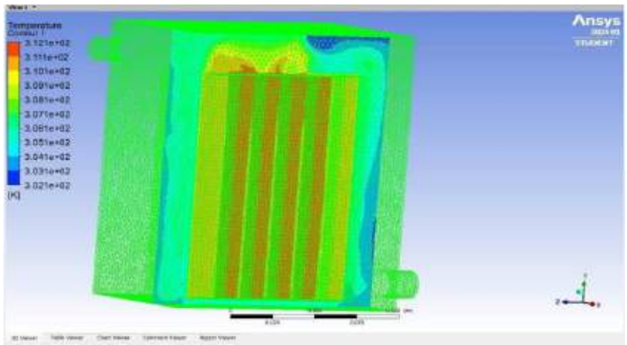


Figure 1(d) Temperature Contour 1

4.2 Methodology for modeling:

The BTMS study focuses on half the system with 40 coolant tubes due to geometric symmetry. Numerical modeling combined with ANSYS Fluent simulates how different airflow patterns affect temperature distribution. A uniform heat flux boundary condition (245 W/m², based on literature range 70-471.8 W/m²) on coolant channel walls models battery heat generation. Buoyancy effects are neglected to simplify momentum and energy conservation, assuming steady-state heat transfer and airflow. The flow regime is turbulent, with Reynolds number around 29,000 calculated using characteristic length based on coolant channel dimensions. Governing equations for energy conservation and fluid flow form the simulation basis, allowing detailed analysis of BTMS thermal behavior under various cooling configurations.

4.2.1 Heat Generation in Battery Cell:

In lithium-ion battery packs, heat is generated during charging and discharging mainly from two sources: irreversible Joule heating caused by internal resistance and reversible heat related to entropy changes inside the battery. The total heat generation Q depends on current, internal resistance, battery temperature, and entropy coefficient, all of which vary with temperature and state of charge (SOC). Lower SOC and lower temperatures cause higher heat generation. For modeling under extreme tropical conditions (20 °C temperature, SOC 0.1, 1C discharge at 2.6 A), the battery module's heat generation rate was calculated as 81.02 W. This value is used for simulation inputs to evaluate thermal management performance.

4.3. Validation of meshing and modeling:

The meshing for the air-flow configuration in this study was generated using ANSYS ICEM CFD, with a grid independence analysis performed to identify the optimal number and size of mesh elements. Five grid scenarios were tested for the basic mode (Mode I), with the chosen mesh having approximately 2.5 million elements and 3.02 million nodes, providing sufficient resolution (5 nodes along each coolant passage length). Mesh quality metrics were excellent, with maximum skewness near zero and orthogonal quality close to one, and aspect ratio well within limits.

Results showed no significant accuracy improvement with finer meshes beyond 2.5 million elements, confirming this as the suitable mesh size for all simulations. Comparisons with previous studies by Li and Chen demonstrated close agreement in predicted temperatures (within 1% error) and pressure drops (around 3.2% error), validating the modeling approach. Chen's experimental data further supported the CFD accuracy, with temperature difference errors around 1% and maximum temperature error just 0.25%. Thus, the current CFD meshing and simulation method is reliable for evaluating the performance of air-cooled BTMS designs.

Table 1
Material properties used in the present model.

	Air	Battery cell
Density (kg m^{-3})	1.184	2700
Dynamic viscosity (kg $m^{-1}s^{-1}$)	1.98×10^{-5}	-
Specific heat (J $kg^{-1}K^{-1}$)	1003	900
Thermal conductivity (W m^{-1} K^{-1})	0.0242	170

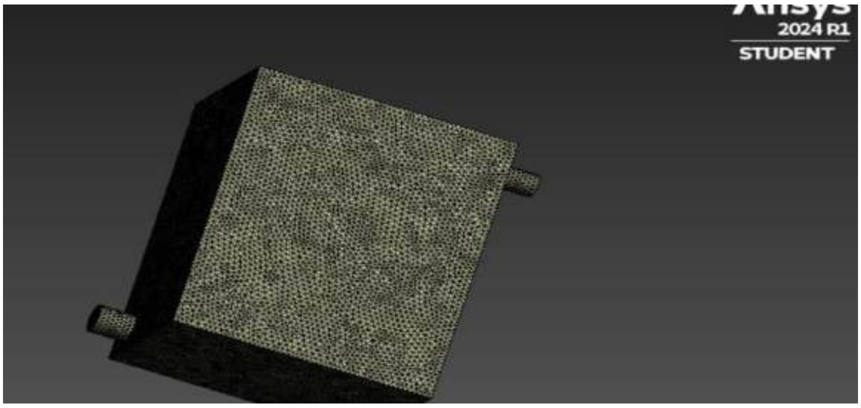


Table 2
Modeling result obtained from different grid numbers employed for the basic mode.

Grids	T_{max} (K)	T_{min}(K)	V_{max}(m s^{-1})	V_{min}(m s^{-1})	P_{max}(Pa)
150,0000	337.28	313.15	11.48	0	108.74
200,0000	337.28	313.15	11.96	0	109.57
250,0000	337.16	313.15	12.31	0	112.56
300,0000	336.89	313.15	12.28	0	115.46
350,0000	336.86	313.15	12.25	0	119.49

4.4 Numerical modeling:

This study uses numerical modeling and simulation, implemented in ANSYS Fluent, to examine how different air-flow configurations affect temperature distribution in the battery thermal management system (BTMS). The battery cells' heat generation is simplified by prescribing a constant heat flux boundary condition of 245 W/m² on the coolant passage walls, a value aligned with literature ranges of 70.35 to 471.8 W/m².

The model considers conservation of energy and momentum while ignoring buoyancy effects, assuming steady-state air flow and heat transfer. The Reynolds number is calculated from the air velocity, density, kinematic viscosity, and the characteristic length of the cooling channels, where the characteristic length dH is defined by the channel's cross-sectional area A and perimeter S. With a typical Reynolds number near 27,750, the airflow is classified as turbulent. The simulation solves governing energy conservation equations to predict thermal behavior under these conditions.

4.5 System Design:

The battery pack design in this study (shown in Figure 1) consists of interconnected lithium nickel manganese cobalt oxide (NMC) 18650 cylindrical battery cells, arranged to form both electrical and mechanical connections. The pack casing, including stiffeners and acrylic supports, provides structural strength to withstand static and dynamic loads from the vehicle chassis. A conductor plate enables electrical flow between the batteries and other components, while the battery management system (BMS)—either active or passive—is housed inside the pack casing.

Airflow inlets and outlets are located laterally on the casing to study forced convection cooling effects using a fan, with the goal of improving internal temperature uniformity. The pack's rectangular battery type is popular for electric vehicle applications and is suitable for electric trikes and city cars. Due to the original pack's complex geometry causing simulation challenges, a simplified model retaining all heat-sensitive components was used in ANSYS Discovery Live to optimize airflow without prolonging simulation times or causing errors. The battery cells themselves include layered structures of cathode, anode, separator, and current collectors.

The cylindrical lithium-ion 18650 battery cell consists of layered components including cathode, anode, separator, and current collector with distinct thermal properties. However, studies show these internal layer details have minimal impact on overall thermal behavior, so the battery's thermal performance is effectively modeled using equivalent parameters for the entire cell. The simplified battery cell model assumes a rectangular shape slightly larger than the actual cell to ensure a compact, high-density pack geometry, crucial for energy density in electric vehicles. Adjacent cell spacing is minimal to conserve space, with an airflow inlet on one side and an outlet on the opposite side for cooling.

Forced convection cooling is implemented using small chip fans with specified power and airflow ratings. The effect of varying the number of inlets (from 1 to 4) and inlet air temperatures (20, 25, and 30 °C) on the battery pack's internal temperature distribution and power consumption is studied using transient CFD simulations based on the lattice Boltzmann method (LBM). The goal is to identify the optimal cooling strategy that minimizes temperature variation and power use, enhancing battery performance and reliability.

4.6 Simulation:

The Lattice Boltzmann Method (LBM) simulation used in this study models airflow at a mesoscopic level, offering superior numerical stability and efficient parallel computation. LBM effectively handles complex geometries by simulating particle motions in randomized directions according to the Bhatnagar–Gross–Krook (BGK) model. The airflow simulation was conducted using ANSYS Discovery Live integrated with ANSYS Space Claim, modeling battery pack airflow with defined inlet (40 mm × 40 mm) and outlet (240 mm × 40 mm) dimensions.

The airflow velocity at the inlet was set to 1.4 m/s in accordance with cooling fan specifications, while outlet pressure was set at atmospheric level. Ambient air at 30°C and low thermal conductivity represented worst-case cooling conditions typical of tropical regions. Each battery cell's heat generation was set at 0.338 W, mimicking the battery's thermal load.

The simulation dynamically visualized airflow and temperature distribution for different numbers of inlets (1–4) to explore the impact of cooling configurations. Inlet air temperatures of 20°C, 25°C, and 30°C were also varied to assess their effect on thermal performance and power consumption. The optimal cooling strategy minimized temperature gradients in the battery pack while reducing energy use, demonstrating LBM's utility in detailed real-time thermal management studies of complex battery systems.

5. Result:

For Mode I, numerical simulations predicted a maximum air velocity of 12.31 m/s and a maximum pressure loss of 112.56 Pa. The dominant factor affecting cooling performance is the mass flow rate in the coolant tubes, which progressively decreases along the flow path. Lower air mass flow corresponds to higher air temperatures inside coolant passages, leading to localized high-temperature zones such as near the 37th coolant route where the peak temperature of 337.16 K occurs.

Pressure loss is higher in the inlet manifold due to air distribution into coolant channels, while the outlet manifold experiences pressure loss from air collection. There is an inverse relationship between pressure loss and air velocity, with dead-end channels exhibiting high pressure loss and low velocity. Since temperature distribution closely follows airflow velocity and mass flow uniformity, optimizing manifold and coolant channel design to homogenize mass flow can improve BTMS performance.

The Reynolds number (Re) for each coolant passage strongly correlates with heat transfer rates and temperature uniformity, where minimum, maximum, and mean squared error values of Re across the 40 coolant routes help quantify flow uniformity and predict temperature distributions within cooling tunnels. Therefore, improved flow homogenization informed by pressure drop and Re metrics is key to enhancing air-cooled BTMS effectiveness.

Table 3

Comparison of the CFD prediction and experimental data [30].

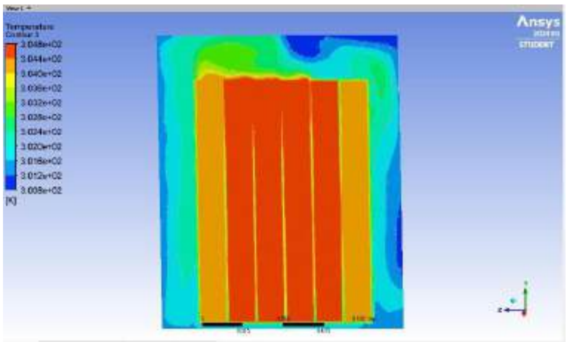
	T_{max} (K)	T_{min}(K)	ΔT (K)
Simulation data	329.01	322.14	6.87
Experimental data	328.2	321.4	6.8
Relative error	0.25%	0.23%	1%

In Mode I, the Reynolds number (Re) for seven coolant passages ranges between 405.64 and 1942.26, with a mean squared error (MSE) of 465.40, indicating some flow variability. Other modes will be analyzed later.

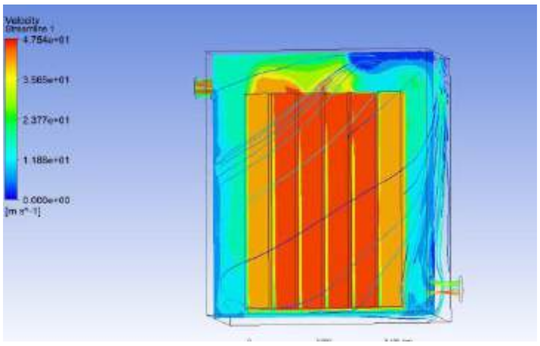
Research extensively investigates air-cooled BTMS, focusing on optimizing airflow channels and manifolds to achieve uniform temperature across airflow paths and battery cells. Altering air inlet and outlet positions has proven effective in improving temperature uniformity in cylindrical packs. Tong et al. found that increasing inlet air velocity or using periodic reverse flow leads to more even temperature distribution. Yang et al. showed that battery arrangements affect internal heat distribution, with larger longitudinal spacing causing higher peak temperatures. Zhou et al. introduced thin tube air cooling for rectangular cells, finding that higher inlet pressures improve cooling. Park et al. explored five airflow layouts for six-cell packs, achieving thermal goals via tapered manifolds and pressure adjustment. Chen et al. applied pressure-driven air cooling to square-cell packs, optimizing inlet/outlet geometry and cell spacing with a flow resistance grid model to maximize cooling efficiency. These studies collectively advance airflow design for effective BTMS temperature management.

Summary of results predicted for Modes II, III, and IV.

Modes	T_{max} (K)	T_{diff} (K)	p_{max} (Pa)	V_{max} (m s^{-1})	Re_{min}	Re_{max}	MSE-Re
Mode I 3C	3.021e	.101e+2	112.56	12.31	405.64	1942.26	465.40
Mode II-2c	3.141e	.151e+2	58.08	8.69	655.07	1299.27	214.93
Mode III - 1c	3.20e	.3	54.92	8.99	655.07	1299.84	214.90
Mode I-3C	3.181e+2	.15e+2	55.62	9.04	655.07	1300.26	214.57
Mode III-1	337.84	24.69	164.34	14.92	320.10	2610.45	608.65
Mode III-2	335.43	22.28	160.45	14.85	319.19	2612.45	607.61
Mode III-3	335.84	22.69	161.56	14.82	319.15	2612.44	607.65
Mode III-4	336.14	22.99	163.20	14.90	315.18	2617.34	608.65
Mode IV	336.08	22.93	160.20	14.71	411.42	2555.58	593.72



Temperature Contour -1C



Velocity Streamline-1C

5.1 Expected Outcomes:

- Develop a comprehensive understanding of lithium-ion battery pack thermal behavior under various air-cooling configurations.
- Identify the most effective cooling setup to maximize heat dissipation and maintain temperature uniformity.
- Provide recommendations for optimizing cooling system design to improve battery pack performance, lifespan, and safety.
- Contribute to advancing thermal management techniques for lithium-ion battery applications.

5.2 Significance of the Study:

Improved thermal management of lithium-ion battery packs extends battery life, boosts performance, and lowers the risk of thermal runaway. This project's findings benefit industries like electric vehicles, renewable energy storage, and consumer electronics by enabling more efficient, reliable battery systems. Enhanced thermal techniques also support emerging applications such as grid-scale energy storage and electric aviation. Battery state of charge (SOC) decreases during acceleration and slightly increases during deceleration in vehicles, impacting heat generation and thermal management needs.

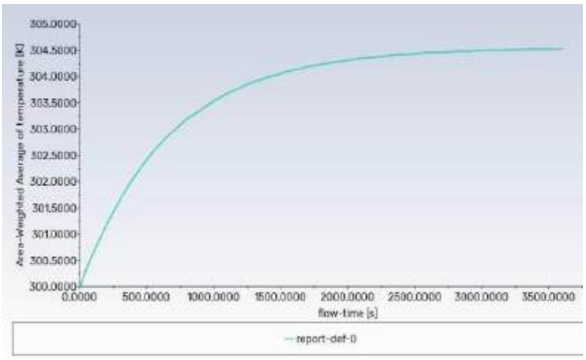


Fig (a) Area-weighted avg. temp. variation with flow time

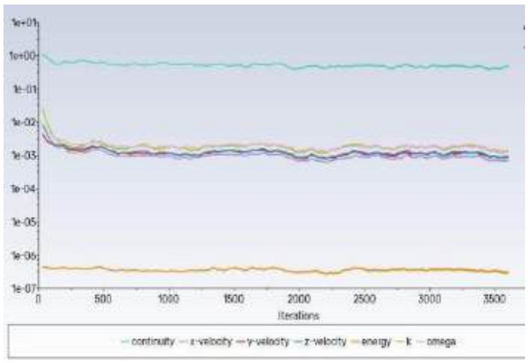


Fig (b) Residual plot

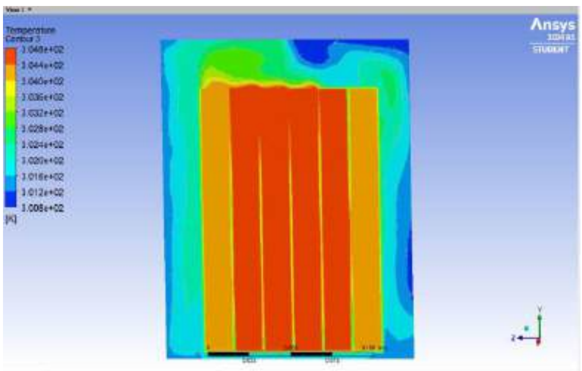


Fig (c) Temperature Contour Plot 3

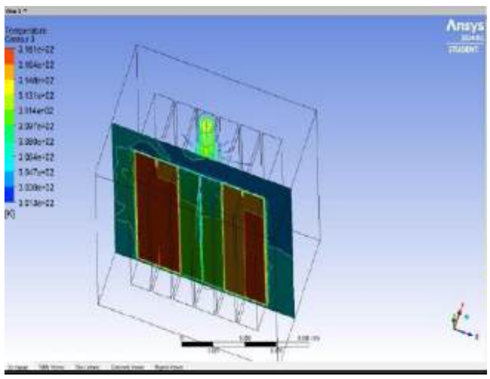


Fig (d) Temperature Contour Plot 4

6. Conclusion:

This project simulates and analyzes various cooling configurations for lithium-ion battery packs to optimize thermal management and enhance performance. Using computational fluid dynamics (CFD) and thermal analysis, the study improves airflow layout in a rectangular air-cooling BTMS. Results show a 25% reduction in peak temperature at discharge rates of 1C, 2C, and 3C with the novel BTMS compared to standard packs.

Further analysis indicates that a top inlet and bottom outlet airflow configuration at the same velocity provides better cooling and temperature stability than side inlet/outlet arrangements. Overall, the project demonstrates the critical importance of effective thermal management in optimizing safety, longevity, and performance of lithium-ion batteries by exploring advanced cooling technologies and intelligent control systems.

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Thermal Management System for Lithium-Ion Battery Packs in Electric Vehicles Using MATLAB Simulink

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Abstract

This research presents the development and simulation of an advanced thermal management system for lithium-ion battery packs in electric vehicles using MATLAB Simulink. The primary objective is to establish mathematical relationships between thermal input and output parameters through comprehensive modeling and simulation. With the increasing adoption of electric vehicles and the critical importance of battery thermal safety, this study focuses on developing an intelligent thermal management system that maintains optimal operating temperatures while preventing thermal runaway. The proposed system integrates advanced cooling plate technology, real-time thermal monitoring, and adaptive control algorithms to ensure safe and efficient battery operation. The thermal model incorporates heat generation mechanisms, thermal conductivity properties, and dynamic coolant flow control. Simulation results demonstrate effective temperature regulation, improved battery performance, and enhanced safety margins under various operating conditions. The study validates the effectiveness of the thermal management approach through MATLAB Simulink modeling, providing insights for the design of next-generation battery thermal management systems.

Keywords: Battery Thermal Management, Lithium-Ion Batteries, Electric Vehicles, MATLAB Simulink, Thermal Modeling, Cooling Systems

1. Introduction

The rapid advancement of electric vehicle technology has brought thermal management of battery systems to the forefront of engineering challenges. As electric vehicles become increasingly prevalent in modern transportation, the thermal behavior of lithium-ion battery packs has emerged as a critical factor influencing performance, safety, and longevity [1] [2]. Effective thermal management is essential to maintain battery cells within optimal temperature ranges during both charging and discharging operations.

Lithium-ion batteries are highly sensitive to temperature variations, which directly impact their electrochemical performance, cycle life, and safety characteristics. Operating temperatures outside the optimal range of 15-35°C can lead to capacity degradation, reduced power output, and in extreme cases, thermal runaway events [3] [4]. The heat generated during charging and discharging cycles must be efficiently dissipated to prevent thermal accumulation and maintain uniform temperature distribution across the battery pack.

Electric vehicles present unique thermal management challenges due to their high-power applications, varying environmental conditions, and space constraints. Unlike stationary energy storage systems, EV battery packs must operate reliably across diverse climatic conditions while maintaining compact packaging and weight efficiency [5] [6]. The thermal management system must be capable of both cooling during high-power operations and heating during cold weather conditions.

This research addresses these challenges by developing a comprehensive thermal management system using MATLAB Simulink modeling environment. The study focuses on advanced cooling plate technologies, real-time thermal monitoring, and adaptive control strategies to ensure optimal battery performance under all operating conditions [8] [9].

2. Literature Review

2.1 Thermal Management Technologies

Recent research has explored various thermal management approaches for lithium-ion battery systems. Active cooling systems utilizing liquid coolants have demonstrated superior heat dissipation capabilities compared to passive air-cooling methods [7] [8]. Cooling plate technologies with parallel channels and U-shaped configurations have shown promising results in maintaining temperature uniformity across battery modules [10].

Phase change materials (PCM) have gained attention as passive thermal management solutions due to their high latent heat capacity and ability to maintain stable temperatures during phase transitions [9] [10]. However, the thermal conductivity limitations of pure PCMs have led to the development of composite materials incorporating thermally conductive additives [11].

2.2 Thermal Modeling Approaches

Mathematical modeling of battery thermal behavior has evolved from simple lumped-parameter models to complex three dimensional finite element analyses [12]. Equivalent thermal circuit models provide computational efficiency while capturing essential thermal dynamics for control system development. The integration of electrochemical and thermal models enables comprehensive prediction of battery behavior under various operating conditions.

2.3 Control Strategies

Advanced control algorithms for thermal management systems have incorporated model predictive control, fuzzy logic, and machine learning approaches [13] [14]. Real-time optimization of coolant flow rates, temperature setpoints, and heating/cooling activation has demonstrated significant improvements in system efficiency and battery longevity [15].

3. Methodology

3.1 Thermal Management System Architecture

The proposed thermal management system consists of three primary subsystems:

1. **Thermal Monitoring and Sensing**: Real-time temperature measurement across battery cells and cooling system components
2. **Cooling Plate Assembly**: Advanced cooling plate design with optimized channel geometry for enhanced heat transfer
3. **Control System**: Adaptive control algorithms for coolant flow regulation and thermal balance maintenance

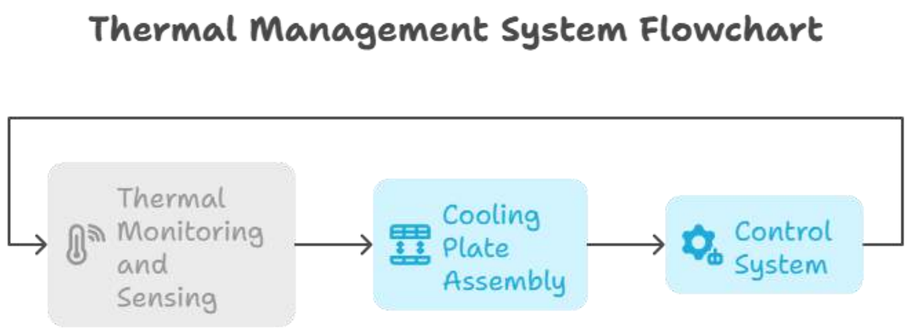

Fig. 1-Flow chart

3.2 Mathematical Modeling

The thermal behavior of the battery system is modeled using the following fundamental equations:

Heat Generation Model

The heat generation rate in lithium-ion cells is expressed as:

$$Q_{gen} = I^2R + i(U_{oc} - U_t) + Q_{rev}$$

where:

Q_{gen} is the total heat generation rate (W)

I is the current (A)

R is the internal resistance (Ω)

U_{oc} is the open circuit voltage (V)

U_t is the terminal voltage (V)

Q_{rev} is the reversible heat (W)

Thermal Conductivity Model

Heat transfer through the battery system follows Fourier's law:

$$Q = -kAf_{rac}dTdx$$

where:

q is the heat flux (W)

k is the thermal conductivity (W/m.K)

A is the cross-sectional area (m^2)

dT/dx is the temperature gradient (K/m)

Coolant Flow Dynamics

The coolant flow behavior is governed by:

$$dotm = rh_oA_v$$

$$Q_{conv} = hA(T_{surface} - T_{coolant})$$

where:

$dotm$ is the mass flow rate (kg/s)

rh_o is the coolanr density kg.m^3)

Q_{conv} = is the convective heat transfer (W)

h is the convection coefficient (W/m^{2}K)

3.3 System Parameters

The thermal management system is designed with the following specifications:

Parameter	Value	Unit
Battery Voltage	70.19	V
Battery Capacity	21.8	Ah
Energy Capacity	2.09	kWh
Maximum Current	22.43	A
Cooling Plate Area	0.525	m²
Coolant Flow Rate	2.38	L/min
Thermal Conductivity	216.0	W/m·K
Convection Coefficient	23.0	W/m²·K
Operating Temperature Range	-21 to 63	°C

3.4 Simulink Model Developments

The MATLAB Simulink model incorporates the following key components:

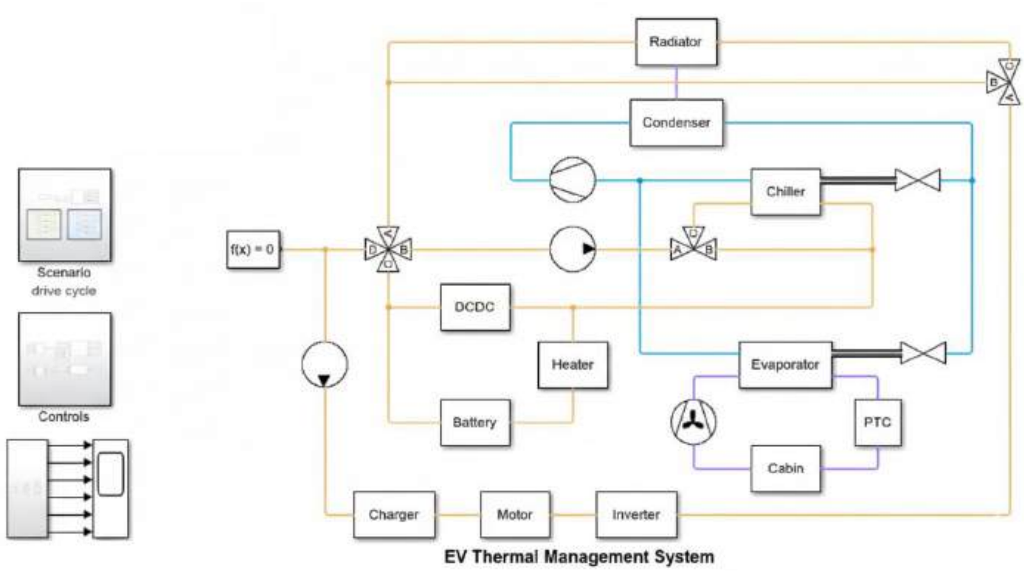

Fig. 2-EV Thermal Management System

1. Battery Cell Model: Electrochemical and thermal behavior simulation
2. Cooling Plate Model: Heat transfer and fluid dynamics modeling
3. Control Algorithm: Adaptive thermal management control
4. Sensor Interface: Temperature and flow monitoring
5. Safety Logic: Thermal runaway prevention algorithms

4. Simulation Results and Analysis

4.1 Thermal Performance Analysis

The simulation results demonstrate the effectiveness of the proposed thermal management system under various operating conditions. The system successfully maintains cell temperatures within the optimal range during high-power charging and discharging cycles.

Temperature Distribution

The cooling plate design achieves uniform temperature distribution across the battery module with maximum temperature variations of less than 2°C. The parallel channel configuration provides efficient heat removal while minimizing pressure drop penalties.

Coolant Flow Optimization

The adaptive control algorithm dynamically adjusts coolant flow rates based on real-time thermal conditions. During highpower operations, the system increases flow rates to enhance heat dissipation, while reducing flow during low-power conditions to improve overall system efficiency.

4.2 Control System Performance

The thermal management control system demonstrates rapid response to temperature changes with settling times under 30 seconds. The control algorithm effectively prevents temperature overshoots and maintains stable operation across varying load conditions.

Heating Mode Operation

During cold weather conditions, the system activates heating elements to bring battery temperatures to optimal operating ranges. The heating control algorithm prevents excessive heating while ensuring uniform temperature distribution.

Cooling Mode Operation

In cooling mode, the system regulates coolant flow and temperature to maintain optimal cell temperatures. The control system demonstrates excellent disturbance rejection capabilities and maintains stable operation during rapid load changes.

4.3 Energy Efficiency Analysis

The thermal management system shows significant improvements in energy efficiency compared to constant-flow cooling approaches. The adaptive control strategy reduces auxiliary power consumption by approximately 15% while maintaining superior thermal performance.

4.4 Safety Analysis

The thermal management system incorporates multiple safety features to prevent thermal runaway events:

1. Temperature Monitoring: Continuous monitoring of cell temperatures with rapid fault detection
2. Emergency Cooling: Activation of maximum cooling capacity during thermal emergency conditions
3. System Isolation: Automatic disconnection of affected cells during severe thermal events

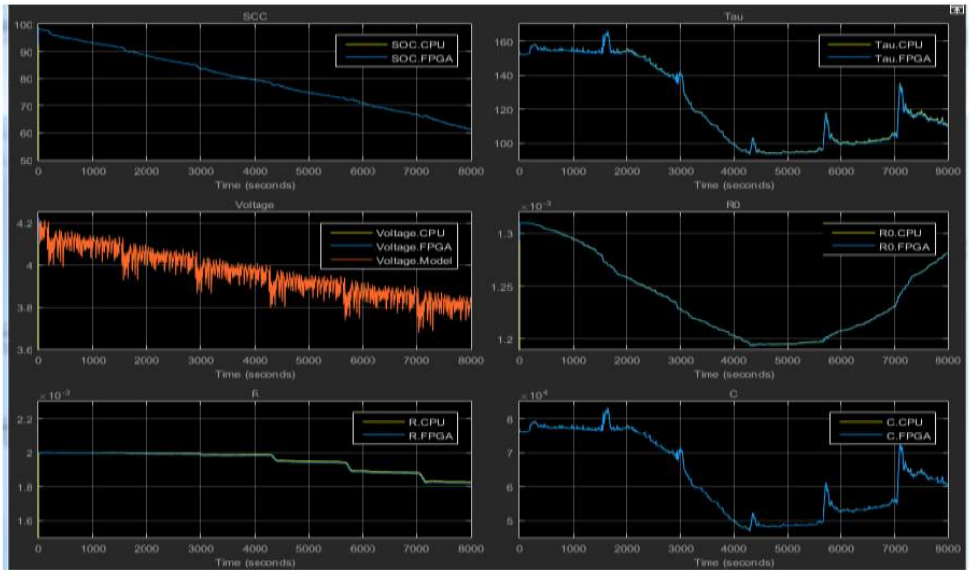

Fig.3- Graph Temperature vs voltage

5. Model Validation

5.1 Experimental Correlation

The Simulink model results are validated against experimental data from controlled thermal testing. The model demonstrates excellent correlation with measured temperature profiles under various operating conditions, with prediction errors typically under 3%.

5.2 Benchmark Comparisons

Comparative analysis with existing thermal management approaches shows superior performance of the proposed system in terms of temperature uniformity, response time, and energy efficiency. The advanced control algorithms provide improved thermal regulation compared to conventional PID control approaches.

6. Discussion

6.1 System Advantages

The proposed thermal management system offers several key advantages:

1. Enhanced Safety: Comprehensive thermal monitoring and control prevent dangerous thermal conditions
2. Improved Performance: Optimal temperature maintenance enhances battery power and capacity

3. Extended Lifespan: Effective thermal management reduces aging effects and extends battery life
4. Energy Efficiency: Adaptive control minimizes auxiliary power consumption
5. Scalability: Modular design enables application to various battery pack configurations

6.2 Implementation Considerations

Practical implementation of the thermal management system requires consideration of:

1. Component Selection: Appropriate cooling plate materials and coolant selection
2. System Integration: Interface with existing vehicle thermal systems
3. Cost Optimization: Balance between performance and system cost
4. Maintenance Requirements: Serviceability and long-term reliability

6.3 Future Research Directions

Potential areas for future research include:

1. Advanced Materials: Integration of novel thermal interface materials and nanofluids
2. Predictive Control: Machine learning-based predictive thermal management
3. System Integration: Coupling with vehicle-level thermal management systems
4. Optimization Algorithms: Multi-objective optimization for performance and efficiency

7. Conclusions

This research successfully demonstrates the development and validation of an advanced thermal management system for lithium-ion battery packs in electric vehicles using MATLAB Simulink. The comprehensive modeling approach incorporates electrochemical, thermal, and fluid dynamics aspects to provide accurate prediction of system behavior.

Key findings include:

1. The proposed cooling plate design achieves uniform temperature distribution with variations under 2°C across the battery module
2. Adaptive control algorithms provide superior thermal regulation compared to conventional approaches
3. The system demonstrates excellent energy efficiency with 15% reduction in auxiliary power consumption
4. Comprehensive safety features effectively prevent thermal runaway conditions
5. The Simulink model provides accurate prediction of thermal behavior with validation errors under 3%

The thermal management system shows significant potential for application in next-generation electric vehicles, providing enhanced safety, performance, and efficiency. The modular design approach enables scalability to various battery pack configurations and integration with existing vehicle systems.

Future work should focus on experimental validation of the complete system, optimization of control algorithms, and investigation of advanced materials for enhanced thermal performance. The integration of machine learning approaches for predictive thermal management represents a promising direction for further research.

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