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GKU JOURNAL OF MULTIDISCIPLINARY RESEARCH

Volume - II, Issue - I, April - 2026, ISSN: 3049-298X

Peer - Reviewed Journal



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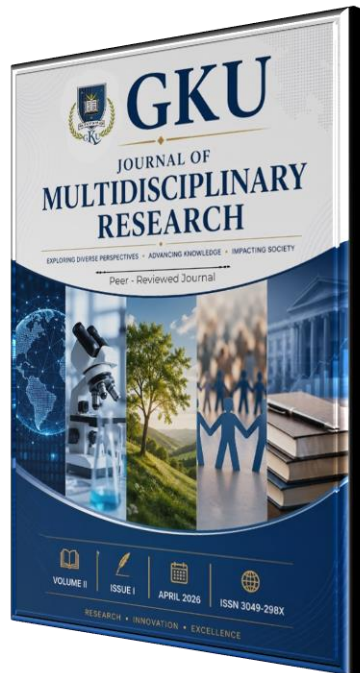
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The aim of the GKU Journal is to promote high-quality, original research and scholarly work across diverse academic disciplines, with a focus on advancing knowledge, fostering innovation, and supporting the academic and professional growth of researchers, educators, and students.



SCOPE

Scope of GKU Journal of Multidisciplinary Research

The scope of the journal includes interdisciplinary research in fields such as Science, Technology, Engineering, Management, Humanities, Social Sciences, and Education. It welcomes theoretical and applied studies, case studies, review articles, and technical reports. The journal encourages contributions that address contemporary challenges, propose innovative solutions, and reflect a commitment to academic integrity and societal impact.

By providing an open and inclusive platform, the GKU Journal aims to facilitate academic dialogue, strengthen industry-academia linkages, and contribute to national and global research communities.

Chancellor Message

It is with immense pride that I introduce the latest edition of the Guru Kashi University Journal of Multidisciplinary Research. This journal represents the continued mission of our university to nurture scholarly achievement and interdisciplinary inquiry. In this regard, as a cross-disciplinary academic platform, it is designed to link different areas of knowledge addressing the disparate issues facing our world today.



I warmly congratulate all contributors whose work and commitment to research and scholarship are reflected in this journal. Their strong commitment and collaboration, as well as that of the editorial board and reviewers, contribute to maintaining this journal at high standards.

At Guru Kashi University, we believe in promoting curiosity that transcends the boundaries of faculties, and this journal is a testament to that belief. It will continue to inspire future scholars and researchers to stretch, create, and read work that is part of an essential scholarly conversation.

S. Gurlabh Singh Sidhu
Honourable Chancellor

Vice Chancellor Message

It gives me great pleasure to present the inaugural issue of the GKU Journal of Multidisciplinary Research. This journal is an important step in Guru Kashi University's mission to promote academic excellence, innovation, and meaningful research.

In a world where boundaries between disciplines are steadily dissolving, true progress lies in multidisciplinary inquiry. This journal is designed as a peer-reviewed platform for scholars, researchers, and practitioners to share original ideas and solutions that address contemporary challenges.



I congratulate the editorial team, contributors, and reviewers whose dedication has made this first issue possible. I am confident the GKU Journal of Multidisciplinary Research will soon grow into a respected forum for knowledge creation and collaboration, reflecting our motto of "Empowering Youth, Empowering India."

Prof. (Dr.) Jagtar Singh Dhiman
Esteemed Vice Chancellor

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A Structured Review of AI-Assisted Requirements Engineering: Capabilities, Limitations, and Research Gaps

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Accepted: 10.04.2026

Published: 30.04.2026

Page No. 06 – 16

DOI: 10.5281/zenodo.19882923

Abstract

The software industry considers that Large Language Models (LLMs) will soon automate the core tasks of Requirements Engineering (RE). Current literature proves this assumption is premature. This paper reviews 25 recent studies to document exactly what AI can and cannot do during the software specification phase. Current studies split the engineering workflow into elicitation, analysis, generation, and traceability. The reviewed data suggests that AI is highly effective at basic pattern recognition and drafting initial text. This literature shows that these same tools consistently fail when processing ambiguous stakeholder language, lose project context during extended interactions, and frequently hallucinate invalid system requirements. The evidence we discovered shows that AI currently functions strictly as a supplementary tool in RE, not an autonomous replacement for human engineers. The paper concludes that future research must prioritize human-in-the-loop validation frameworks rather than focusing purely on automation.

Keywords: Requirements Engineering; Artificial Intelligence; Large Language Models; Software Specification; AI Hallucination; Automation.

1. Introduction:

Requirements Engineering (RE) is about the structural and functional specifications for software development. Tech companies built AI and large language models specifically to automate the tedious parts of software specification. These models are used by engineers today in the software

development life cycle (Hou et al, 2024). They're using natural language processing to detect ambiguity and machine learning to get requirements from customers.

Industry predictions aren't measured performance. AI can't read between the lines. Hybrid machine learning approaches will be required to handle this (Izhar et al, 2015). LLMs forget the architecture and invent impossible system requirements after extensive dialogues. The hallucination is always mentioned in the evaluation of LLMs (Hu et al., 2026).

A recent study assesses the performance of AI for elicitation, analysis, generation, and traceability. Elicitation models recognise functional features in stakeholder data. Analysis models categorise non-functional requirements. Structural inconsistencies are detected. Generative algorithms generate initial user stories (often using training data sets (Yamani et al., 2025)). Traceability algorithms re-establish links between the code and the requirements.

The review assesses the empirical results and inherent weaknesses of AI-based RE. Large language models (LLMs) are incapable of substituting human engineers (Edwards et al., 2025). The importance of hybrid intelligence to maintain human control is stressed (Sterling & Oliveira, 2026). The following sections quantify the errors of the AI specification, and the factors that need to be verified by a human-in-the-loop. Research Objectives and Questions:

Current industry expectations regarding automated software specification often ignore operational realities. This review separates proven

utility from theoretical hype. We want to find out what these algorithms get right in the field. The review also maps exactly how the tools fail and points out the massive gaps still left in current software specification research.

The analysis targets three core questions:

RQ1: What specific tasks can AI and LLMs reliably execute across Elicitation, Analysis, Generation, and Traceability?

RQ2: Under what exact conditions do these automated tools fail, lose project context, or hallucinate system requirements?

RQ3: Which validation frameworks are currently missing to support practical human-AI collaboration in the field?

2. Methodology:

This review follows a simplified PRISMA approach for literature selection.

2.1. Search Strategy The search was conducted across Google Scholar and IEEE Xplore. The search string: ("Requirements Engineering" OR "Software Specification") AND ("Artificial Intelligence" OR "Large Language Models" OR "Machine Learning").

2.2. Our search focuses on papers from 2019-2026 that address the use of AI for requirements. We have excluded non-peer-reviewed preprints. we have not included the studies that were focused on other phases of software engineering, such as automatic testing or code generation.

2.3. Selection Process The initial database search found 58 potential papers; only English based literature was considered. Screening the titles and abstracts removed 21 irrelevant articles. We then read the full text of the remaining 37 papers. Twelve were dropped because they lacked clear empirical data or reused older datasets. The final review is based on the 25 selected papers. This number was considered

sufficient to capture representative trends across AI-assisted RE applications.

2.4. Paper Classification Scheme The papers were classified according to the major contribution made to Requirements Engineering. The categories were: (1) Elicitation - studies focused on extracting requirements from stakeholders; (2) Analysis - studies that deal with requirement classification, ambiguity detection or validation; (3) Generation - studies using AI to generate requirement artifacts; and (4) Traceability - studies linking requirements through development processes. All papers were classified according to their main methodological contribution.

2.5. Data Extraction For each selected study, specific attributes were extracted. We tracked the publication year, the specific RE target area, the exact AI model used, the core contribution, and how researchers tested the tools. These attributes populated the comparative analysis table to identify patterns across the literature.

2.6. Limitations of Methodology The review is limited to selected databases and may not capture all emerging industry work or unpublished studies

Table 1 maps the technical landscape of some studies analysed in this review. We broke down each paper by its specific RE task and the type of AI algorithm deployed to solve it. This summary provides a high-level view of how researchers currently test and validate automated specification tools.

Table 1: Literature Selection Matrix

Paper	Year	Area	AI Technique	Key Contribution	Evaluation Type
Cheliger et al.	2022	Elicitation	Machine Learning	Maps ML tasks for automated requirement extraction.	Conceptual

Paper	Year	Area	AI Technique	Key Contribution	Evaluation Type
Izhar et al.	2025	Analysis	Machine Learning	Tests a hybrid model for ambiguity detection.	Experimental
Yamani et al.	2025	Generation	LLMs	Creates the UStAI dataset for drafting user stories.	Empirical
Hou et al.	2024	Generation	LLMs	Tracks LLM hallucination rates in software engineering.	Empirical
Alturayef et al.	2025	Traceability	Machine Learning	Reviews automated algorithms for traceability link recovery.	Conceptual
Sterling & Oliveira	2026	Generation	Generative AI	Argues for human-in-the-loop models to stop metacognitive offloading.	Conceptual
Luitel et al.	2024	Analysis	LLMs	Tests LLMs on finding missing requirements in specifications.	Experimental

3. Background And Related Work:

The most recent literature breaks down the use of AI in Requirements Engineering into four operational areas. Figure 1 shows this operationalization. This categorization draws out discrete machine learning abilities from the more general software development processes, and sets the stage for today's research

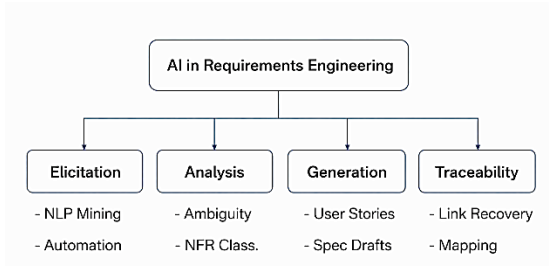


Figure 1: AI in Requirements Engineering Framework

3.1. AI for Elicitation:

Software teams start the baseline by directly extracting the constraints from stakeholders. This

raw interview data is now analysed using algorithms instead of text mining. Using machine learning, algorithms search qualitative user feedback for system features independent of human interpretation (Cheliger et al., 2022). This reduces the time in the initial data collection phase. Engineers employ such systems to convert thousands of unstructured survey responses into structured data quickly than qualitative coding (Siddeshwar et al., 2024). These speeds up time in the "time to baseline" phase. However, these systems don't record implicit variables in interactive sessions (Ahmad et al., 2024). Automation consistently fails to capture implicit cultural restrictions and other non-verbal cues that engineers instinctively note. Models fail to pick up on the intricate power dynamics of stakeholder conversations (Rosado da Cruz & Cruz, 2025). The algorithmically generated output needs significant post-processing. The algorithmically suggested lists need to be validated by domain experts, to ensure the final software specification contains important, un-documented features.

3.2. AI for Analysis:

Analysis is the time to detect structural problems. Natural language processing models audit text dumps for non-functional requirements classification and identification of natural language ambiguity. Hybrid machine learning systems are specifically designed to verify the clarity of human phrasing of millions of specifications (Izhar et al., 2025). The industry follows up automated reviews to identify conflicting constraints that human eyes can easily overlook. Text processing with algorithms reduces the time required for manual reviews (Necula et al., 2024). The new models can also scan the system architecture to ensure it's complete. Large language algorithms scan technical documents to identify missing security and logical processes (Luitel et al., 2024). Specialised techniques convert natural language constraints to

formal models in an agile setting (Umar et al., 2025). This highlighted detection avoids costly architectural redesigns. The models detect variations from industry best practices immediately. Despite this, human engineers still must check the anomaly to ensure it's a fault and not a deliberate design decision required by the client.

3.3. AI for Generation:

Generation phase expands the effort from text analysis to generating technical documents. The algorithms take the notes of the stakeholders and attempt to generate artifact such as a user story or system design. To enable this, special datasets are being prepared to train neural networks in just writing requirements (Yamani et al., 2025). This leveraging of software artifact generation is a huge trend in software engineering today (Cheng et al., 2026). The networks essentially convert well-known patterns into new application outlines. This allows engineering teams to produce standard documents on-the-fly and create early prototypes without having to wait for drafts. But the sheer velocity of this stage poses huge operational risks. Generative models suffer from a lack of domain knowledge, and often invent technical constraints (Norheim et al., 2024). Human engineers produce far better system requirements than models, in direct comparisons (Edwards et al., 2025). Neural networks invent functional dependencies as soon as they leave the protection of their training sets. To keep hallucination rates low, the literature is strongly in favour of hybrid intelligence systems (Sterling & Oliveira, 2026). The main purpose is to avoid developers' naively follow the AI blueprints, showing the generation is unsafe without human validation protocols.

3.4. AI for Traceability:

Software teams lose sight of requirements as software becomes larger. Human link analysis doesn't keep up to agile sprints. Enter the machine

learning models, able to regenerate broken links (Alturayef et al., 2025). They process code commits and tickets to re-establish the traceability. And they don't need any human help. This allows compliance for big projects. It prevents developers from spending hours searching for the function that relates to a client's request. Until that is, the documentation gets out of date. Automated tracing completely fails if the code is changed but new notes are not added. The neural networks need hybrid logic models to be accurate for this (Li et al., 2020). the code changes but the text does not, the AI can't determine what the intent was for the changes (Wang et al., 2019). It simply matches on the text. It will link a database script to a user story because it has the word "login". All these false positives mean high-level engineers must watch the AI. They must clean up the traceability matrix to avoid bad links accumulating.

4. Capabilities of AI in RE:

Software developers spend several weeks interviewing customers and surveying the market to discover what to develop. Machine learning skips this step of reading. Software snares functional requirements directly from the clutter of interview responses without having to label it with a human (Cheliger et al., 2022). This heavy-lifting makes it possible to process large volumes of stakeholder data that would exhaust a human. Emerging AI models instantly organise these user stories and establish a framework for the project (Siddeshwar et al., 2024). Even when building complex machine learning applications themselves, teams use automated elicitation tools to gather the initial design constraints (Elvira et al., 2024). The main benefit here is raw speed. Developers do not waste their first month of a project just sorting through client emails and meeting notes. The AI organizes the chaos into a structured list of features so the team can start planning the architecture.

Finding logical problems in a massive technical document is incredibly tedious work. Natural language processing tools shine here because they never get tired of reading technical jargon. These systems scan thousands of sentences to find vague words or confusing rules that human reviewers usually miss (Necula et al., 2024). Some specific NLP approaches cross-check requirements across entirely different project domains to spot structural ambiguity before any code gets written (Ferrari & Esuli, 2019). The tools also check if the project blueprint covers everything it needs to. Large language models run automated audits on the specifications to find missing security protocols or forgotten client constraints (Luitel et al., 2024). Recent machine learning models measure exactly how precise a stated requirement is against known industry standards (Izhar et al., 2025). This automated error detection is highly reliable. because of this they can figure out a bad architectural decision early in the planning phase, which saves developers from having to rewrite thousands of lines of code later.

AI does not just read documents; it writes the initial drafts for the engineering team. Large language models take the sorted client data and instantly generate standard user stories and system blueprints (Marques et al., 2024). The industry is heavily investing in this specific generative capability to speed up the software lifecycle (Cheng et al., 2026). Researchers are even building specialized datasets to train these neural networks purely on how to write better software requirements (Yamani et al., 2025). The major benefit of this generation phase is that it completely removes the blank-page problem. Developers do not have to sit down and write formal technical specifications from scratch. The AI spits out a highly structured preliminary document in seconds. Teams then use this generated draft as a starting point. They review

and edit the machine-made blueprint instead of writing the whole thing manually, which drastically cuts down the time it takes to move from the planning phase into active development (Hemmat et al., 2025).

Managing and checking which piece of code matches which original client request is a nightmare on large projects. As software scales, human analysts simply cannot maintain these traceability matrices manually (Cuddeback et al., 2010). Deep learning networks solve this by automating the entire tracking process. As coders commit new changes during rapid agile development sprints, machine learning algorithms automatically restore and update the traceability mapping (Alturayef et al., 2025). Software developers push new code into the system and these systems trace it back to the original software specifications (Wang et al., 2023). This ongoing mapping is an enormous boon. And it ensures the entire project is compliant and structurally aligned without having to halt the coding process every time the project's spreadsheet needs to be updated. The AI handles the administrative burden of tracking software evolution. This lets developers overhaul the architecture quickly while making sure every new feature still lines up with what the client asked for.

Table 2 isolates the specific operational advantages of artificial intelligence across the four primary engineering domains. In the elicitation phase, machine learning completely changes how teams handle raw input by processing massive stakeholder datasets instantly. This high-speed text mining prevents the usual project bottleneck. For the analysis phase, natural language processing acts as an automated, high-speed audit system. It spots vague wording and missing logical rules before any actual coding begins. This early detection directly stops expensive architectural rework. During the

generation phase, large language models solve the blank-page problem. They instantly draft initial requirement documents so technical writers can start editing rather than writing from scratch. Finally, in the traceability domain, algorithms provide dynamic link recovery. They map new code commits back to the original client rules automatically. This continuous background mapping keeps the entire software architecture compliant without forcing developers to stop their active sprint work.

Table 2: Proven AI Capabilities by Domain

Domain	Primary AI Capability	Practical Engineering Benefit
Elicitation	High-speed text mining	Processes huge stakeholder datasets instantly.
Analysis	Automated NLP audits	Spots vague wording and missing rules before coding.
Generation	Instant requirement drafting	Removes the blank-page problem for technical writers.
Traceability	Dynamic link recovery	Maps new code commits to old rules automatically.

5. Limitations and Failures of AI in RE:

Machines are not good with humans. The algorithms which gather requirements don't read between the lines. They can't be in a room and determine from the body language of an angry stakeholder during an interview (Rosado da Cruz & Cruz, 2025). A client can be highly frustrated with the system and not say so, the machine learning algorithm doesn't pick it up. This causes gaps in the project baseline before writing any code. The systems have difficulty with cross-system journeys that involve context switching (Ahmad et al., 2024). The situation is even worse when people try to use AI to capture requirements to develop real AI

systems. The algorithms don't pick up on hidden data constraints and model parameters required to build sophisticated AI systems (Villamizar et al., 2021). They also fail to comprehend interdisciplinary terms. An AI may read the word "current" and think of it in terms of physics, rather than in electrical engineering, leading to immediate structural inconsistency (Ferrari & Esuli, 2019). The software simply doesn't know the context humans know that helps us to understand the confused client. Even when attempting to formalize rules for agile development, the AI can't convert human wishes into model-driven rules unless a developer holds its hand (Umar et al., 2025). Developers spend hours combing through the AI's raw output to weed out such blindingly obvious errors.

The greatest threat occurs during the generation process. Large language models don't know anything about software engineering. They simply guess the next word that might come based on training data (Hou et al., 2024). This guessing results in hallucinated requirements. The models often come up with complicated technical constraints that are not required by the client or the software (Norheim et al., 2024). This is particularly true with general chatbots. When software teams try to use tools such as ChatGPT to generate their software requirements, the resulting requirement documents look great but are shallow (Marques et al., 2024). They will generate a highly structured user story that looks great but is not doable. In controlled experiments, human students can write better and more reliable software requirements than the powerful neural networks (Edwards et al., 2025). The AI simply makes up functional relationships if it veers even slightly from its main training set. Thorough reviews of the existing literature show we still do not have a way to ensure the LLM's models of requirements are correct (Hemmat et al., 2025). Developers can't rely on the generated blueprints

without scrutinising each line of code. Over-relying on the models makes the developers build features based on complete fantasy. This destroys software architecture and requires huge refactoring (Sterling & Oliveira, 2026).

Automated traceability algorithms quickly run into problems when facing undocumented software evolution. The software automation is only feasible if the code and text are very similar. If the developer rewrites a legacy module but uses different variable names, the machine learning is lost (Alturayeif et al., 2025). The neural network connections are merely word matches. The algorithms just use keywords, which do not capture any meaningful information (Wang et al., 2019). This huge blind spot means the tools propose thousands of false positives. They will link a random database script to a random user story because they both contain a word like "login" or "execute". Research on deep learning in software development demonstrates that these algorithms are often used as black boxes, which makes it hard for developers to comprehend why a specific user story should be connected to a specific software code file (Wang et al., 2023). To overcome this issue researchers, need to create hybrid systems that force the AI to follow logical rules (Li et al., 2020). Prior to this human-designed logic layer, the automated traceability matrix gradually becomes filled with junk data. These software engineers are put on a tedious semi-automated grind where they spend long hours in manual verification of links and removal of false positives from the simple classifiers (Etezadi et al., 2025).

Figure 2 illustrates how these individual algorithmic errors snowball into catastrophic failure. It documents the entire engineering process from initial stakeholder interview to the final software. An error doesn't remain localised. For instance, if an elicitation model fails to pick up on a cultural nuance

during initial stakeholder interviews, it will pass that along. The analysis tools interpret this bad data and spit out false positives due to misinterpreted cross-disciplinary terminology. Generative models then hallucinate unfeasible technical constraints based on bad analysis. The traceability algorithms then embed the hallucinations forever into the architecture by linking arbitrary keywords together. This failure showcases how automated bugs create a snowball effect. Programmers can't simply fix a traceability bug in the last stage. They need to clean the data all the way back at the top of the pipeline to prevent a system collapse.

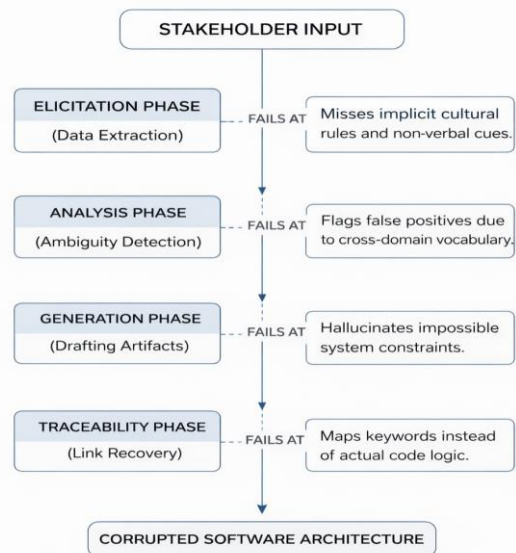


Figure 2: AI Failure Pathways in Requirements Engineering

6. Research Gap and Future Works:

The software industry has absolutely no working frameworks for human-AI collaboration. Studies claim we need a "human in the loop" to stop AI failures. Nobody knows what that means during a live agile sprint. Right now, validation is just a senior engineer reading every single machine-generated word to catch hallucinations. This brute-force manual review kills the entire speed advantage of using automation. The field urgently needs hybrid intelligence protocols so developers do not end up acting as glorified AI spell-checkers (Sterling &

Oliveira, 2026). Future tools must force the AI to flag its own uncertainty. If a generative model highlights the exact technical constraints it guessed at, reviewers can just check those specific lines instead of reading a fifty-page document. Until researchers design these specific workflows, AI remains a dangerous experimental tool instead of a safe engineering standard (Hemmat et al., 2025).

We also lack realistic ways to test these models. Current benchmarks test language models against perfectly clean computer science problems. Real client data is never clean. It is a mess of contradictions and missing variables. Models trained on pristine academic datasets crash completely when given an actual disorganized client transcript. The field needs new benchmarks designed strictly around the chaos of real-world software engineering (Hu et al., 2026). These new tests must track exact hallucination rates. Engineering teams need to know exactly how often an algorithm fakes a functional dependency before they trust it to write a blueprint. In the future studies we should stop treating artificial intelligence as a magic bullet. Researchers must isolate which specific machine learning architecture works for elicitation and which works for traceability. Building domain-specific testing environments is the only way to separate real operational utility from academic hype (Norheim et al., 2024).

7. Conclusion:

Software companies' continuous attempts to automate the whole specification process. The field data shows this just does not work right now (Hou et al., 2024). Machine learning gives teams a huge head start during early planning. They process messy stakeholder interviews and sort the raw data without any human help (Cheliger et al., 2022). The algorithms spot confusing wording in giant technical files much faster than a tired developer can (Izhar et al., 2025). Some tools even draft basic frameworks

specifically for agile sprints (Umar et al., 2025). This makes AI an excellent tool for sorting text. But the whole system crashes when it tries to grasp actual software architecture. The models lack the real-world context to figure out what a confused client is really asking for (Ahmad et al., 2024). They fail hard at extracting the hidden data rules you need to build complex machine learning applications (Villamizar et al., 2021). The generation tools just invent impossible technical constraints out of nowhere (Norheim et al., 2024). Traceability algorithms map bad links using basic keyword matching instead of reading the real code logic (Alturayef et al., 2025). Allowing these tools run by themselves can cause the architecture failure before anyone writes a single line of actual code.

Automated tools are not going to replace human engineers. The industry needs to stop chasing full autonomy and focus entirely on hybrid intelligence models (Sterling & Oliveira, 2026). Developers spend way too many hours right now just double-checking AI output. They must manually catch the algorithmic lies and delete all the fake tracking links (Etezadi et al., 2025). Researchers must build workflows where language models flag when they are guessing about a technical artifact (Cheng et al., 2026). The testing benchmarks also need a total overhaul. We need tests built on ugly, real-world client data instead of clean academic computer science problems (Hu et al., 2026). Using generic chatbots to write system rules just makes all these architectural risks worse (Marques et al., 2024). Until researchers fix these specific functional gaps, generative AI is just a dangerous drafting assistant. It is not a reliable engineering standard (Hemmat et al., 2025). Teams should absolutely use AI to speed up data extraction and text audits. But they must force senior engineers to stay in the loop. A human expert must validate every single blueprint to stop

algorithmic mistakes from ruining the logical architecture (Wang et al., 2023).

8. Implications For Future Work:

The software industry needs to completely change how it builds AI tools for requirement engineering. The industry needs to abandon the idea of a single, all-purpose AI system. Future development must focus on creating narrow, highly specialized algorithms. We need one specific tool that only handles data elicitation and a completely different tool that only maps traceability links. Building domain-specific tools is the absolute only way to reduce the massive hallucination rates we see right now. Developers also need completely new interface designs. Future AI dashboards must force the language model to show its statistical confidence for every single sentence it writes. If an algorithm is only fifty percent sure about a system constraint, the text needs to visibly highlight itself on the screen. This leads to the human engineer to review the exact point of failure instead of wasting hours guessing where the machine made a mistake.

Future AI tools also must completely rethink how they handle non-functional requirements. Right now, automated models only look at basic system performance or data security. They completely ignore human psychological barriers. For instance, AI generates a specification for an e-governance platform, it almost never includes constraints for cognitive load or technology anxiety. This algorithmic blind spot causes the digital exclusion of older adults and other vulnerable groups. The models just blindly assume every end-user has perfect digital literacy. Researchers must build specific training datasets that teach language models how to draft psychological constraints. Engineering teams need the AI to automatically flag when a proposed system flow will overwhelm an older user. If we do not force the automation to prioritize these hidden human-centric barriers, the industry will just

use machine learning to build highly exclusionary software much faster than before.

University computer science programs also must adapt immediately. Professors are still teaching students how to write software requirements entirely from a blank page. This is becoming a total waste of time. Future curriculum must teach junior engineers how to aggressively audit AI-generated blueprints instead (Sterling & Oliveira, 2026). Students should learn how to spot algorithmic hallucinations and fix broken traceability matrices. On the corporate side, software companies must establish strict new policies for their agile development sprints. Teams cannot legally or functionally rely on a machine learning model to sign off on a system architecture. Future research must define exactly who takes the blame when an AI hallucinates a requirement that causes a massive software crash. Until the industry sets hard legal and operational boundaries, relying blindly on automated specification remains a massive corporate liability (Etezadi et al., 2025).

Declaration of Conflicting Interests: The authors report no personal or financial conflicts of interest related to this study.

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A Comparative Review of Machine Learning Approaches for Manufacturing Applications in Industry 4.0

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Accepted: 10.04.2026

Published: 30.04.2026

Page No. 17 – 21

DOI: 10.5281/zenodo.19908584

Abstract

Industry 4.0 has transformed the way modern manufacturing is being approached with the interplay of cyber physical systems, industrial internet of things (IIoT), cloud edge computing, and data driven intelligence. Machine learning (ML) has become one of the core technologies to enable the derivation of actionable insights out of heterogeneous manufacturing data. This paper provides a longer and comparative analysis of ML and deep learning (DL) algorithms with supervised, unsupervised, semi supervised, reinforcement learning and hybrid algorithms used in basic manufacturing areas like predictive maintenance, quality inspection and defect detection, process optimization, production planning and supply chain management. The review compares the performance of algorithms, the computational complexity, interpretability, and deployability based on a systematic review of the literature published since 2015. To increase methodological clarity, mathematical expressions of popular modeling, such as regression, support vector machines, convolutional neural networks (CNNs), and long short-term memory (LSTM) networks, are provided. The new areas of transfer learning, federated learning, edge AI, and explainable artificial intelligence (XAI) are presented in the framework of industrial scalability and reliability. This paper concludes that the key to closing the gap between

laboratory scale ML models and real-world smart manufacturing systems lies in context aware model selection, hybrid, and explainable frameworks.

Keywords: Machine Learning, Deep Learning, Industry 4.0, Predictive Maintenance, Quality Inspection, Smart Manufacturing

1. Introduction

Industry 4.0, also known as Industry 4.0, is a paradigm shift in the manufacturing industry that is characterized by the interplay of digital technologies, automation, and intelligent decision-making systems. State-of-the-art sensing, IIoT devices, and cyber physical systems keep on producing immense amounts of data that are in high volume, high velocity, and high variety in the production environments [1]. The strategic need to utilize this data well has become a strategic requirement in the attainment of efficiency in operations, quality of products and sustainability.

Machine learning (ML) is an artificial intelligence (AI) that is at the center of converting raw manufacturing data into predictive and prescriptive intelligence [2]. Complex patterns can be learned by data using ML algorithms, so no explicit rule-based programming is required. Deep learning (DL) is a special branch of ML that expands this ability by automatically deriving hierarchical features of images, signals, and time series data with multi-layer neural networks [3].

ML driven solutions have proved to be highly advantageous in manufacturing in the form of shorter downtime by forecasting the necessity to perform maintenance, higher accuracy in defect detection, better process parameter optimization, and robust supply chain activities. Nevertheless, the issues of imbalance of data, interpretability of models, constraints in computations, and compatibility with legacy systems still hamper large scale implementation.

Significant contributions of this review are:

- Systematic and comparative evaluation of the ML and DL methods in various manufacturing applications.
- Addition of mathematical equations to aid in the comprehension of algorithms.
- Determination of performance trade-offs between conventional ML and DL methods.
- Emerging research directions related to sustainable and intelligent manufacturing were discussed.

The rest of the paper is structured in the following way: Section II explains the review methodology. Section III introduces the ML paradigms that have a mathematical basis. Section IV talks of CNNs and sequence models. Section V gives comparative analysis application wise. The last part of the paper is the section VI which ends with future research directions.

2. Review Methodology

This paper is done using a systematic literature review (SLR) approach to facilitate transparency and reproducibility. Keywords such as machine learning in manufacturing, deep learning defect detection, and predictive maintenance Industry 4.0 were used to query major scholarly databases, such as IEEE Xplore, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar.

Manifold Publications published between 2015 and 2025 were taken into consideration to include

the foundational and the recent developments. Inclusion criteria were based on peer reviewed journal articles and reputed conference proceedings describing empirical use of ML in manufacturing. Following the pre-screening of over 150 articles, about 90 high impact studies were identified based on relevance, frequency of citation as well as methodological rigor.

The chosen literature was divided into the field of application, ML paradigm, type of data, and measures of evaluation. This temporal analysis shows that the number of publications rapidly grows after 2020, which is associated with a faster adoption of Industry 4.0 and further developments of the DL frameworks [4].

3. Machine Learning Paradigms and Mathematical Foundations

The techniques of manufacturing based on ML can be characterized into supervised, unsupervised, semi supervised, and reinforcement learning [5].

A. Supervised Learning: Supervised is a learning method that is based on labeled datasets and is commonly applied to regression and classification problems.

Linear regression model can be defined as:

$$\hat{y} = \beta_0 + \sum_{i=1}^n \beta_i x_i$$

where (x_i) represents input features and β_i are model parameters.

The aim of the Support Vector Machines (SVMs) is to determine an optimal hyperplane by solving:

$$\min_{w,b} \frac{1}{2} \|w\|^2 + C \sum_{i=1}^N \xi_i$$

subject to margin constraints, making them effective for small and medium sized datasets.

B. Unsupervised Learning: Unsupervised learning methods like dimensionality reduction and

clustering are used where there are no labeled data. The K means clustering goal is:

$$J = \sum_{k=1}^K \sum_{x \in C_k} \|x - \mu_k\|^2$$

where μ_k denotes the centroid of cluster C_k .

C. Reinforcement Learning: Reinforcement learning (RL) is a framework of sequential decision-making problems that employs a framework based on a reward. The best policy is that which maximizes the expected total reward:

$$R_t = \sum_{k=0}^{\infty} \gamma^k r_{t+k}$$

where γ is the discount factor. RL is increasingly applied in robotic assembly and adaptive process control.

D. Deep Learning: DL models build upon ML paradigms with deep neural networks, which have the power to extract features automatically [6].

4. Convolutional and Sequential Neural Networks

The most popular DL architecture in image-based manufacturing tasks like detecting surface defects is the Convolutional Neural Networks (CNNs) [7]. The mathematical definition of convolution operation is:

$$(F * K)(i, j) = \sum_m \sum_n F(i + m, j + n) K(m, n)$$

where F is the input feature map and K is the convolution kernel.

Advanced CNN variants such as ResNet, YOLO, and Mask R CNN have achieved detection accuracies exceeding 95% in real time industrial inspection systems [8], [9].

For sequential sensor data, Long Short-Term Memory (LSTM) networks model temporal

dependencies using gated mechanisms. The LSTM cell state update is given by:

$$C_t = f_t \odot C_{t-1} + i_t \odot \bar{C}_t$$

where f_t and i_t represent forget and input gates, respectively [10].

5. Applications and Comparative Analysis

A. Predictive Maintenance: Predictive maintenance uses ML models to predict health and useful life (RUL) of the equipment. Research shows that with ML based maintenance strategies, 30-50 percent reduction in downtimes has been achieved [11]. The LSTM and CNN-LSTM hybrids are better in multivariate time series data than the traditional methods [12], whereas the Random Forest (RF) and SVM are also competitive on engineered features [13].

B. Quality Inspection and Defect Detection: CNN based visual inspection systems perform at state of the art, with accuracies of up to 99% on benchmark data sets like steel surface defects [15], [16]. DL carries much less overhead in manual feature engineering compared to the traditional ML [17].

C. Process Optimization and Supply Chain Management: Additive manufacturing and process parameter optimization use reinforcement learning and RF models [18]. Inventory classification and optimization of logistics are supported by unsupervised learning [19].

Comparative Summary:

- DL models are ideal in high dimensional and unstructured data cases.
- Traditional ML is interpretable and less costly to compute.
- Hybrid and transfer learning models overcomes data scarcity and domain adaptation issues [20].

The main obstacles are the imbalance in data, the computational overhead, and integration of the legacy system. The latest ones are federated learning, explainable AI, and edge-based inference [21].

6. Conclusion and Future Directions

This review has shown that both ML and DL are now essential components in Industry 4.0 manufacturing. CNNs prevail in visual inspection and LSTM based architecture prevails in predictive maintenance. Nevertheless, the use of industrial adoption must be a balance between accuracy, interpretability, and scalability.

Future research directions are:

- Regulatory-compliant, explainable, and trustworthy ML.
- Interoperability with digital twins and next generation (6G capable) IIoT.
- Energy efficient and sustainable ML models in green manufacturing [22].

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Cybersecurity Threats and Prevention Techniques: A Comprehensive Review

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Accepted: 10.04.2026

Published: 30.04.2026

Page No. 22 – 26

DOI: 10.5281/zenodo.19908876

Abstract

The rapid expansion of cloud services, digital platforms, and online communication has significantly amplified cybersecurity risks. Cyberattacks, including ransomware, phishing, malware, and unauthorized access, persistently threaten the confidentiality, integrity, and availability of data. This review paper examines prevalent cybersecurity threats impacting modern information systems and explores effective prevention techniques to mitigate these risks. Key security measures such as firewalls, encryption, intrusion detection systems (IDS), access controls, and user awareness training are analysed. Recent data indicates that global cybercrime costs are projected to reach \$10.5 trillion annually by 2025, underscoring the urgency of robust defences. The paper emphasizes the importance of a layered (defence-in-depth) security approach, incorporating risk assessment models, to protect systems and ensure secure digital operations. Emerging threats like AI-driven attacks and supply chain vulnerabilities are also discussed.

Keywords: Cybersecurity, Cyber Attacks, Malware, Phishing, Ransomware, Data Protection, Network Security, Prevention Techniques, Risk Assessment

1. Introduction

Cybersecurity plays a crucial role in protecting digital systems and sensitive information against

more advanced cyberattacks. Since organizations are becoming more dependent on internet-based technologies, attackers use the loopholes to amass wealth, steal information, or interfere with the services [1-3]. These attacks impact both individuals and businesses as well as critical infrastructure. Recent news indicates that cyberattacks take place about every few seconds, ransomware, and phishing are the most popular vectors. The paper will recognize the typical cybersecurity threats and the prevention measures as well as integrating quantitative risk assessment to offer a complete review.

2. Overview of Cybersecurity

Cybersecurity refers to technologies, processes and practices that are aimed at securing networks, devices, programs and data against attack, damage, or unauthorized access [4, 5]. It encompasses areas like network security, application security, information security and operational security. Cybersecurity is defined as the set of technologies, policies and practices that aim at securing information systems against cyberattacks [6, 7]. It covers several areas such as:

- Network Security
- Information Security
- Application Security
- IoT Security.

One of the key goals of cybersecurity is to uphold the CIA triad:

"Security"= {Confidentiality, Integrity, Availability}

The defense-in-depth strategy is one of the key principles and entails the use of various layers of security controls to reduce the risks.

Defense in Depth/ Layered Defense Model

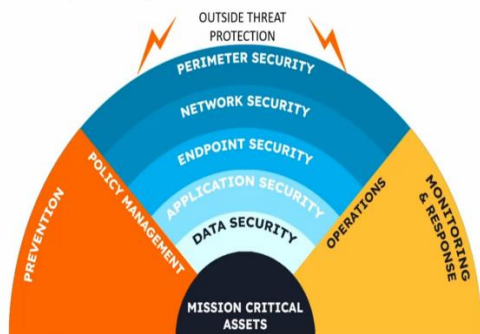


Figure 1: Layered Defence-in-Depth Model in Cybersecurity (Illustrating multiple security layers: physical, network, endpoint, application, and data) [11].

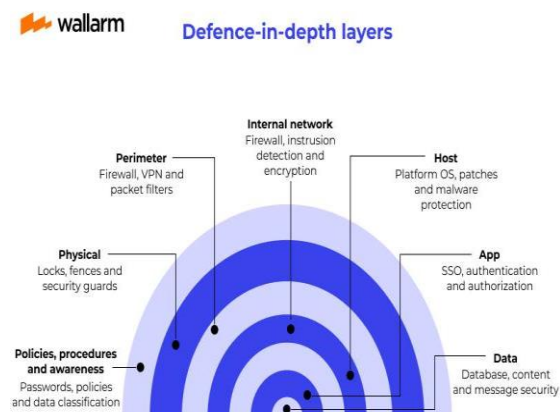


Figure 2: Alternative Representation of Defence-in-Depth Layers [12].

This multi-layered approach ensures that if one layer fails, others remain effective.

3. Common Cybersecurity Threats

The threats of cyber-attacks are also dynamic, and hackers’ resort to sophisticated methods, such as AI [8-10]. Key threats include:

- **Malware:** Virus software that can harm or to be installed without authorization.
- **Phishing:** Fraudulent attempts to gain access to sensitive data through phishing messages.

- **Ransomware:** Scramble data and requires money to be decrypted.
- **Denial-of-Service (DoS/DDoS):** Floods systems to affect availability.
- **Unauthorized Access:** Weak credentials or vulnerabilities exploitation.
- **Third-party vendors (emerging in 2025)** are a threat to the supply chain.
- **Artificial Intelligence Threats:** Deepfakes and attacks by machines.

Table 1: Common Cybersecurity Threats and Their Impact

Threat Type	Description	Possible Impact
Malware	Malicious software	Data loss, system damage
Phishing	Fake emails or links	Credential theft
Ransomware	Data encryption attacks	Financial loss
DoS	Service overload	System downtime
Unauthorized Access	Illegal system entry	Data breach



Figure 3: Infographic of Common Cyber Threats [13].

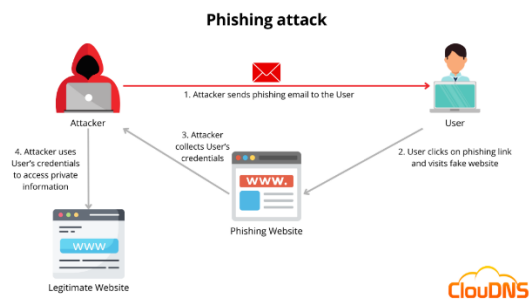


Figure 4: Illustration of a Phishing Attack Process [14].

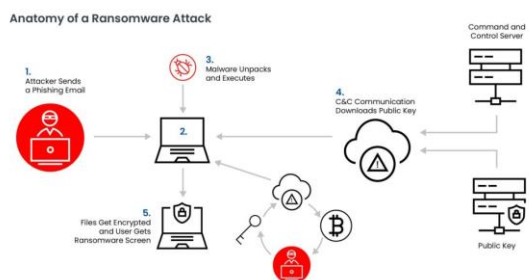


Figure 5: Diagram of a Ransomware Attack Lifecycle.

Table 2: Common Cybersecurity Threats, Impacts, and 2025 Statistics

Threat Type	Description	Possible Impact	2025 Insights/Statistics
Malware	Malicious software	Data loss, system damage	Part of rising malware-free attacks
Phishing	Fake communications	Credential theft	Leading breach cause (~16% of breaches)
Ransomware	Data encryption for ransom	Financial loss, downtime	Attacks every 11 seconds; \$10.5T global cost projection

Threat Type	Description	Possible Impact	2025 Insights/Statistics
DoS/DDoS	Service overload	System downtime	25% rise in multi-vector attacks (2024-2025)
Unauthorized Access	Illegal entry	Data breach	Often via weak credentials
Supply Chain	Third-party compromise	Widespread infiltration	45% of organizations affected

4. Risk Assessment in Cybersecurity

Prioritization of threats requires the use of quantitative risk assessment. One of the fundamental equations is:

$$\text{Risk} = \text{Likelihood} \times \text{Impact}$$

Where Likelihood is the likelihood of happening (0-1), and Impact is the possible loss (e.g. in dollars). An enhanced formula incorporates vulnerabilities and controls:

$$\text{Risk} = \frac{\text{Threat} \times \text{Vulnerability} \times \text{Impact}}{\text{Controls in Place}}$$

$$\text{Single Loss Expectancy (SLE)} = \text{Asset Value} \times \text{Exposure Factor}$$

$$\text{Annualized Loss Expectancy (ALE)} = \text{SLE} \times \text{Annual Rate of Occurrence (ARO)}$$

These equations enable organizations to quantify risks and justify investments.

Cybersecurity Prevention Techniques

To be effective in prevention, a multi-layered approach is needed:

- Firewalls:** sieve network traffic.
- Encryption:** Safeguard data privacy.
- Intrusion Detection/Prevention Systems (IDS/IPS):** Detect and block malicious activity.
- Access Control & Multi-Factor Authentication (MFA):** Restrict access.

5. **Frequent Software Updates and Patching:**
patch vulnerabilities.
6. **User Awareness Training:** Fight social engineering.
7. **Endpoint Detection and Response (EDR):**
Real time threat hunting.

5. Encryption Model

Data encryption can be represented as:

$$C = E(P, K)$$

where

P = Plaintext,

K = Encryption key,

C = Ciphertext.

Multiple Network Security Perimeters

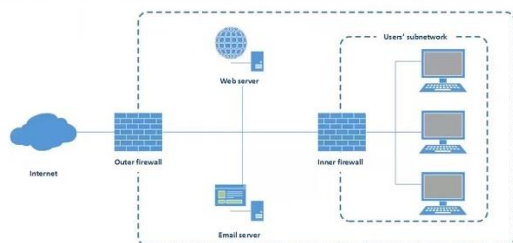


Figure 6: Diagram Showing Firewall in Network Security.

Table 3: Prevention Techniques and Purpose

Technique	Purpose	Effectiveness Insight
Firewalls	Block unauthorized traffic	Core network defence
Encryption	Protect sensitive data	Essential for data in transit/rest
IDS/IPS	Detect/block suspicious behaviour	Real-time monitoring
Access Control/MFA	Restrict system access	Reduces unauthorized entry
Software Updates	Patch known vulnerabilities	Prevents exploitation

Technique	Purpose	Effectiveness Insight
User Training	Reduce human errors	Addresses ~34% insider threats
Zero-Trust Architecture	Verify every access request	Adoption rising to 60% in enterprises

6. Challenges in Cybersecurity

Among the challenges are the changing threats (e.g. AI-enhanced attacks), skills gaps (3.5 million unfulfilled jobs worldwide in 2025), supply chain complexity, and regulatory fragmentation. One of the main causes of breach is human error. Even with technological changes, cybersecurity has several challenges:

- Quickly developing attack methods.
- A shortage of qualified cybersecurity specialists.
- Low level of security awareness among users.
- Complexity of IT infrastructures.
- Human error has been the most common cause of security breaches, and hence the importance of conducting training and awareness programs.

7. Conclusion

This review indicates the importance of cybersecurity as a critical component in the protection of contemporary digital ecosystem. Detection of cyber threats and application of effective prevention methods will greatly minimize security threats. Multi-layered defence strategy, coupled with encryption, monitoring, frequent updates and user awareness is critical in ensuring secure computing environments. Artificial intelligence, automation, and sophisticated threat detection mechanisms will become more and more powerful in cybersecurity development in the future. Risk mitigation through awareness of cybersecurity threats and layered prevention methods go a long

way in minimizing risks. Cybercrime expenses have now become trillions of dollars; therefore, quantitative risk models, frequent updates and awareness training are crucial. The future will use AI to detect threats and automate to increase resilience in a more complex landscape.

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Analysis of Digital Governance Implementation in Indian Organizations: Challenges and Strategic Solutions

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Accepted: 10.04.2026

Published: 30.04.2026

Page No. 27 – 38

DOI: 10.5281/zenodo.19909028

Abstract

India Organizations in India are shaken by the aspect of digital governance due to such immense initiatives as Digital India, as well as the National e-Governance Plan. This study plunges into the reality of challenges that the Indian organizations (publicly or privately owned) encounter in their lives. Having flipped through heaps of documentation and managed to monitor developments in policy changes, the study sets down the most significant challenges: poor infrastructure, lack of digital expertise, security risks, disorganized regulations, and lack of resources. The study does not only identify issues, but also provide evidence-based solutions, such as ramps in infrastructure with BharatNet, capacity-building with investments, the introduction of the Digital Personal Data Protection Act 2023, the simplification of regulations, and even a leap of new technologies such as AI and big data. The results do not merely remain theoretical. The study provides organizations with viable frameworks in which the things can become more transparent and accountable in addition to integrating global digital governance concepts into the Indian specific social and economic realities.

Keywords: Digital Governance, E-Governance, Digital India, Cybersecurity, Digital Literacy, BharatNet, DPDP Act 2023, AI Governance, Smart Cities Mission

1. Introduction

The fast growth rate of information and communication technologies (ICT) has essentially

changed the paradigm of governance in the world, forcing companies to redefine their business models, service products, and their relationship strategies with stakeholders [1]. The visionary national programs such as the National e-Governance Plan in 2006 and the overall Digital India Mission in 2015 have pioneered this digital transformation in India as both seek to use technology to promote transparency, efficiency, and accessibility in governance [2][3]. These programs symbolize the effort of India to make a shift towards the traditional.

bureaucratic systems into digitally-enabled systems of governance which are capable of dynamically responding to the needs of over 1.4 billion citizens.

Digital governance in the Indian context, is much more than digitizing the paper-based processes. It is a comprehensive strategy that combines policy frameworks, technological infrastructure, human capability, and regulations in the accomplishment of organizational goals and ensuring the principles of transparency, accountability, participatory decision-making, and legal compliance [4]. Digital governance is increasingly being perceived by modern Indian government departments, public sector undertakings, corporate entities in the country as well as non-governmental entities as a necessity not only in terms of operational efficiency but also in terms of organizational competitiveness in a globally intertwined economy [5].

The State of India Digital Economy Report 2024 states that India currently occupies the third place in terms of digitalization, as the digital economy has become 11.74% of national income in 2022-23 and is expected to increase almost to 20 percent of GDP by 2030 [6][7]. Such an impressive growth pattern has been supported by sensational increases in digital infrastructures. The number of internet users increased three times to over 970 million in 2024 as compared to 250 million in 2014, and the cost of data dropped to ₹9.34 per GB as compared to 308 per GB, making digital access more democratic [8].

Nevertheless, the way to full implementation of digital governance is still full of significant difficulties. These challenges are not limited to technical factors, which includes cultural resistance, capacity issues, regulatory ambiguity and socio-economic differences that exist in the diverse Indian terrain [9]. The urban-rural digital divide is a continuing illustration of such complexity as major urban centres have high connectivity and digital literacy, large rural areas are still grappling with poor infrastructure and lack of information [10]. By March 2025, BharatNet had service-enabled 2.18 lakh Gram Panchayats, but has not been able to ensure comprehensive last-mile connectivity [11]. Threat to cybersecurity is another critical issue to digital governance in India. In 2025, more than 265 million cyberattack attempts were witnessed in the country and an estimated financial loss in the country was above ₹20,000 crores [12]. Large-scale data breaches of organizations like BoAt (7.5 million users), BSNL (278 GB of data), and Hathway ISP (41.5 million customers) in 2024 demonstrate the uncertainty and high security risk of digital systems and the importance of effective security infrastructure [13]. In India, the cost of data breach on average increased 13 percent to 220

million rupees in 2025, highlighting the cost factor associated with poor cybersecurity efforts [14].

Digital regulations governing digital governance in India are dynamic but have not been unified yet. Another novel move is the Digital Personal Data Protection Act 2023, adopted by Parliament on August 11, 2023 that marks a significant success in providing extensive data protection frameworks [15]. Nonetheless, its application needs concerted effort on the part of various ministries and regulatory agencies, complicating the tasks of organizations trying to meet requirements on compliance [16]. Likewise, the India AI Governance Guidelines publishes in November 2025 by NITI Aayog set guidelines on responsible AI usage, but institutional processes to regulate its use continue to be operationalised [17].

The differences in infrastructure among regions have a major effect on the implementation of digital governance. Although the rural population is served by more than 400,000 Common Service Centres that bridge the digital divide [8], selective quality and poor broadband coverage, whereby only 37% of villages are linked up with reliable connections limits the delivery of the services [10].

The ambitious 1.5 crore high-speed Fiber-to-the-Home connections that BharatNet is set to implement in rural India have seen 11.74 lakh connections is positive and, however, achievements but also reflects the bespoke work left to do [18].

Another key challenge is human resource preparedness. Even after the huge digitalisation efforts, disparities in digital literacy levels among demographic groups are staggering, with rural populations, women and disparities in socio-economic groups exhibiting relatively high differences [19]. The fear of obsolescence or a lack of understanding of digital systems often is the root cause of employee resistance to technological change, which may hamper change efforts in both

the government and the marketplace [9]. The Smart Cities Mission, which was initiated in 2015 to design technology- based solutions to governance in 100 cities, is a good example of the opportunities and possibilities of digital governance in India [20]. They are the lighthouse cities that have been leading in the ways of integrated command and control centres, intelligent traffic management systems, and online grievance redressal mechanisms, but implementing such models in smaller cities and rural nations needs a major adjustment and investment [21]. It is in this context of both transformational opportunities and threats that this study uses a systematic approach to examine the nature of digital governance deployment in Indian organizations, the presence of major barriers, and the development of strategic remedies to fit within the Indian context. The paper will help to fill the gap between theoretical knowledge and practical implications of the problem by synthesizing recent academic sources, policy documents, and empirical data of current initiatives, which will in turn be applicable to the policy makers, organizational leaders, and other researchers working on enhancing the digital governance agenda in India.

2. Methodology

The study design is a qualitative literature review, which will be used to undertake an in-depth and systematic analysis of how Indian organizations have implemented digital governance. The study uses the combined sources of information provided by a variety of secondary sources like peer-reviewed academic journals, government policy documents, social reports by ministries and agencies, research publications, and contemporary analysis of digital governance projects since 2020 to 2026 [22].

This data gathering was specifically on Indian contexts and it used materials such as that of the ministry of Electronics and Information Technology (MeIT), NITI Aayog, the Unique Identification

Authority of India (UIDAI), and the National e-Governance Division amongst others. The search keywords were based on the following: academic databases, digital governance India, challenges related to e-governance, Digital India implementation, cybersecurity in India organizations, smart cities governance frameworks.

They used thematic coding as the analytical method to remove common patterns, problems, and solutions to the same problem throughout the literature. Indian experiences were also compared with global best practices to place findings in digital governance wider context within the wider understanding of the digital governance scholarship. Special consideration was given to latest trends such as the Digital Personal Data Protection Act 2023, India AI Governance Guidelines 2025, and new data on BharatNet expansion, Aadhaar authentication and hacking [23]. This approach allowed an overall synthesis of the theoretical frameworks and application implementation experience, as well as a strong base of comprehending the dynamics of digital governance issues and solutions to the current Indian organizational environment. It is not denied that the use of secondary sources limits the sources, but the scope and the up-to-date nature of materials research makes this a limitation, as it guarantees the relevance and credibility of results.

3. Challenges in Implementing Digital

Indian Organization Governance.

3.1 Digital Divide and Infrastructure Inadequacies.

The most basic challenge to equal digital governance in India is the digital divide. Nevertheless, even at the current blistering pace, there is a growing connection between internet penetration of between 285 percent between 2014 and 2024 yet huge gaps still exist between urban and rural communities, socio-economically disadvantaged groups, and various geographic

locations [8]. Connection to the rural areas remains exceptionally poor, with only about 63 villages having productive broadband as of 2025 [10]. Its flagship rural connectivity programme, BharatNet has come a long way in bridging 2.18 lakh Gram Panchayats with the high-speed internet by March 2025 [11]. But the implementation of the programme has not been even across states and the quality of services differs significantly. The amended programme to offer 1.5 crore Fiber-to-the-Home connections needs an investment of 1.39 lakh crore, which shows the huge financial burden needed to undertake the enormous infrastructure generation [18]. Infrastructure issues are further exacerbated by network reliability and bandwidth limits. The connectivity in many rural and semi-urban places is intermittent and this means that organisations may not easily implement cloud-based digital governance systems that demand constant internet connectivity. Such inconsistency in technology acts against the confidence of the user, which curtails the viability of e- governance [9].

3.2 Cybersecurity Vulnerabilities and Data Protection Concerns.

Increased digitalization of India has rendered it one of the countries that have been targeted by cyberattacks worldwide. In 2025, a total of more than 265 million attempts to attack computers have been reported, and financial damages have been more than 20,000 crores [12]. The threat environment includes hospitals and educational institutions efforts against ransomware attacks, UPI and digital payment frauds resulting in monthly losses to the tune of thousands of crores of funds, and high-level phishing campaigns based on AI use [13].

In 2024, the security of even large institutions was revealed due to huge data breaches. The BoAT data breach resulted in the leak of personal data of 7.5 million users, and BSNL breach

involved the leakage of sensitive data amounting to 278 GB of data including IMSI numbers, SIM card details, and so on [13]. In the case of 41.5 million customers hit in a breach by hackers against Hathway ISP, the hackers abused risks in the content management system owned by the company, which is based on Laravel [13]. In India, in 2025, the average cost of data breaches rose by 13 per cent to 220 million rupees, not only of direct financials, but also of reputation and loss of confidence of the population [14]. Large numbers of institutions or mostly small and medium enterprises and government departments with fewer budgets find it hard to establish full security lines such as encryption, multi- factor authentication, frequent security audits and incident response guidelines.

The Digital Personal Data Protection Act 2023 creates high standards of data fiduciaries which includes immediate breach informing the Data Protection Board and making users aware within 72 hours [15]. Nevertheless, most organizations do not have the technical abilities and procedures required in compliance, especially when it comes to consent management systems and data localization requirements. Maximum of 250 crore fines on security failures raises compliance pressure [24].

3.3 Poor Digital Literacy and Human Resource Capabilities.

Digital illiteracy has been a major obstacle to digital governance in India. Even though the governments have been trying to empower the general population with digital literacy skills including the Digital Saksharta Abhiyan (Digital Literacy Mission), large sections of the population, especially rural populace, older generations of the population, as well as socio-economically disadvantaged sections, are archaic in digital literacy [19]. This limits the demand side (citizens who do not have access into the digital services) as well as

the supply side (employees who cannot work with the digital systems efficiently).

Resistance to change in organizations is often a major issue that occurs in organizations. Digital systems can be perceived as a threat to the employment of employees who are used to working with traditional paper also due to their inability to work with digital gadgets and tools. This resistance reduces the adoption rates and require all-encompassing change management strategies that most organisations particularly in the public sector and that are difficult to enact effectively [9]. Literacy is also another problem that is enhanced by the gender digital gap. The rural rural women are experiencing the doubled disadvantage of reduced access to digital devices, cultural limitation to the use of technology, and reduced education level that poses a major challenge of inclusive digital governance [19]. Equally, linguistic diversity is a challenging issue- although most digital platforms are the ones that are becoming more accommodating of multilingual interfaces to accommodate the 22 scheduled languages of India, there is still little available in terms of content and user service in regional languages. The training programmes are usually lacking in scope, duration, and pedagogical practice. Several organisations have one-off training, which does not develop a lasting competency or in line with the never-ending transformation of digital systems. There is also a dearth of qualified trainers especially in rural areas which further limits capacity building efforts [10].

3.4. regulatory fragmentation and policy uncertainty.

Digital governance regulatory framework in India is poorly organized with different ministries, departments, and agencies generating problems relating to coordination and inconsistency in policies [25]. There is a lack of clear jurisdiction in digital governance, with overlapping roles by the Ministry

of Electronics and Information Technology, Ministry of Communications, NITI Aayog, and state governments on various aspects of digital governance, creating a complex bureaucracy. Policy uncertainty has an implication on the strategic planning and investment. Although the Digital Personal Data Protection Act 2023 offers a comprehensive framework, specific rules were only announced in November 2025, which caused a lengthy ambiguity period when it comes to actual compliance requirements [26]. Equally, the India AI Governance Guidelines outdated in November 2025 assert principles, but they need institutional structures, including the suggested inter-ministerial AI Governance Group to be in full effect [17].

States have taken different governance forms of digital governance building inconsistencies in the implementation standards and interoperability issues. The e-governance platforms that are designed by individual states are usually not compatible with national systems and therefore they require entry of the data more than once and this generates inefficiency [9].

To harmonise these various systems, technical standardisation, and political consensus may be hard to realise in the federal Indian system.

The procurement policies and tendering of digital technologies are in most cases biased towards lowest bidding instead of quality or long-time value. This may lead to deployment of non-optimal systems that may need regular replacement, or extensive customisation, leading to the overall higher cost of ownership and providing poor user experiences [21].

3.5 Financial Constrains and resource allocation.

The process of rolling out end-to-end digital governance systems is time and money consuming in terms of infrastructure, software licensing, cybersecurity, and training initiative, as

well as long-term maintenance. Small organisations and many government departments have budgetary limitations which restrict their potential to invest in digital transformation sufficiently [9].

Initial cost of digital infrastructure such as servers, networking, security, and specialized software can be restrictive, especially when used by a state and local government organization with constrained fiscal independence. These operations costs such as maintenance of the system, software upgrades, subscriptions to cloud services and cybersecurity are the continued predetermined financial obligations that must be maintained over time [10].

Digital governance initiatives can also be a hard perspective on calculating a return on investment, especially where the outcome is a qualitative benefit like a better transparency rating, citizen satisfaction, or better accountability. This complicates the allocation of budget to the competition with other urgent needs like healthcare, education, or infrastructure development [4].

There are also specific funding constraints of rural and tier-2/tier-3 city organizations, as they are not able to access the same revenue bases or defer to the same central government funding as metropolitan areas. This contributes to the urban-rural digital divide and increases the differences of service quality in various regions [19].

3.6 System Integration and Interoperability Problems.

Lots of organizations in India use legacy systems that have been developed at various times and with different types of technology making integration difficult. Siloed applications and databases thwart smooth flow of data, which involves entering the data manually in numerous systems and this generates an inefficiency and rate of errors [9].

Interoperability between departments, levels of administration of a given government is hampered by lack of standardisation in data formats, API protocols and technical architectures. Integration failures make visible to citizens-facing services that involve coordinating services of multiple agencies, like business registration, which involves municipal corporations, state commercial tax agencies and central government registrars, needlessly complicated [4].

Lack of long-term strategies to integrate technology into an organization means that most organizations are adopting technology ad hoc without strategic enterprise architecture provisions. This technical debt has a temporal build-up, resulting in more and more challenging and costly efforts in subsequent integration [21].

Another challenge of integration is Vendor lock-in. Efforts to work in proprietary systems with certain vendors of technology can impose dependencies that restrict flexibility, raise costs and make it more difficult to work towards open standards or migrate to other platform choices [9].

3.7 Organizational Culture and Change Management.

The main obstacle to the implementation of digital governance is the traditional hierarchical ways of organization that many Indian public sector entities have adopted. The appearance of digital systems can often add transparency and standardization of processes that interfere with traditional power relationships and informal relationships, provoking opposition on the part of stakeholders beneficiary of status quo arrangements [9].

Organizational cultures, which are risk-averse, do not encourage experimentation and innovation, both of which must occur with successful digital transformation. The fear of failures, responsibility issues and red tape

bureaucracy can freeze the decision-making process and digital initiatives may languish in lengthy procedures of approval [10].

Poor change management culture exacerbates cultural problems. Organisations often center their attentions on the technologies implementation and they overlook human aspects viz. communication, stakeholder engagement, incentive alignment and psychological support that are critical towards success in adoption [22].

Leadership commitment is a major success factor in digital governance and most firms are devoid of champions at the top leadership positions who are knowledgeable in the digital technologies and can lead agendas to achieve transformation. In the absence of visible leadership, digital efforts find it difficult to mobilize the needed resources and have a way through bureaucratic hurdles [4].

4. Strategic Solutions for Strengthening Digital Governance

4.1 Expansion of infrastructure and improvement of network reliability.

The implementation of BharatNet needs to be a national agenda, and efforts to meet the aim of reaching 100 percent Gram Panchayats and delivering 1.5 crore FTTH connections in rural regions [18] should be given priority. This entails high efficiency in project execution, improved coordination among both BSNL and the state governments and performance check systems to guarantee quality. Connectivity in geographically remote or challenging terrain locations where can be tackled by leveraging satellite internet technologies. fiber installation cannot be economically viable. Recent developments in the low- earth orbit satellite, satellite constellations can provide options other than in bridging the last-mile connectivity gaps [10].

Public-private partnerships could mobilise the expertise and capital of the private sector to develop infrastructure and make sure that mandates

of covering the whole population are fulfilled. Provisions like the revenue sharing scheme or state subsidies of the rural deployments can render commercially marginal areas a lure to the private telecommunications producers [11].

The use of quality-of-service standards and monitoring mechanisms will make sure that connectivity where offered, has bandwidth and reliability below the minimum required to support digital governance in good practice. Penalty provisions on non-compliance and regular audits drive the service providers to uphold the quality of infrastructure [9].

4.2 Full enforcement of the Cybersecurity Framework.

Companies should implement global security audits including ISO 27001 on information security management systems that sets out methodology on how to locate, evaluate, and reduce information security risks [9]. Periodic third-party security audits can help independently validate security postures and identify potential vulnerabilities before exploitation.

The comprehensive adoption of the requirements of the Digital Personal Data Protection Act 2023 will help to secure information about citizens and instill trust in citizens in digital governance systems [15]. This involves ensuring that there is a clear consent process, data minimization processes, purpose limitation process and a strong breach notification process [26].

The development and maintenance of internal cybersecurity capacities by establishing Chief Information Security Officer positions, security operations centres and specialized security teams are necessary to make sure that organisations can quickly react to any new threats [12]. All employee cybersecurity training covers the human factor, which is the weakest aspect of most security breaches [13].

This implies that implementing a zero-trust security architecture, multi-factor authentication, data-at-rest/data-in-transit encryption, and active or passive monitoring systems delivers defence-in-depth against advanced attack vectors [24]. Business continuity plans and incident response plans ensure organisations are operating in critical functions even when security breaches take place.

4.3. Capacity Building and Digital Literacy Programmes.

To scale the Digital Saksharta Abhiyan and such other programs to realize universal digital literacy, specialized programmes with target demographics such as women, the elderly citizens, rural and underprivileged communities are needed [19]. Support learning materials and content: Multilingual training materials and content that support the 22 scheduled languages in India make it inclusive.

In organisations, it is the aim of creating structured training curricula progressing between the ease of digital literacy to technical skills that will allow employees to build up capabilities with time. Practice with real systems, digitally-paired mentoring programmes capable individuals with students and acquisition of secure spaces to experiment help learning to fasten [10].

Collaborating with schools, non-governmental and training organizations as well as individual training providers taps the knowledge and channels of delivery. We can offer scaled access through online learning platforms and workshops that cover the hands-on skills development requirements, in person [22].

Organic knowledge transfer can be achieved through creating digital champions networks in organizations, such as employees who are skillful and demonstrate their interest in digital tools and can support each other in order to create internal capacity in a sustainable manner [9].

Rewarding the development of digital skills by providing opportunities to advance the career or financial incentives or even public recognition is an incentive to engage in such activities and is a sign that an organisation is willing to transform into a digital entity [4].

4.4 Policy Clarity and Regulatory harmonisation.

To mitigate regulatory fragmentation, establishment of inter-ministerial coordination mechanisms like the proposed AI Governance Group [17] will help to provide uniform policy implementation across agencies. Evidence based policymaking is informed by regular stakeholder consultations with industry, civil society, and academic experts [25].

Creating detailed national guidelines on emerging technologies such as artificial intelligence, block chain, Internet of Things in such a way that it gives the organizations a clear direction on responsible usage and encourages innovation [30]. The India AI Governance Guidelines are a significant step, though need specific sectoral implementation road maps [17]. Adopting open standards and interoperability protocols by government regulation enables integration of systems between organizations and aversion of vendor lock-in [9]. India Enterprise architecture framework is a platform, which needs to be more extensively adopted and enforced [4].

Making procurement processes more streamlined with the focus on the total cost of ownership, quality, security, and long-term value over the focus on upfront costs only promotes the investment in durable digital governance solutions [21]. Procurement can be fastened by framework contracts and em Paneling of qualified vendors.

4.5 In innovative financing Models and Resource Optimisation.on

Creating special digital transformation funds at federal and state level will be long-term funds that support long-term plans that are not tied to annual cycle of budgets [10]. Such funds may be used in infrastructure investments as well as the recurrent expenses like training and maintenance.

The use of government e-Marketplace (GeM) platform in the procurement of digital technology can save on expense by buying in bulk, competing on price and specifications that are consistent [8]. Analytical tools of GeM assist organisations in price benchmarking and finding cost effective solutions.

The use of cloud- first policies allows organisations to transition to operations spending models rather than capital intensive models of infrastructure ownership with less upfront cost, and with scalability [9]. MeghRaj is a shared government cloud providing secure yet inexpensive hosting of e-governance applications [4].

Partnership activities and corporate social responsibilities can complement the government funding especially in projects that target the rural and underprivileged regions [11]. Digital inclusion is becoming an established goal by technology companies in the following aspects of social responsibility as well as market development:

4.6 Advanced Technology Integration

Digital governance can be improved with the help of artificial intelligence and machine learning applications, such as automated service delivery, predictive analytics, chatbots that provide answers to citizen concerns, and anomaly recognition in order to prevent fraud [17]. The India AI Mission offers guidelines and tools towards responsible AI uptake [30].

By being able to identify patterns in large datasets that are sourced by various topics such as social media, transaction records, sensor networks allow the provision of information on the needs of

citizens and programme success [9]. Nonetheless, analytics should be accompanied by fierce privacy rights as required by the DPDP Act 2023 [15].

The promise of blockchain technology includes tamper resistant record management, transparent supply chains and security when authenticating credentials. The implementation of blockchain in government issues based on pilot projects in the land records management area as well as education credential verification show that blockchain can be effectively applied to the problems of governance [22].

Smart cities made through the implementation of Internet of Things allow real-time tracking of infrastructure such as traffic flow, air quality, water supply, waste management, which helps to promptly respond and allocate resources more optimally [20]. Nonetheless, IoT security vulnerabilities need special consideration to avoid making devices an attack point [12].

4.7 Improving Organisational Culture and Change Management.

To ensure observable executive support using executive champions with a clear view of transformation and understanding digital technologies, offers the needed propulsion of change in the organization [4]. Leadership communication on a regular basis that focuses on digital priorities is a positive indication of organizational commitment.

Installing systematic change management systems such as stakeholder analysis, communication plans, training programmes, resistance management strategies and feedback systems that are responsive to the human aspects of digital transformation [22]. Staged deployment gives the opportunity to adjust and shows rapid wins which generate trust [9].

Promoting organizational cultures of experimentation and innovation via special innovation laboratories, hackathons and funding

pilot projects can lead to creative problem solving and to decreased fear of failure [10]. Publically celebrating success and using failures as a learning experience creates psychological safety to innovation.

By redesigning performance management systems to pay to go digital, collaborate and deliver services in a way that is citizen-oriented, the individual incentives is congruent with the organizational goals of digital governance [4]. This can be in terms of digital service adoption rate, score of citizen satisfaction, or increase in process efficiency.

5. Conclusion

The deployment of digital governance in Indian organizations is a multifaceted tapestry of issues, which have existed on technological, human, regulatory, and financial levels. Infrastructure includes urban and rural areas, and risks to cybersecurity place millions of users at risk of data breaches, issues in digital literacy hold back citizens and employees, regulatory fragmentation among multiple agencies, and available resources limits holistic investments all contribute to the burden of the implementation of the Indian digital governance vision.

Nevertheless, such daunting obstacles are overcome with an integrated, situation-specific plans. Increasing BharatNet coverage to 100% rural connectedness, thoroughly adopting the Digital Personal Data Protection Act 2023 to foster trust, and capacity building programmes to realise inclusive digital literacy, harmonisation of regulatory frameworks across ministries and states, and the development of new models of financing long-term investments are pillars to success.

The combination of innovative technologies, such as artificial intelligence regulated through the recently published India AI Governance Guidelines, big data analytics to make evidence-

based decisions, blockchain to store the records transparently, and IoT to control the work of the smart city have transformative potential when supplemented with adequate security policies and ethical governance principles.

Cultural change in organizations is also important. Digital governance is not only effective with the use of technology but can be successful with the application of fundamental changes in the mindsets processes, responsibility, and relationships with the stakeholders. The key enablers include leadership commitment, systemic change management, organizational cultures that embrace transparency, experimentation, and citizen-centricity.

India the digital governance has made impressive achievements with 970 million internet users, 1.38 billion Aadhaar numbers issued containing 9.6 crore daily authentications, UPI processing over 100 billion transactions yearly and the digital economy is expected to contribute 20% of GDP by 2030 [6][7][8][28]. Such accomplishments reflect the groundbreaking capabilities of digital governance and pinpoint the magnitude of the work still to be done.

The way forward should involve a long-term commitment of government both at the state and local level, involvement of the private sector in provision of technology, involvement of the civil society groups representing the interests of citizens and the agency of the citizen as the active end users that can create a digital governance system. Not only the level of technological sophistication will be viewed as a measure of success, but will also be the degree to which digital governance fulfils its core functions, which include transparency in decisions governing its operations, accountability of elected leaders, efficiency in using available resources, and provision of services to all citizens without

geographical, language, and socio-economic boundaries.

With India still on its way to becoming one of the most digital economies and societies, digital governance will be both an enabler and a measure of success. The problems found out in this study are huge but not unfeasible. The solutions described will contain practical guidelines that can be used by organisations aiming at navigating this convoluted landscape. Future studies need to concentrate on longitudinal studies of implementation results, cross-state and cross-sector comparison, and the new challenges presented by new-generation technologies. India utilises evidence-based policymaking, sustained investments, inclusive capacity building, and adaptive governance frameworks to achieve the full potential of digital governance as a strategic national development and global competitiveness resource.

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Smart Car Parking System Using Arduino and Sensor

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Accepted: 10.04.2026

Published: 30.04.2026

Page No. 39 – 44

DOI: 10.5281/zenodo.19909180

Abstract

As population grows perpetually with an ever-rising rate of urbanization, the rate of vehicles on the road has been rising drastically, a phenomenon that has posed a severe problem of parking within most cities. Finding an empty parking lot has become a frustrating and time-consuming activity particularly during commercial places and urban zones that have a high density. As a result of this, drivers tend to embark on an endless tour of finding car space and this creates undue movement of vehicles, traffic jam, wastage of fuel and higher levels of air and noise pollution. To solve these problems, intelligent parking systems can now be thought of to monitor the parking space in a better way and organize the parking space in a more efficient manner.

The proposed system will be an arduino and sensors smart car parking system, which will be designed to provide a simple yet intelligent and automated way of controlling parking slots. It uses a microcontroller in the form of arduino uno, an infrared (ir) sensor, a servo motor, and a 16×4 lcd display. The ir sensors scan the entry and exit of cars and relay it to arduino. With this information, the servo motor will automatically either close or open the gate. In the meantime, the lcd screen shows the availability of parking slot in real time where the drivers can know immediately whether a parking spot is available or not.

Such a system conserves time, man power and unnecessary wastage of fuel expenses occasioned by time trying to find a parking spot. It will also help to reduce pollution, improve efficiency of parking

facilities. This is a feasible parking system which is not expensive, has proven reliability and can be easily utilized to help make cities of to-morrow cleaner and smarter.

Keywords: Arduino uno, automation, infrared sensors, smart parking system, ultrasonic sensors, vehicle detection

1. Introduction

The contemporary urban cities have had great difficulties in controlling the parking facilities as the number of vehicles is rising and the available space is inadequate. It takes many hours by drivers to find empty parking spaces leading to unnecessary use of fuel, traffic jams, and pollution of the environment. Das and basu [1] claim that one of the largest sources of urban mobility issues is inefficient parking management.

Smart parking systems have come out as a viable solution to these challenges. These systems incorporate sensors, microcontrollers and digital displays which show real time slot availability information. Recent research indicates that sensor-based parking models can help to save considerable time on search and enhance the overall parking efficiency, particularly in congested parking lots as noted by lin et al. [2].

Arduino-based automation is popular in academia and prototype-level projects due to its affordability, flexibility, and ability to work with various sensors. Shaikh and pathan [3] showed that arduino in conjunction with ir or ultrasonic sensors offer precise and dependable vehicle identification

about experimental smart parking systems. More recent efforts by patel and karamta [4] justify the application of ir sensors in short-range detection in low-budget designs.

The suggested project aims at creating a low-cost, easy-to-use smart car parking system based on an arduino uno, ir sensors, and lcd display. Previous studies demonstrate that lcd-based display guidance is more effective in enhancing user experience by enabling drivers to find available slots faster and minimize time wastage and congestion as reported by kim and lee [5]. This background sets the necessity and pertinence of smart parking systems in the contemporary city setting.

2. Methodology

The methodology starts with the analysis of the current parking problems including the inability to find free parking places, the congestion due to slow movement of vehicles, and the use of more fuel. According to das and basu [1], a large percentage of traffic in urban areas is as a result of drivers who are trying to find parking spaces.

This was followed by a comprehensive literature review based on the need to know the current smart parking methods such as arduino based automation, ir sensor detection and real-time display system. Surveys on research undertaken by lin et al. [2] and shaikh and pathan [3] clarified the existing progress and constraints in smart parking technologies.

Using the results of this review, an arduino uno microcontroller and ir sensors to detect vehicles were used to design the proposed system. The choice of ir sensors was due to their precision in short-range detection and their cost-effective applications as proved by patel and karamta [4]. The arduino interprets the sensor signals received and determines the occupancy or freedom of each slot.

The slot availability is then displayed on a liquid crystal display (lcd) and the drivers can easily

locate the free spaces. Earlier literature, such as that by kim and lee [5], indicates that lcd-based guidance has the capability of minimizing the duration of search and enhancing the parking process.

Calibration tests were done so that their sensing under various lights and environments could be accurate. The last methodology will provide an efficient and cost-effective smart parking system that will improve the convenience of users and help decongest the parking areas.

3. Literature survey

To enhance the process of slot detection and decrease manual surveillance, several researchers have created arduino- and sensor-based smart parking systems. Gupta et al. [6] developed an ultrasonic parking model using arduino that was able to detect the presence of a vehicle with great accuracy. On the same note, patel and kaur [7] utilized ir sensors in order to use a low-cost parking detection system that is applicable in an indoor setting. A gsm-based parking availability design was also suggested by raut and kale [8] and enhanced the accuracy of notifications.

Rahman et al. [9] added iot-enabled models with wi-fi modules to monitor them on the cloud. In order to minimize energy usage in real-time parking systems, banerjee and iqbal [10] investigated energy-efficient sensor networks. Thomas et al. [11] conducted a comparative survey of various urban smart parking designs and emphasized the advantages and difficulties of the iot-based systems.

Sinha and mehta [12] experimented with hybrid systems, with automated gate control via servo motors. In choudhary et al. [13], rfid was used to establish secure entry systems to increase authentication accuracy.

Fernandes and pinto [14] suggested more sophisticated methods and used machine-learning to forecast the occupancy of parking slots. Khan et al.

[15] optimized sensor networks to build real-time monitoring techniques that are more reliable.

Based on the literature review, it can be noted that despite the existence of different smart parking models, most of them are faced with the challenge of being costly, complex, and have the challenge of interfering with the environment. Ir sensor systems based on arduino are still a viable and cheap alternative to low-budget prototypes.

4. Design System

4.1 block diagram

The initial stage of the project started with a literature review and the assembly of all the required components. This was followed by preparing the block diagram as shown in figure 1. And studying the circuit connections in detail. Arduino microcontroller is programmed with the arduino ide software. As a car approaches the entrance, the ir sensor will sense that it is there and transmit a signal to the Arduino. Arduino then takes this signal and turns on the servo motor to open the gate to allow the car to pass through. I have another ir sensor at the exit to sense cars who are moving out of the parking space and the arduino will update the number of available parking spaces. In the case where all parking slots are occupied, the servo motor will be off until a car leaves. The analog signal of the ir sensors is converted into a digital signal by the built-in adc of arduino to be processed.

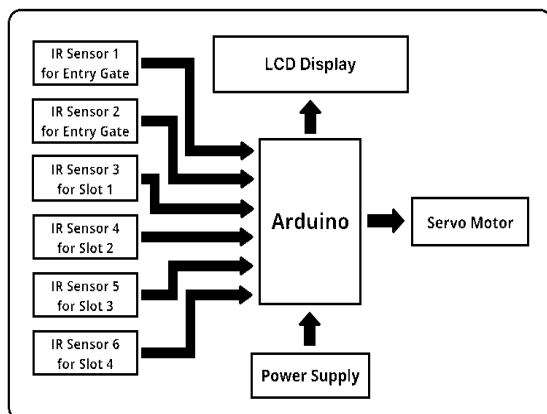


Figure 1: block diagram of smart parking system

5. Components List and Specification

5.1. Arduino uno

Figure 2. Arduino uno is an open-source microcontroller board, and is built based on the microchip atmega328p microcontroller, created by arduino. The board has a set of digital and analog input/output (i/o) pins which can be connected to other expansion boards (shields) and other circuits. It has 14 digital i/o pins (six of which can produce pwm data), 6 analog i/o pins and can be programmed using the arduino ide (integrated development environment), through a type b usb cable. It can be charged by the usb cable or an external 9-volt battery.



Figure 2. Arduino uno board

5.2. Lcd display

A liquid crystal display (lcd) as shown in figure 3. Is an electronic screen that shows numbers, letters, or messages using liquid crystals. These crystals do not produce light by themselves; instead, a backlight helps make the display visible. Lcds are widely used in digital clocks, calculators, and electronic projects.

In this smart car parking system, the lcd is used to display the number of available parking spaces and system status. It works by controlling light passing through the crystals to form readable characters. The 16x2 lcd module connected to arduino can show two lines of text, making it simple, reliable, and easy to use for small embedded systems.



Figure 3. Lcd display

5.3. I²c module

I²c or iic stands for inter-integrated communication. I²c is a serial communication interface to communicate with other i²c devices. I²c uses multi-master / multi slave method. As shown in figure 4. I²c uses 2 lines named scl and sda for transmission/reception and another 2 lines for power supply and ground. Each i²c device has i²c address to identify. I²c addresses of multiple devices may have the same address. The address is in the format of "0x20".

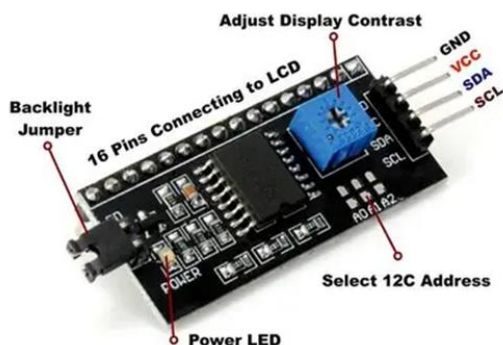


Figure 4. I²c module

Steps to find out i²c address device is discussed in the following. The serial clock (scl) pin is to synchronize the transmitter and receiver. Serial data (sda) pin is to transfer data.

5.4. Servo motor

A servo motor is an electromechanical motor that can turn to a certain angle in an extremely precise manner. As in figure 5. It consists of three primary wires; one is a power (positive) wire, another is a ground (0v) wire, and the third wire is the control signal which is supplied by the arduino. The arduino transmits a sequence of electrical pulses to the servo, which calculates how much the motor should rotate.

Servo motors come in various sizes of mini, standard, and giant, based on the amount of torque they can manage. Most small and standard servos can be operated directly by the arduino without a driver.

The servo motor, in this smart automobile parking system, is to raise or lower the entry gate when the sensors identify a vehicle. The rotation angle (generally between 0° to 180°) is controlled by the width of the signal pulse. For example, a 1.5 ms pulse turns the servo to the center (90°) position, while shorter or longer pulses move it to the left or right.



Figure 5. Servo motor

5.5. Ir sensor

An infrared (ir) sensor as shown in figure 6. Is an electronic device that detects objects or motion using infrared light. Every object around us emits a small amount of infrared radiation, which cannot be seen by human eyes but can be sensed by an ir sensor. The sensor mainly consists of two parts — an emitter and a detector.

The emitter is an ir led (light emitting diode) which emits infrared light and the detector is an ir photodiode which absorbs this light. When an object is presented in front of the sensor, the light emitted reflects off to the photodiode. This alters resistance and output voltage and this is interpreted by the arduino as a signal.

This smart car parking system employs ir sensors to detect a car in a parking slot or not. When a car is identified, the arduino receives the signal and

displays lcd or drives the servo motor.

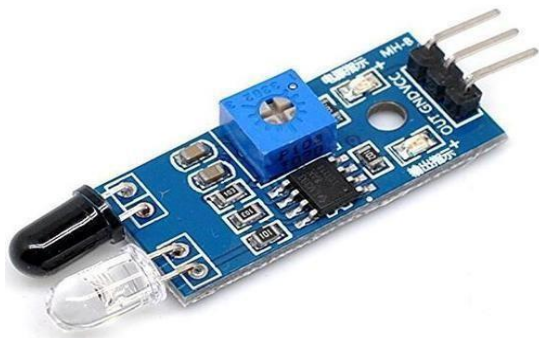


Figure 6. Ir sensor

5.6. Connecting wires

Figure 7 illustrates. Connecting wires are crucial elements that are used to connect various electronic components within a circuit. They enable electric current and signals to flow between the arduino board, ir sensors, servo motor, and lcd display. They are typically copper wires; copper is a good conductor of electricity and minimizes energy loss.

In the smart parking system, all modules are connected by wires that form the appropriate electrical connections. Jumper wires are often used on a breadboard, either male-to-male, female-to-female or male-to-female, depending on the pin type. Wiring done properly so that its communication and operation are smooth.

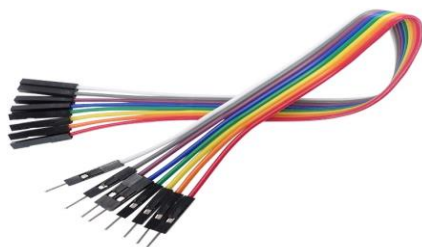


Figure 7. Connecting wires

5.7. Battery

The lithium battery illustrated in figure 8. Is a high-energy, small rechargeable power source that is commonly used in electronic and embedded systems. It offers a constant dc voltage output, typically, 3.7v, and is therefore applicable in

applications related to driving sensors, arduino boards and small modules. The density of lithium batteries is high, i.e., it can hold more energy in a small space and, they have longer life cycles than other types of batteries.

There is the possibility of using a lithium battery in the smart car parking system to provide backup power, such that the ir sensors, servo motor and arduino do not stop functioning in the event of power loss.

Its constant output ensures the correct sensor data and proper operation of the entire system.



Figure 8. Battery

6. Result and conclusion

The intelligent car parking system that has been invented in this project is effective in identifying vacant parking spaces and assisting motorists to locate free parking spaces, even in new locations. It effectively lowers the mean waiting and searching time to find a parking space, enhances convenience and minimizes unnecessary vehicle movement. This decreases the usage of fuel and reduces traffic congestion.

The principles behind the system are the concept of the internet of things (iot), relying on infrared sensors to precisely identify the presence or absence of vehicles. The smart car parking management system is an iot-based system designed to monitor

parking availability in real time using the arduino and sensors to create a prototype. The ir sensors sense the presence of vehicles and the information is immediately shown on the lcd display. The system also stores sensor data in a database and constantly updates information on parking so that it may be properly monitored.

Although the prototype was designed for a single parking area, the concept can be extended to managing multiple parking zones. An additional management interface can record the vehicle's entry and exit time for administrative purposes. According to the results, this system can be implemented in various public and private parking areas to help drivers easily locate available slots, saving time, energy, and fuel. A user acceptance test showed that most users found the system effective and practical. In the future, the system can be enhanced with a mobile application for booking and tracking parking spaces online.

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Quantum Management: Integrating Quantum Physics with Management Principles

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Accepted: 10.04.2026

Published: 30.04.2026

Page No. 45 – 64

DOI: 10.5281/zenodo.19909288

Abstract

The research bridges ideas from Quantum Physics and Complexity Science with everyday managerial practices. In addition to explaining the potential use of uncertainty, superposition, entanglement, and non-linearity as guides for managerially designing choices like paired kpis, parallel options, shared results, clean interfaces, short feedback cycles and distributed controls it provides an easy-to-understand framework to organize concepts to practices (i.e., A Concept to Practice Framework). The study's authors propose simple metrics using typical operational data (e.g., Uncertainty budgets, a Tension Index for paired tradeoffs, Portfolio Entropy, Variety Audits, Network Centrality, Decision Latency, Reversal Rate) that can be used by managers to measure their organizations' ability to navigate uncertainty. Using a qualitative narrative review of literature published between 1990-2025 the authors have developed a conceptual model that maps principles to design choices, measures and outcomes with mediator and moderator variables. Two brief examples illustrate how the concepts can be applied in practice. The primary contribution of this research is providing a clear and testable set of routines that enable agility, innovation, and decision quality under uncertainty. The study identifies limitations and calls for field-based validation studies of the proposed measures and comparative analysis of quantum inspired routines with conventional plans in various settings.

Keywords – Quantum management, Complexity science, Systems thinking, Organizational agility, Management Principles

1. Introduction

The concept of Quantum Management is a new paradigm for viewing companies that incorporates concepts from Quantum Physics & Complexity Science but only to the extent they are useful for today's manager dealing with uncertainly, dependency among people working together and nonlinear (smooth) change. The Classical Paradigm for Management was built around the Newtonian model of the World which states that the whole is equal to the sum of its parts, cause leads to an effect that can be predicted and control comes from a rule-based system with better forecasting. When both the environment is stable and all work activities are repetitive this classical model will continue to function. It breaks down when information is incomplete, when small nudges produce big swings, and when outcomes depend on relationships across teams, partners, and technologies. Quantum management reframes the task: do not try to eliminate uncertainty or force linear plans onto nonlinear realities. Instead, design organizations to sense, learn, and adapt; treat relationships and feedback as core assets; and make decisions that recognize probability, ambiguity, and emergence [2], [22], [24], [26], [47], [38]. This is not physicng cosplay. It is a disciplined use of ideas from physics and complexity to sharpen management questions and to build practices that match the world managers

live in. Several basic concepts from quantum theory are helpful as metaphors and, in some subfields, as formal tools. The time-dependent Schrödinger equation $i\hbar \partial\Psi/\partial t = \hat{H}\Psi$ describes how a system's state, represented by a wavefunction Ψ , evolves under constraints captured by a Hamiltonian \hat{H} . In organizations, we can think of the "state" as a distribution over strategic options and capabilities. The "Hamiltonian" is the design of incentives, resources, information flows, and constraints that shape how those possibilities change over time. The "state" of the firm would likely be changed when you decide to make some changes for example moving decision rights, changing the weight assigned to bonuses or opening a data platform and an external shock occurs but the external shock is the same [14] even though Schrödinger (1926/translation) has framed this as acceptable to the extent that it is based on options based governance and staged investment and that firms can simultaneously pursue multiple possible paths (a type of superposition of managerial choices) and use evidence and learning to collapse these alternative choices down into one focused path of choice [44], [13].

The Heisenberg Uncertainty Principle; $\Delta x \cdot \Delta p \geq \hbar/2$ is the theoretical basis that provides a limit of precision when measuring two conjugate quantities such as Position & Momentum at the same time. In management there is a similarity to this - The tighter you squeeze the margin of error in one direction (e.g., A specific KPI, a very accurate forecast or a single delivery date) the larger the margin of error will be in the other direction(s) (e.g., quality, exploration, etc). This is not mystical; it is a reminder that observing and measuring change behavior, and that organizations have trade-offs baked into how they gather information and act [15], [35]. A practical reading is simple: budget for uncertainty instead of pretending it is zero. Use

ranges and confidence intervals, not point targets. Track paired metrics that are known to trade off speed and quality, exploitation and exploration and manage the product of their variances the way physicists mind the product $\Delta x \Delta p$ [23], [38].

Entanglement is the quantum idea that parts of a system can be so deeply linked that you cannot describe them independently; measurements on one part correlate with measurements on the other in ways classical theories cannot explain [7], [17], [29]. That is a good metaphor for modern firms and ecosystems. Product, engineering, operations, and compliance often move together because they share data, platforms, and goals. A local change pricing, say can instantly change behavior in sales and supply even without a direct meeting or memo. The managerial lesson is to design coordination for coherence, not just for local efficiency: shared outcomes, clean interfaces, and boundary-spanning roles keep "entangled" units aligned when they act at speed [35], [3], [27]. Where coupling is unavoidable and valuable, leaders should strengthen trust and information symmetry. Where coupling only adds risk, leaders should modularize to reduce cascade failures [49], [10].

Energy–mass equivalence, $E = mc^2$, is not a literal management equation, but it is a useful reminder that potential energy can be converted into work under the right conditions. Organizations store "potential energy" in ideas, skills, culture, and trust. With the right "Hamiltonian" the right incentives, tools, and connections this latent energy becomes visible output: better services, new products, social impact. This is the core of dynamic capabilities: sense opportunity, seize it with a coherent configuration, and transform the organization so learning sticks [12], [45], [44]. Information theory gives us a simple, quantitative handle on potential variety. Shannon entropy $H(X) = -\sum p(x)\log p(x)$ measures uncertainty and diversity in a distribution

[36]. Managers can use it to monitor variety in an innovation portfolio, the spread of scenarios in planning, or the range of skills in a team. Very low entropy can mean dangerous concentration; very high entropy can mean noise without focus. Complexity science fills in the dynamics that classical management often misses. Lorenz (1963) showed that deterministic systems can be chaotic and sensitive to initial conditions, and May (1976) demonstrated that even simple nonlinear maps such as $x_{t+1} = r x_t (1 - x_t)$ can jump from stability to cycles to chaos as a single parameter r change. Organizations show similar thresholds when leaders adjust incentives, utilization, or work-in-process. A small change can push queues into oscillation or trigger quality collapse. The safe response is not to clamp down harder; it is to shorten feedback loops, set guardrails, and simulate before scaling [43], [26]. Cybernetics adds structure: Ashby's (1956) law of requisite variety says that a regulator needs at least as much variety as the disturbances it faces. That means in practical terms decision making needs to be pushed out to the edges of organizations with well-defined constraints on each and teams need to be developed with multiple skills to perform tasks and all processes need to be instrumented to provide data flow as close to real time as possible [6], [11]. Systems thinking has transformed these into day-to-day advice for designers: "Change the information flow and incentives first then add people or resources"; "Identify potential delays that may undermine what appears to be an optimal policy"; and "Use learning routines such as after-action reviews, quick experimentation and transparency through dashboards to continuously adapt and improve [25], [26], [35]. Network science provides a common language for "interconnectivity". Most collaborations and supply chain networks exhibit characteristics of being small world networks (i.e., short path length with clustering) and scale free

networks (i.e., A few key nodes have many more connections than others). Small world network structures facilitate rapid dissemination of ideas and alerts; Scale free structures provide high levels of efficiency but will result in significant instability when one of the critical nodes fail [3], [49], [27]. For managers this means map your networks, protect central nodes, cultivate bridges across clusters and avoid single points of failure. It also explains why culture and norms matter: they spread on networks and can make or break change efforts.

Management research has been converging toward these ideas from its own side. March (1991) framed exploration versus exploitation and warned that firms can get trapped exploiting the familiar while the world changes. Ambidexterity research showed that some firms survive by separating or cycling between these modes [46]. Dynamic capabilities clarified the routines sensing, seizing, transforming that make ambidexterity practical [13], [44]. Complexity leadership theory recast leaders as enablers who shape conditions so sensible novelty can emerge, instead of chiefs who predict and command [47]. The Cynefin framework helped leaders match action to context: standardize in the clear domain, analyze in the complicated, probe in the complex, and act fast to stabilize the chaotic [38]. All this fits naturally with a quantum-and-complexity lens: hold options, embrace range, tune interactions, and manage by constraints and feedback more than by detailed up-front plans. There is also a more technical bridge in the study of judgment and decision making. Classical probability sometimes fails to predict how people choose: order effects, context effects, and interference between narratives are common in strategic meetings and customer behavior. Quantum probability models explain some of these patterns without forcing them into classical additivity, by allowing "states of belief" to behave like superpositions that collapse

differently depending on measurement order and context [9], [30], [51]. This does not mean our brains are quantum computers in a physical sense. It means the math of quantum theory can be a better behavioral model for some choice patterns, which is useful for designing decision processes that reduce bias and reveal tacit knowledge.

At the same time, caution is healthy. Physicists and philosophers have warned against smuggling physics words into social theory without clear meaning or evidence [39]. Recent philosophical work distinguishes between claiming that quantum effects literally operate in social systems and using quantum metaphors or mathematics to structure thinking; the latter can be legitimate, but only if the link is made explicit and the claims are testable or at least pragmatically useful [18]. The safest ground for managers is where the ideas are already empirically strong: complexity dynamics, network effects, systems leverage, information flows, and decision design. Quantum language can help leaders remember the right habits: respect uncertainty, keep options alive, build coherence across entangled units, and treat incentives and information as the “Hamiltonian” that shapes how the firm evolves [26], [35], [47].

Notation

Ψ : system state (here, the organization’s option set or capability mix).

\hat{H} : Hamiltonian (here, incentives, decision rights, and information flows that shape behavior).

\hbar : reduced Planck’s constant (appears in uncertainty and Schrödinger equations; used metaphorically).

$\Delta x, \Delta p$: standard deviations (uncertainty) of paired variables (e.g., speed and quality).

$H(X) = -\sum p(x) \log p(x)$: Shannon entropy (variety of a portfolio, scenarios, or skills).

$x_{t+1} = rx_t(1 - x_t)$: logistic map (simple nonlinear dynamics, thresholds).

Management proxies. WIP = work-in-process;
tension index $T = \sqrt{V_a \cdot V_b}$ For paired kpis;
centrality = network importance (degree or betweenness).

Core Equations:

- **Uncertainty principle:** $\Delta x \cdot \Delta p \geq \hbar/2$
- **Schrödinger (time-dependent):** $i\hbar \frac{\partial \Psi}{\partial t} = \hat{H}\Psi$
- **Entropy:** $H(X) = -\sum p(x) \log p(x)$
- **Logistic map:** $x_{t+1} = rx_t(1 - x_t)$

This paper builds on that stance. Quantum and complexity concepts guide managers in their use of disciplined frameworks to direct decisions rather than as a means of applying exact physical models. It utilizes simple formulae, when possible, to illustrate or enhance managerial decision-making processes. Schrödinger dynamics to inform the design of option portfolios; uncertainty to provide justification for using both ranges and paired metrics; entropy to measure variety; logistic maps to warn of approaching thresholds; and network-based metrics to manage change. It speaks in plain language and stays close to practices that organizations already use when they work well: short feedback loops, modular teams, shared outcomes, staged bets, and transparent learning. In short, quantum management is a practical way to align scientific habits of thought with managerial craft in environments where certainty is rare and relationships do most of the work [1], [16], [20], [4], [5], [50], [52].

2. Literature Review

Scholarship on “quantum management” sits at the intersection of management theory, systems thinking, complexity science, and selected ideas from modern physics, and it has evolved along two intertwined paths: first, a sustained critique of linear, mechanistic organization models inherited from classical physics, and second, a constructive

search for concepts uncertainty, emergence, nonlinearity, superposition, entanglement, feedback, and self-organization that better fit turbulent environments and knowledge work. Early foundations emerged before the term “quantum management” was popular, in cybernetics and information theory, which reframed organizations as adaptive, feedback-driven systems rather than static machines; Ashby’s (1956) law of requisite variety argued that only variety can absorb variety, a principle used to justify decentralized sensing and flexible control in complex firms, while Conant and Ashby (1970) formalized the regulator–model equivalence, implying that effective managerial control requires generative internal models of the environment. In addition to this Shannon’s (1948) “theory of information” offered a mathematical language for describing uncertainty and signal-to-noise ratios in communications thereby creating an avenue from physical science through information flow and redundancy (slack resources as buffers) to organizational design. In addition to Shannon’s work there was another body of research in non-linear dynamics, and chaos theory which has shown that even purely determinate systems may exhibit sensitivity to initial conditions (a feature known as “unpredictability”) and thus behave randomly. The first application of non-linear dynamics to study of a natural phenomenon was provided by Lorenz (1963), in his examination of weather patterns, and a year later, May (1976), examined a simple model (the logistic map) and found that small changes in parameters could result in significant regime shifts (now well understood as tipping points in organizations or markets). In turn, these studies have been cited by management writers who have identified organizations as Complex Adaptive Systems (CAS) exhibiting emergent characteristics. Holland (1992) identified how CAS can adapt using local rule-based mechanisms and feedback between

agents; Simon (1962) emphasized that modular hierarchies can be effective in controlling complexity in organizations and that such architectures will provide a practical means for managing large scale systems. This foundation for understanding CAS has allowed the development of systems thinking and its translation into managerial practice; e.g. Senge (1990/2006) used feedback loops, mental models, and shared vision to develop his concept of the “learning organization”, and Meadows (1999; 2008) developed maps of “leverage points” where managers can intervene to improve the behavior of a system, but cautioned that policy interventions based solely on understanding system delay, and structure will likely fail. In complexity leadership theory, Uhl-Bien, Marion, and McKelvey (2007) reconceived leadership as enabling adaptive dynamics rather than top-down control, while Snowden and Boone (2007) proposed the Cynefin framework to help leaders match decision styles to complexity contexts simple, complicated, complex, and chaotic thereby legitimizing experimentation and safe-to-fail probes in uncertain environments. Networks became a third pillar, translating “interconnectedness” into measurable structure: Watts and Strogatz (1998) showed small-world properties that facilitate rapid diffusion and robustness, Barabási and Albert (1999) identified preferential attachment and scale-free degree distributions (implicating hub risk and influencer dynamics), and Newman (2003) systematized network metrics relevant to collaboration, supply chains, and innovation ecosystems. These science-to-management bridges prepared the ground for “quantum-inspired” managerial ideas that explicitly borrow from quantum physics as metaphor and, in some subfields (e.g., quantum cognition), as formal modeling. Writers such as Wheatley (1992/2006) and Stacey (1995, 2001, 2000) contrasted “Newtonian”

assumptions predictability, reductionism, centralized control with “new science” assumptions interdependence, nonlinearity, and emergence arguing that organizational realities are better captured by dynamic, relational, and context-sensitive perspectives; the same argument appears in dynamic capabilities theory, where change routines such as sensing, seizing, and transforming explain adaptation under rapid technological and market shifts [13], [44]. Within quantum management discourse, several concepts recur. First, the uncertainty principle is invoked to portray the inevitability of ambiguity in managerial observation: Heisenberg’s relation $\Delta x \cdot \Delta p \geq \hbar/2$, derived from non-commuting operators operators $[X,P]=i\hbar$, symbolizes a trade-off between precision in one variable and disturbance in its conjugate (Illinois lecture notes; see also encyclopedia summaries), which has been analogized to the balance between granularity and speed in decision making more measurement and control can slow action or distort the very phenomenon being measured (e.g., performance metrics gaming). Second, superposition formalized by the Schrödinger equation $i\hbar \partial/\partial t \Psi = \hat{H}\Psi$ is used to represent option-rich strategic postures in which multiple potential paths coexist until a “measurement” (a commitment or market test) collapses possibilities into one realized trajectory; advocates argue that leaders should cultivate “creative ambiguity” to preserve optionality until signals clarify (via staged experiments and discovery-driven planning). Third, entanglement the non-separable structure of joint quantum states, often illustrated by Bell states and captured formally in density matrices and Bell-inequality violations has been adopted as a metaphor for deep interdependence across teams, partners, and stakeholders, where local actions create non-local effects through hidden couplings; in organizations,

this invites attention to lateral coordination, boundary-spanning ties, and shared narratives that align distributed action [31]. These metaphors sit alongside richer developments in “quantum-like” modeling of human judgment, where quantum probability provides tools for order effects, context dependence, and violations of classical rationality; Busemeyer and Bruza (2012) offered a comprehensive treatment, and Pothos and Busemeyer (2013) showed how quantum probability can model many empirical puzzles in cognition, suggesting that managerial phenomena such as framing, sequential decisions, and preference reversals may benefit from non-classical probabilistic frameworks [9], [30]. Related work by Yukalov and Sornette (2015) explored quantum decision theory to formalize attraction factors and context effects, further motivating the claim that “quantum-like” formalisms can capture organizational choice under ambiguity better than classical models [51]. However, there is still caution as well: researchers have been cautioned by critics that they should not extend the metaphors of physics to social systems too far beyond the boundaries of empirical evidence or operational definition. Sokal and Bricmont (1998/1999), for example, had provided an extensive documentation of abuses of scientific language in the humanities which serve as a warning to management scholars to avoid committing category errors [39], while Jaksland (2023) has made a distinction between the claims that physical quantum effects are actually operating within the context of society and the claims that quantum metaphors are being used metaphorically; both would need to be justified carefully for them to be relevant to knowledge construction [18]. Even sympathetic commentators, including physicists and methodologists, emphasize that quantum phenomena are rigorously defined within microphysical regimes, and translation into

organizational contexts must be either explicitly metaphorical or backed by empirical evidence from fields like quantum cognition where the mathematics demonstrably improves predictions [9], [18]. Within management, the most mature crossovers are those grounded in complexity science and systems thinking rather than direct physical instantiation: Meadows' (1999; 2008) leverage points (e.g., information flows, feedbacks, rules, and goals) have influenced organizational diagnostics and policy design; Senge's (1990/2006) learning disciplines encourage distributed sensing; and complexity leadership treats innovation as an emergent property of networked interaction under enabling constraints [47]. Furthermore, network science offers empirically testable principles with direct managerial implications: small-world connectivity reduces path lengths (speeding knowledge diffusion), while scale-free structures imply vulnerability to targeted hub failures and the outsized influence of central actors [49], [3], [27]. Complementary perspectives highlight thermodynamics and self-organization: Prigogine and Stengers (1984) and Nicolis and Prigogine (1977) introduced dissipative structures that emerge far from equilibrium, inspiring the managerial idea that sustained innovation requires "constructive disequilibrium," continual influx of energy/information, and openness to fluctuation [32], [28]. Anderson's (1972) "More is Different" further legitimized the search for emergent laws at higher levels of organization, implying that managerial science need not reduce to microphysics to be rigorous: organizational dynamics can display their own regularities [1], consistent with empirical work on complex systems [10]. The "quantum management" label is most closely associated in practitioner literature with Zohar's writings [52], which contrast "Newtonian" command-and-control with "quantum" organizations that prize meaning,

ethics, and adaptive networks; while these books are influential, academic commentary urges distinguishing inspirational metaphor from falsifiable theory. Stacey's writings and Wheatley's narrative popularization played a similar role helping managers imagine non-mechanistic organizing while more mainstream strategy research supplied analytic scaffolding for adaptation: March's (1991) balance between exploration and exploitation, Eisenhardt and Martin's (2000) identifiable dynamic capabilities, and Teece's (2007) microfoundations of sensing, seizing, and transforming all articulate how firms can navigate uncertainty without invoking physics too literally [23], [13], [44]. Meanwhile, applied fields (healthcare, public services, and education) experimented with complexity-informed interventions that align with "quantum-inspired" sensibilities, such as iterative pilots, feedback-rich redesign, and local autonomy within guiding constraints (e.g., Rosenhead, 1998; complexity applications in leadership and systems practice). Across this literature, formulas from physics function mainly as analogies that illuminate managerial trade-offs: the uncertainty relation represents observation–action limits (more monitoring can perturb behavior, akin to performance paradoxes); Schrödinger's equation, through its linear superposition, supports the idea of holding multiple strategic possibilities in parallel until real-world tests update the organizational "wavefunction"; entanglement illustrates systemic coupling and the need for shared aims and trust, especially in cross-functional or inter-organizational work; and energy–mass equivalence $E = mc^2$ is sometimes used rhetorically to symbolize potential energy stored in intangible assets (ideas, culture, trust) that can be converted into observable outcomes when aligned by leadership, though such uses should remain

metaphorical, not literal. Systems leverage through the narrative strand of complexity leadership: altering the way that information moves and is governed by rules may produce greater impact than increasing resources [25]; in complex environments, leaders should transition from a planning paradigm to a probing paradigm [38]; create an environment where self-organizing behaviors are allowed to occur [47]; and develop networks that have both robustness and adaptability [49], [3]. The middle ground has been further developed by recent research: quantum-like probabilistic framework applications continue to advance the field of behavioral strategy and decision analysis [30], [51], [9], while reviewers and philosophers emphasize the need for clarity regarding what is literal, what is metaphorical, and what is testable empirically [18]. In short, the literature converges on several points: (a) linear, mechanistic models are often insufficient for volatile environments; (b) systems and complexity science provide empirically grounded principles for organizational design and leadership; (c) quantum concepts can be useful as disciplined metaphors or as formal tools in specific subdomains like quantum cognition, but translation to management must avoid overreach; and (d) networked, feedback-rich, learning-oriented organizations supported by dynamic capabilities best embody the spirit of “quantum management” without claiming unwarranted physical literalism [2], [11], [36], [22], [24], [37], [16], [35], [25], [26], [47], [38], [49], [3], [27], [1], [32], [28], [50], [40], [42], [41], [23], [13], [44], [9], [30], [51], [10], [19], [31], [18], [52].

3. Research Gap

Despite rich theory, empirical work that directly operationalizes physics equations in managerial contexts is limited. Many contributions remain analogical, with few validated measures that map, for example, uncertainty bounds or

entanglement-like coordination to organizational performance. Interdisciplinary frameworks exist, but consolidated metrics, cross-industry tests, and causal identification strategies are scarce.

4. Objectives

- To study how key ideas from quantum physics and complexity (uncertainty, superposition, entanglement, nonlinearity) connect to core management practices.
- To propose a simple operational framework, with basic measures, to enhance agility, innovation, and decision quality.

5. Research Methodology

The study used a qualitative, narrative review and conceptual synthesis. Sources were searched in Google Scholar and major academic databases (e.g., Scopus, Web of Science) for the period 1990 to November 2025 using simple keywords: “quantum management,” “complexity leadership,” “cybernetics,” “requisite variety,” “network science,” “quantum cognition,” “nonlinearity,” and “systems thinking.” Inclusion criteria were peer-reviewed journal articles, academic books and chapters, and reputable open resources for core definitions (e.g., the Stanford Encyclopedia of Philosophy, Encyclopaedia Britannica). Exclusions were blogs, non-English items, duplicates, and sources without a clear link between physics/complexity and management practice. Screening was done in two steps (title/abstract, then full text). For each included source, the study extracted: (a) the core physics or complexity idea and any basic formula (e.g., uncertainty, Schrödinger dynamics, entropy, Lorenz/logistic models, network measures), (b) the matching management idea (planning, teamwork, decision-making, structure), (c) the type of evidence (theory, case, empirical), and (d) any simple measure or routine suggested. Notes were then

coded into themes aligned with the objectives (uncertainty trade-offs; superposition and options; entanglement and cross-unit links; nonlinearity and feedback; requisite variety; networks; quantum-like decision behavior). These themes informed a consolidated **concept-to-practice** framework with basic checks (e.g., uncertainty budgets, portfolio entropy, variety audits, network centrality checks, decision-latency ranges). Backward and forward citation tracing reduced omissions and helped cross-check key claims. This was not a statistical meta-analysis; it was a clear, practice-oriented synthesis designed to guide future field testing. Figure 1 shows the conceptual model linking principles, design choices, measures, and outcomes, with mediators and moderators.

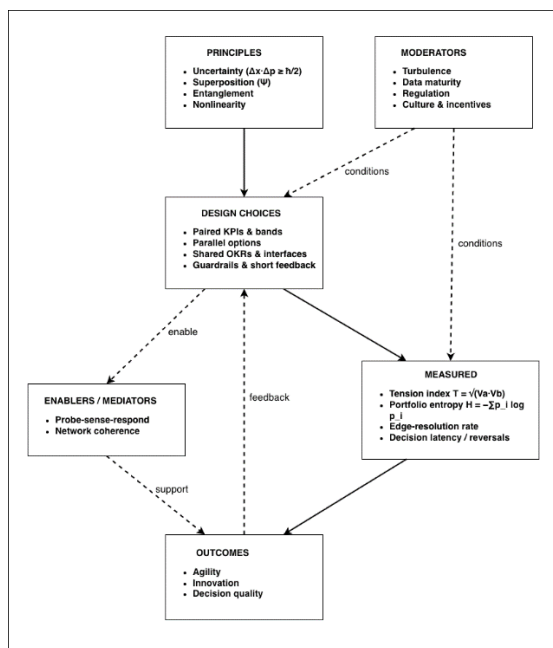


Figure 1: Conceptual model for quantum management.

6. Results and Discussion

6.1 Quantum physics principles and their managerial analogies

1. Uncertainty and trade-offs: In quantum theory, the uncertainty principle says we cannot know two linked variables with perfect precision at the same time. It is expressed as $\Delta x \cdot \Delta p \geq \hbar/2$ [15]. In management, an echo of this appears every day.

When a team fixes a very tight deadline and a single strict KPI, quality and learning often suffer. When leaders demand perfect forecast accuracy, speed of response slows. The lesson is simple: acknowledge trade-offs in advance. Report ranges instead of single points. Track paired metrics together, such as speed–quality, efficiency–resilience, and exploitation–exploration [23]. A helpful practice is to set an “uncertainty budget.” For example, allow a $\pm 10\%$ forecast band and a ± 2 -day delivery band. Treat a breach of both bands together as a red flag. This reduces gaming and keeps the system honest [38]. Over time, teams learn to balance the product of the two variances, much like guarding the product $\Delta x \cdot \Delta p$ in physics. The goal is not zero variance. The goal is a healthy, known band that supports fast action and steady quality.

2. Superposition and option sets: Before measurement, a quantum system is described by a wavefunction Ψ that holds several possibilities at once. Its evolution follows the time-dependent Schrödinger equation $i\hbar \partial\Psi/\partial t = \hat{H}\Psi$ [14]. Strategy can work in a similar way. A firm can keep multiple options “alive” in parallel. Each option is small and testable. After each sprint, the team updates beliefs using the new evidence. A big bet is made only when the evidence is strong. This is the spirit of real options and staged investment [13], [44]. A practical tool here is a simple option board. For each option, record: the key assumption, the next test, the cost of the test, and the success threshold. Also track portfolio entropy (see 1.5). If entropy drops too early, it means the team is killing options before learning. If entropy stays high for too long, it means the team is not converging. Leaders can tune the pace of “collapse” so the organization learns fast without locking in too soon.

3. Schrödinger dynamics and the “organizational Hamiltonian”: In physics, the Hamiltonian \hat{H} captures the energies and interactions that shape

how Ψ changes over time. In organizations, incentives, decision rights, data access, and meeting rhythms play the same role. They define how the “state” of the firm evolves. Change the bonus mix, change decision rights, or open a data platform, and the culture and behavior shift in a predictable direction. In short, design the interaction rules and information flow, and the system trajectory will change. This view supports an enabling style of leadership: tune constraints and connections first, then look for results [47].

4. Entanglement and cross-unit coherence:

Entanglement means parts of a quantum system can be linked in a way that goes beyond classical correlation [17]. In a firm, product, engineering, operations, and risk can behave as if “entangled.” A small signal in demand instantly changes actions in pricing and supply, even before a formal handoff. This is not magic. It comes from shared data, shared goals, and steady rituals. Leaders can engineer coherence by setting shared okrs, running joint reviews, and keeping interfaces clean. Where coupling is valuable, strengthen trust and transparency. Where coupling only adds risk, modularize, and insert buffers [35], [27], [3]. Practical tools include a dependency map, a set of joint metrics, and a short list of “boundary spanners” who watch cross-team health.

5. Energy–mass equivalence and latent potential:

Einstein’s relation $E = mc^2$ reminds us that potential can convert into work under the right conditions [12]. In a firm, the “mass” is knowledge, skills, relationships, and trust. This potential turns into products, services, and impact when structure, tools, and incentives line up. A simple check is to list key intangible assets and ask, “What is the release path?” Examples: a reusable data asset released through an API; a skilled team released through a clear mandate; a community released through a partner program. Dynamic capabilities sensing, seizing, and

transforming are the routines that make this conversion repeatable [44].

6. Information and variety (entropy as a simple gauge):

Shannon entropy $H(X) = -\sum p(x)\log p(x)$ measures uncertainty and variety [36]. This idea is easy to use. Consider an innovation portfolio with five options. Assign a simple probability to each option. Compute H . Very low H means the portfolio is too concentrated. Very high H means it is noisy and unfocused. Aim for a mid-range band that supports learning and convergence. The same idea helps in planning (scenario spread) and HR (skill diversity). When variety in the environment rises, variety in the system should also rise [2].

6.2 Complexity and systems thinking in management

1. Nonlinearity and thresholds:

Many social and technical systems are nonlinear. Small changes can cause large effects. The logistic map $x_{(t+1)} = r x_t (1 - x_t)$ shows how a simple growth rule can shift from stability to cycles to chaos as r changes [24]. The Lorenz equations show sensitivity to initial conditions [22]. Organizations see similar thresholds. Slightly increase utilization, and queues explode. Slightly change incentives, and quality drops. Good design accepts this risk. It uses guardrails (e.g., max WIP), short feedback loops (e.g., weekly reviews), and pre-mortems before big changes [43], [26]. A small simulation in a spreadsheet can reveal likely oscillations. If the system shows repeated swings, reduce delay, reduce gain, or add buffers.

2. Requisite variety and viable control:

Ashby’s law says that only variety can absorb variety [2]. If customers, regulators, and technologies are diverse, then responses must also be diverse. A central team cannot handle all cases alone. The fix is not more rules. The fix is distributed control with clear boundaries. Beer’s Viable System Model gives a simple pattern: local units handle local variety;

higher levels coordinate and set policy; escalation is fast but rare [6]. A quick "variety audit" will help you see that. Make a list of your main categories of disturbances (e.g. Modes of failure, kinds of market changes). Make a list of different ways to respond to each type of disturbance (e.g. Playbook, trained role, automation). If the number of response types is less than the number of disturbance types, you can strengthen the edges of your network by adding new skills or automation.

3. Leverage points and learning loops: Meadows identified key leverage points to apply relatively minor changes with major implications; changing "rules" and/or "information flow" as opposed to increasing resources can be more impactful; while altering mindset/goals has even greater potential for impact [25], [26]. When possible, apply a general principle of fixing "delays" and improving "visibility" prior to creating new work and or new risk. Create a single-page view of both work and risks. Eliminate conflicting KPI's. Improve alignment of unit-level goals. Implement short-cycle learning loops using after action reviews and "safe-to-fail" pilots [35]. These five disciplines — Personal Mastery, Mental Models, Shared Vision, Team Learning, Systems Thinking — will create an organization that continually learns intentionally.

4. Networks and diffusion: Collaboration networks in real world systems are typically both small worlds (short path lengths and strong clustering) and scale-free (a few large hub nodes with many connections) [3], [49]. Small-world structure helps ideas and alerts travel fast. Scale-free structure brings efficiency but hub risk [27], [10]. Managers can map networks with simple tools. Identify top hubs (by degree) and bridges (by betweenness). Protect hubs with backups. Use bridges to spread change. Avoid single points of failure. During change, start with influential nodes, then reach the clusters they connect.

6.3 Leadership and decision-making under uncertainty

1. Match action to context (Cynefin): Not all situations are the same. The Cynefin framework separates clear, complicated, complex, and chaotic domains (Snowden & Boone, 2007). In the clear domain, use best practices. In the complicated domain, analyze and choose. In the complex domain, run parallel probes and learn. In the chaotic domain, act fast to create order, then switch to learning. A one-page playbook helps leaders pick the right move. It prevents over-analysis in complex work and prevents rash action in complicated work.

2. Enable emergence (complexity leadership): Complexity leadership views leaders as enablers of adaptive dynamics (Uhl-Bien et al., 2007). They set the few key constraints. They connect people who need to talk. They remove friction in information flow. They reward learning and cooperation. In physics language, they tune the Hamiltonian of the organization. They do not try to predict every outcome. They design conditions so good outcomes are more likely. A simple checklist helps: Are goals clear and shared? Are incentives aligned across units? Is data easy to reach? Are boundaries and roles clear? Are experiments safe and cheap?

3. Design the decision process (quantum-like judgment): Human judgments show order effects and context effects. Quantum probability models explain these patterns by treating preferences as states that "collapse" when measured (Busemeyer & Bruza, 2012; Pothos & Busemeyer, 2013). Managers do not need advanced math to benefit. They can design better meetings. Collect independent pre-reads before group talk. Rotate the order of presentations. Separate facts from frames on the slide. Use ranges and probabilities instead of single numbers. Track decision latency (time from first signal to choose) and reversal rate (percent of major choices reversed within 90 days). The aim is

lower latency with stable choices. If reversals rise, slow down or improve evidence.

6.4 Organizational interconnectedness and holistic thinking

1. Engineer coupling on purpose: Some work benefits from tight coupling (shared data, shared goals, shared cadence). Other work needs loose coupling (clear interfaces and buffers). Leaders should choose the coupling on purpose. For tight coupling, use shared okrs, joint reviews, and co-location (even if virtual with always-on channels). For loose coupling, use apis, service-level agreements, and modular designs. Re-check coupling after big changes. If failures cascade, decouple. If coordination delays value, couple [17], [35].

2. Classical vs. Quantum-inspired views

Table 1: Classical vs. Quantum Comparison

Dimension	Classical / Mechanistic	Quantum / Complexity-inspired
View of the firm	Machine with parts	Living system with relations
Causality	Linear and stable	Nonlinear and path-dependent
Planning	One plan, full detail	Options, small probes, rolling choices
Control	Central rules, variance cuts	Distributed control, requisite variety
Metrics	Single kpis, point targets	Paired metrics, ranges, system outcomes
Structure	Silos and strict hierarchy	Networks, modular teams, boundary roles
Change	Top-down program	Emergent change under enabling constraints
Risk	Something to eliminate	Something to sense, bound, and learn from
Learning	After rollout	Continuous, with short cycles and reviews

Table 1 summarizes contrasts referenced in [35], [2], [6], [26], [49], and [3].

3. Simple system health checks: Three fast checks support holistic thinking. (A) Variety check: Is

response variety at least as high as disturbance variety? If no, add skills or automate [2]. (B) Network check: Who are the top hubs and bridges? Are they protected and supported [27]? (C) Coherence check: Do cross-unit metrics align, and do teams share the same few goals [35]? These checks take hours, not months, and often prevent bigger problems later.

6.5 Quantum management in practice: patterns and simple measures

Pattern A: Parallel probes before commitment (superposition): Define 2–4 options. For each option, define one critical assumption and one small test. Run tests in parallel. Update beliefs after each sprint. Kill, pivot, or scale. Portfolio entropy $H = -\sum p_i \log p_i$ should start moderate, then drop as evidence accumulates [36]. Record cost per unit learning (test cost divided by expected information gained). It preserves good options and prevents lock-in. It mirrors superposition and controlled “collapse” [13], [44].

Pattern B: Manage paired trade-offs (uncertainty): Pick a critical pair (e.g., speed–quality). Define acceptable bands for both. Review both every cycle. Do not push one at the expense of the other. A simple tension index $T = \sqrt{V_a \cdot V_b}$, where V_a and V_b are rolling variances of the two metrics. Rising T signals stress and likely failures. It keeps the system inside safe bounds and reduces gaming [15], [23].

Pattern C: Requisite variety audits (cybernetics): List top 10 disturbance types. List distinct response types. Map who can trigger each response and how fast. Count of responses vs. Count of disturbances; median escalation time; share of cases solved at the edge. It makes Ashby’s law operational and turns top-down control into guided autonomy [2], [6].

Pattern D: Network-aware change (interconnectedness): Map collaboration network for the domain. Identify top hubs and bridges. Start

change with them. Give them tools and support. Add redundancy for critical hubs. Betweenness and degree for top nodes; reach (share of the network within two steps of seed nodes). Real networks are small-world and scale-free. Working with the structure speeds diffusion and reduces risk [49], [3], [27], [10].

Pattern E: Probe–sense–respond (complex contexts): When uncertainty is high, design small, safe-to-fail tests. Run several in parallel. Learn fast. Amplify what works; stop what does not. Time-to-learning (signal to insight), amplification rate (tests scaled / tests run), and containment rate (tests stopped with low cost). It matches action to context and avoids long delays [38].

Pattern F: Decision process design (quantum-like behavior): Send pre-reads. Collect independent inputs first. Rotate the order of presentations. Separate facts from frames. Decide with ranges and thresholds. Decision latency and reversal rate. Track forecast calibration over time. It reduces order and context effects that distort choices [9], [30].

Pattern G: Align incentives and information (the Hamiltonian view): List the top five incentives and top five data flows that shape work. For each, ask: does it push the system in the desired direction? If not, change it. Cycle time to key outcomes; hand-off count; signal delay from customer to decision. It tunes the organizational “Hamiltonian,” which shapes system evolution without micromanagement [47].

Table 2 presents the consolidated concept-to-practice framework that links physics/complexity ideas to simple managerial measures and routines.

Table 2: Consolidated Concept-to-Practice Framework for Quantum Management

Physics / Complexity concept	Core formula / notation	Management analogue (plain)	Basic measure (how to compute)	Simple routine / tool	Sample indicators & thresholds
Uncertainty principle	$\Delta x \cdot \Delta p \geq \hbar/2$	Paired trade-offs (e.g., speed–quality). You cannot drive both to extreme precision at once.	Tension index $T = \sqrt{V_a \cdot V_b}$, where V_a, V_b are rolling variances of the paired kpis.	Set uncertainty budgets for both metrics, review together every cycle.	Flag if both metrics breach bands in the same sprint; target steady or falling T .
Superposition	State Ψ holds multiple possibilities	Keep several small options alive until evidence is clear.	Portfolio entropy $H = -\sum p_i \log p_i$. Over current options with subjective probabilities p_i .	Parallel probe-and-learn sprints; real options staging.	Start with moderate H ; let H fall only as evidence accumulates.
Schrödinger dynamics / Hamiltonian	$i\hbar \frac{\partial \Psi}{\partial t} = \hat{H} \Psi$	Incentives, decision rights, and data flows act like the “Hamiltonian” that shapes behavior over time.	Cycle time, hand-off count, signal delay (customer signal → decision), before vs. After policy changes.	Tune incentives, decision rights, data access first; then observe system trajectory.	Expect shorter cycle time, fewer hand-offs, lower signal delay after tuning.
Entanglement	Non-separable joint states; Bell-inequality violations	Tight cross-team coupling for shared outcomes; changes in one area move others.	Outcome coherence (shared OKR alignment), joint defect/uptime, cross-team lead time.	Shared okr, joint reviews, clean interfaces, boundary-spanning roles.	Rising joint outcomes; falling cross-team lead time; fewer conflicting kpis.
Energy–mass equivalence	$E = mc^2$	Latent potential in skills, knowledge, trust turns into visible outcomes under the right structure.	Conversion ratio (ideas → shipped features / quarter), reuse rate of assets, capability coverage.	Map intangible assets; create release paths (apis, playbooks, partner programs).	Higher conversion and reuse rates quarter-over-quarter.
Information / variety (entropy)	$H(X) = -\sum p_i \log p_i$	Right level of variety in portfolios, plans, and skills.	Entropy of innovation portfolio, scenario set, skill mix.	Quarterly variety audit; adjust mix to avoid over-concentration.	Entropy in a target band (not too low, not too high).

Physics / Complexity concept	Core formula / notation	Management analogue (plain)	Basic measure (how to compute)	Simple routine / tool	Sample indicators & thresholds
				ation or noise.	
Nonlinearity & thresholds	Logistic map $x_{t+1} = rx_t(1 - x_t)$; Lorenz system	Small parameter changes can cause big swings (queues, defects).	WIP level, queue oscillation amplitude, defect spikes after policy changes.	Set guardrails (WIP limits), shorten feedback loops, simulate before scaling.	No repeated oscillations after changes; stable WIP within limits.
Require variety (cybernetics)	“Only variety absorbs variety”	Match response types to disturbance types; push decisions to the edge.	Vardist-varresp gap: count disturbance categories vs. Unique responses; edge-resolution rate.	Variety audit; add multi-skilling, automation, or decision rights where gaps exist.	Varresp \geq vardist; rising edge-resolution rate; falling escalations.
Viable System Model (VSM)	Recursive control architecture	Local autonomy with coherent policy and escalation.	Escalation time, policy exceptions, rework due to mis-routing.	Clarify VSM roles; codify escalation and policy cadence.	Faster escalations; fewer exceptions; lower rework.
Network topology	Small-world; scale-free; centrality (degree, betweenness)	Innovation and change spread through hubs and bridges; hubs are fragile.	Degree/betweenness of key nodes; reach within two steps; single-point failures.	Map collaboration network; start change with hubs/bridges; add redundancy.	Higher reach early in change; lower dependency on single hubs.
Cybernetics (match action to context)	-	Clear vs. Complicated vs. Complex vs. Chaotic domains.	Probe ratio in complex work; decision latency; reversal rate.	Use probe-respond in complex contexts; act-respond to stabilize chaos.	Lower latency without higher reversal; higher probe ratio in complex domains.
Quantum-like judgment (order/context effects)	State collapse; interference	Meeting design affects choices; order effects are real.	Decision latency, reversal rate, forecast calibration.	Collect independent pre-reads; rotate agenda order; decide with ranges.	Lower latency with stable reversal; better calibration over time.
Exploration	(linked)	Balance discovery	Exploration share of	Time-box	Exploration

Physics / Complexity concept	Core formula / notation	Management analogue (plain)	Basic measure (how to compute)	Simple routine / tool	Sample indicators & thresholds
vs. Exploitation	to superposition / uncertainty	and delivery.	budget/time; time-to-learning; delivery reliability.	exploration; separate or cycle modes; gate with evidence.	share in a target band; faster time-to-learning.

Formulas are used as guiding analogies or modeling tools, not literal laws for organizations. All measures can be tracked with operational data on monthly or quarterly cycles.

Vignettes

Vignette 1: “Working backwards” at Amazon:

Amazon’s “working backwards” method starts from the customer outcome and then designs the product. A small team drafts a mock press release (PR) and a short FAQ before building anything. Several PR/FAQ drafts can exist in parallel. Each draft tells a different story about who the customer is, what problem is solved, and how success will be measured. This maintains many options alive simultaneously; this is like superposition. Leaders give feedback, ask for evidence, and request small tests (for example, a customer interview or a paper prototype). As evidence grows, weak options are dropped, and one option is chosen. In essence, this is the “collapse” phase. The moment a PR/FAQ is approved, the team will then commit and coordinate based on that plan, all incentives, decision authority and data access. Quantum-wise, the team’s “Hamiltonian” is set so the system state is moving toward the desired point [8]. It also allows for very easy-to-track metrics. Teams can track portfolio entropy $H = -\sum p_i \log p_i$ across active PR/faqs to keep enough variation early in the process and avoid locking-in too quickly. They can also track decision latency (from first signal to executive approval), cycle time (executive approval to first shippable outcome), and reversal rate (reversals of major

decisions within 90 days). They can also set an uncertainty budget (for example, allow $\pm 10\%$ scope variance and a fixed two-week discovery window) and monitor a tension index for paired trade-offs (e.g., speed–quality). This method provides for a common body of knowledge to be used across departments in an organization: Product, Engineering, Design, Legal etc., utilize the same PR/FAQ and the same Outcomes thus increasing Coherence and reducing Hand-Off Friction between Departments; The authors found that this method has resulted in faster decision making, less need for Rework Loops and more defined responsibility among employees, as each employee is able to see the same "Finished Future" before they start building it [8]. In practice, the habit is simple: keep options in parallel, test lightly, choose with evidence, and then align incentives and information so execution flows.

Vignette 2: Spotify squads and tribes: Spotify's model organizes teams into squads (small, cross-functional units) that group into tribes; chapters and guilds connect people with similar skills across squads. The model mixes tight coupling where shared outcomes matter and loose coupling where speed and resilience matter. The work that must work together (shared goals, light-weighted standards, regular "rituals") is connected (coherent; productive "entanglement"), allowing different types of work to progress independently via APIs, well-defined interfaces, and smaller batches (supporting requisite variety: many types of problems can be addressed locally at the edge of the system without a bottleneck in the center [21]). A manager can monitor several key indicators to maintain a healthy balance. Firstly, map the collaboration network using social network analysis (degree and betweenness centrality) to identify key points of connection ("hubs" and "bridges"). Secondly, protect these key points by having backup plans and providing adequate training for those who

are responsible for them. Thirdly, monitor three basic metrics that reflect how quickly ideas turn into products being delivered: lead time from when an idea was created to when it became available for use (Lead Time), deployment frequency (Deployment Frequency), and the number of failures due to a lack of change (Change Failure Rate). Fourthly, when tracking the amount of time it takes for two teams to collaborate (cross team dependency cycle time), pay attention to whether one team depends too much on another (indicating potential bottlenecks). Finally, perform a quarterly "variety audit" to list all the types of disturbances (e.g., compliance requests, sudden increases in traffic) that the squads will experience and confirm each squad has a unique plan (playbook) to address most of these disturbance types. Additionally, measure the "portfolio entropy" across all the backlogs of the squads to ensure there is enough "option variety" as squads go about their discovery process. If the collaboration network becomes too centralized (i.e., there are too many "hubs" and not enough "bridges"), introduce some new "bridges" (e.g., create a new Chapter meeting or a common demo day) to provide additional ways for teams to collaborate. If the work being done is becoming too "coupled" (i.e., too dependent on other work) and creating cascading failures (i.e., a single point of failure causes a chain reaction of downstream failures), break the coupled work into separate modules or make the interface to the dependent work lighter weight. This model allows for "emergence," i.e., small, safe changes are made to the system through a small world network of teams/guilds and thus allow for rapid propagation of good practices throughout the organization (but increase the risk of damage to "hubs" if they are not properly protected). In short, the lesson is simple and repeatable: Design the organization's structure so that the correct work is tightly coupled, the remaining work is decoupled, and the organization's

network is resilient. This will enable faster learning, fewer escalations, and greater overall resilience in release cycles [21].

The common theme of this book can be applied across each of its five parts. Uncertainty should always be treated as a normal part of business life, so that you are able to create an environment to evaluate and mitigate the risks associated with uncertainty by managing trade-offs in pairs [23], [15], hold options open long enough to develop knowledge about your options, and make decisions based on evidence [44], [13], adjust your organization's incentive structures, decision rights and data availability before attempting to evolve the structure or processes of the organization [47], engineer interdependencies when they add value to the organization, but also ensure that those same interdependencies do not create unnecessary risk through modularization [17], [35], and finally match the appropriate action to the appropriate level of complexity in the situation at hand, i.e., determine if the situation is complicated, and if so analyze, or if the situation is complex and requires probing [38]. Using simple metrics such as entropy to measure variety, a tension index to measure paired trade-off, variety audits to measure viability, and network centrality to measure changes will allow you to visualize and measure the impact of these ideas in a repeatable manner [10], [36], [27], [2].

7. Findings

A Quantum Complexity Perspective on Organizational Agility and Innovation is demonstrated to be a useful approach to understanding how managers can operate effectively in uncertain environments. Key concepts from this perspective can be easily translated into management practice. In an environment where uncertainty exists, it will become easier to use pairs of metrics and “budgets” for each type of uncertainty. This makes it possible to apply

“superposition” (i.e., running multiple options at once) with smaller-scale tests of each option prior to large investments of resources. “Entanglement” (e.g., creating a team of people who are all working towards common goals and have clear interfaces between them) facilitates the ability of various teams to share success or failure as a collective outcome. When applying these concepts, there are several simple measures that can facilitate their application; entropy provides a measure of the diversity of a given set of options and outcomes (and can provide a measure of the breadth of the organization’s response); a Tension Index can help organizations manage trade-offs between speed and quality; and a variety audit can be used to determine whether the responses to various forms of disturbance are consistent with the nature of those disturbances. Finally, network centrality analysis can be applied to identify the critical “hubs” and “bridges” within an organization that need to be leveraged in order to enable change. These tools, along with a decision-making framework based upon the Cynefin model, can be used to guide organizational teams to engage in probing actions when confronted with complex problems, and to engage in analytical behaviors when confronted with complicated problems. Additionally, these tools can be used to design decisions that reduce the influence of both the order effect and the context effect using pre-reads, rotating the order of presentations of alternatives, and providing range estimates (as opposed to single point estimates). Furthermore, tuning the organization’s incentive structures, decision rights, and information flows will act similarly to changing the organization's “Hamiltonian”, and will result in changes to behavior without requiring the level of control associated with micromanaging. Overall, these steps can enhance the organization’s agility, promote its ability to innovate, and increase the quality of its decisions. These steps may also

provide a simple, testable, and measurable framework that future studies can assess and modify.

8. Conclusion

The study indicates that a quantum management approach is an appropriate lens through which to view companies that operate in an environment of rapid change and/or great uncertainty. Quantum management incorporates some of the most fundamental concepts from physics and complexity theory into the thinking process of day-to-day management while avoiding the idea that companies will behave in accordance with the laws of physics as they apply to the physical world. The uncertainty principle represents the need to develop solutions that address trade-off pairs and to utilize multiple alternatives (e.g., targets) rather than relying on a single target or alternative solution. Additionally, the uncertainty principle serves as a reminder that there may be limits to one's ability to predict outcomes, and that these limitations should be acknowledged. The concept of superposition is a guideline for developing a range of small alternatives (options), testing each of them briefly, and committing to a particular option only after sufficient evidence exists to justify such a commitment. Finally, entanglement provides a conceptual framework for designing common objectives for linked teams and for establishing clear interfaces among those teams; in doing so, it enables teams to act in concert with less resistance. The basic metrics provide a means to operationalize each of the above concepts. For example, a measure of entropy (a term borrowed from thermodynamics) can be used to track the diversity of a portfolio. Similarly, a tension index (that is based upon two variables that are interdependent, e.g., speed and quality) can be used to monitor the tension that arises between competing demands within a system. Variety audits can be used to determine whether an organization has developed an adequate number of

response strategies to address the types of disruptions that it is likely to experience. Network analysis can be employed to identify the hubs and bridges in a company's network structure that facilitate the diffusion of change throughout the organization and minimize the risk of disruption. In addition, the study illustrates how leaders can create incentives, grant decision-making authority, and establish information flow patterns to effect changes in organizational behavior on a large scale – like how adjustments are made to the "Hamiltonian" function that determines the trajectory of a system. The Cynefin Framework can assist leaders in identifying the type of problem an organization is experiencing (i.e., complicated vs. Complex) and selecting an appropriate course of action to address that problem. However, this does not mean that the above approaches would supplant the established management practices. Rather, the new approaches provide additional balance and reality to the planning and control functions inherent in managing dynamic, living systems. While the review highlights the many accomplishments of quantum management, it also identifies areas that require further research to advance the field. Specifically, the field requires the development of standard metrics that are acceptable across all industries to measure an organization's uncertainty budget, its portfolio entropy, its network coherence, and the degree to which its variety matches the types of disruptions that it is likely to experience. Further, the field requires comparative experimental studies to evaluate the effectiveness of quantum-inspired decision processes relative to traditional planning approaches across various industries. Additionally, the field requires the development of theoretical linkages between the decision processes of individuals and the systemic outcomes of those decisions. From a practical perspective, managers can begin using quantum management today by

identifying the key trade-offs that their organizations must navigate, maintaining multiple options, creating simple boundaries, shortening feedback loops, and aligning teams toward a limited set of mutually accepted objectives. By measuring and refining these practices over time, quantum management can evolve into a tested, replicable, and everyday means of improving decision making, innovation, and agility in actual organizations.

Implications of the Study

The research provides an obvious toolkit that can be used by managers in situations of uncertainty. Managers will have the ability to monitor paired trade-offs; they will be able to run small parallel options; they will be able to monitor shared outcomes as a means of creating alignment between their team members. Simple tools such as portfolio entropy; variety audits; network maps; and decision latency are simple tools which can be put on a manager's dashboard (i.e. Dashboard) at some frequency. Leaders can create incentives; and alter how managers make decisions (in terms of decision rights) and alter how information is distributed (in terms of data flows) as a way of creating appropriate behaviors without having to create overly controlling processes. Trainers can take the ideas from this research and develop them into short play books and/or training routines. When managers and trainers work together, they can provide a basis for faster learning; improved innovation; and improved reliability with regards to decision-making.

Future Research Directions

This study is mostly theoretical and would benefit from further empirical testing to support these concepts. It is recommended that future research develop and test new, easy to use measurement instruments for uncertainty budgeting, portfolio entropy, the tension index, network coherence and variety matching. The empirical validity of these methods should be tested using both

field research and longitudinal designs within a range of sectors. The research also should provide empirical evidence of how team and organizational performance are affected using quantum style decision making models as well as which situations will result in successful or unsuccessful use of this methodology. A wide range of methodologies such as randomized trials, quasi-experimental designs, simulation studies and public data sets may be used to increase the causal power of this research and the external validity of its findings.

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Working Capital Management on Corporate Firm Performance of NSE Listed Companies in Indian

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Accepted: 10.04.2026 Published: 30.04.2026 Page No. 65 – 71 DOI: 10.5281/zenodo.19909421

Abstract

The goal of this research is to determine whether WCM influences the financial success of Indian publicly traded enterprises. Accounts Payable and Accounts Receivables, a metric of Working Capital Management and Return on Capital Employed, a measure of financial performance was taken from the annual reports and 14 firms between 2014 and 2023. The obtained data were analyzed by employing both Fixed Effect Model and Random effect Model using panel data estimate strategies. The findings of the research suggest that one of the most important factors that determine the profitability of service-oriented businesses that are publicly traded in India is how well the working capital is managed. Businesses in India should make it a top priority to develop and apply efficient practices for managing their working capital if they want to improve their overall performance. In addition, the management of service firms needs to make certain that the amount of time taken to pay back creditors is increased; doing so would be beneficial for increasing service companies' overall performance.

Keywords: Publicly Listed, Financial Performance, Annual Report, Fixed Effect Model and Random Effect Model

1. Introduction

Managing working capital has been a concern for organizations since the beginning of time, and it is regarded as one of the most prevalent issues. Regardless of whether the company in issue is public or private, WCM is a crucial metric for assessing the

financial health of a business (Abbas and Isiaka 2021). A sizable amount of a company's operating capital is comprised of WCM in addition to other non-current assets like real estate, buildings, plant, and equipment, and so forth.

According to Umenzekwe et al. (2021) in the business world, working capital refers to the money that a company has on hand to carry out its operations daily. WCM can also be thought of as operational capital. The net current assets of a corporation are what are used to calculate working capital. According to Nguyen et al. (2020) research, WC is the primary factor that contributes to the success of any given business. In a similar vein et al. (2020) define WC as the resource that is required daily by an organization in order to convert raw materials into finished goods that can then be sold to end consumers. According to Demireli et al. (2019), for a company to achieve long-term success and sustainability, management needs to take workplace culture very seriously.

India's publicly traded companies are successful due to the efficiency and effectiveness of their finance departments, including their WCM. According to Gitman and Zutter (2014) a cash management program is one that enables an organization to meet its immediate obligations. The goal of WCM is to create a stable balance between a company's assets in order to ensure enough cash flow for short-term obligations in the future.

The significance of effective WCM for the performance of publicly traded companies in India cannot be overstated. The profitability of a firm, together with its operational efficiency and financial

performance, may be positively impacted by enhancing its working capital management capabilities. According to Oke and Adeyemi (2017) assert that companies that effectively manage their working capital stand a better chance of achieving long-term growth as well as good returns on investment. This is so that the company would be in a better position to expand over time with properly managed working capital.

On the other side, if a firm performs a poor job of managing its working capital, it could impair the company's financial success. A high inventory level or a large accounts receivable balance can negatively affect cash flow and lead to decreased profitability and liquidity. A business may have an excess of inventory or receivables if it has an excessive amount of inventory. If the debtor is not able to fulfill its financial obligations, the excessive amount of short-term debt can similarly damage the reputation and credit rating of the organization.

Working capital management is primarily concerned with current assets, such as cash and inventory. WCM makes ensures that the company's commitments do not always go beyond the extent of its liquid assets. According to Ironkwe and Wokoma (2017) state that maintaining a sufficient balance between payables, inventory, and receivables is a prerequisite for WCM. Businesses' daily activities are impacted by this requirement.

Working capital management (WCM) is defined by Etale and Bingilar (2018) as the process of managing a business's assets and liabilities to reduce the likelihood that it won't be able to pay its present debts and to avoid acquiring unnecessary assets. This highlights the significance of efficient WCM, as research has shown that it significantly affects a company's profitability and financial performance (Hiram & Willy, 2017).

Furthermore, considering the conflicting results of previous research on the topic, a study is

required to ascertain whether WCM influences the financial performance of publicly traded service companies in India. In addition to the literature review, the remaining sections include the research procedure, findings, discussion, and recommendations.

2. Review of Related Literature

Odiri (2016) suggests that a company should be able to maximize its liquidity and profitability by having a balance between its current assets and its current liabilities. Joseph and Amah (2016) state that when management can balance the business's immediate assets and debts in a way that guarantees it can pay all its short-term obligations when they fall due, that is when working capital management is effective.

The phrase "working capital management" (WCM) was first used by Tanveer et al. (2016) to describe the process of keeping an eye on a business's short-term assets and liabilities while avoiding overinvesting in the former. WCM is the act of overseeing an organization's "working capital." The goal of working capital management is to keep short-term assets and liabilities in a balanced and healthy proportion. This led to the development of this accounting style.

In terms of cash conversion, inventory turnover times, AR/AP cycle lengths, operational cycle lengths, and other metrics, Chen et al. (2016) believe that WCM is effective. According to Adamu and Hussaini (2015) suggest that the reason behind the creation of WCM objectives might be attributed to their direct influence on a firm's financial viability and solvency.

Inventory conversion period, cash conversion cycle, times for collection and payment, AR and AP cycles, and net trading cycles are some of the aspects of WC management. The research's conclusions indicate that WCM is crucial to an organization's productivity and financial health.

Despite this assertion, not much study has been conducted to evaluate the potential influence of WCM metrics, such as accounts payable and receivable, on the financial performance of publicly traded service companies in India.

3. Financial Performance

The idea of financial performance can be defined and examined using a range of written resources. Odiri (2016) says that because financial ratios show connections between factors that may be found in yearly reports and accounts, they offer a more thorough study of a company's financial performance. A company's financial performance at the firm and market levels can be assessed using a variety of approaches found in the accounting literature, including Tobin's Q, share price value, return on invested capital, earnings per share, book value per share, earnings yield, and many more metrics.

The return on capital employed (ROCE) ratio was the only financial efficiency parameter used in this investigation. One of the best ways to assess how well a business is doing is to look at its return on capital employed (ROCE; Adamu & Hussaini, 2015). Divide operating income by total capital utilised to get return on capital employed, profitability metric. A higher return on capital employed (ROCE) is indicative of improved financial performance, according to Abbas and Isiaka (2021).

Akir and Kucukkaplan (2020) as well as Nguyen et al. (2020) claim that ROCE is a highly effective indicator of a company's performance and success. Although prior studies have linked WCM to the financial performance of organizations in both developed and developing nations, it is unclear whether WCM is a key factor of ROCE for publicly listed service companies in India. This does not alter the reality that WCM and financial performance are related. We developed a conceptual model of the

research that may serve as a basis for estimating the empirical model of the study after taking all this information into consideration.

4. Research Methods

The research sample consisted of all non-financial companies that were listed on the National Stock Exchange (NSE) trading floor. In India's non-financial sector, there are seventy-five (75) publicly listed enterprises.

Additionally, the service companies that are publicly listed on the NSE were selected using a procedure known as stratified random sampling. As of December 31, 2023, twenty publicly traded service companies were listed on the NSE. Out of them, fourteen (14) were carefully selected based on inclusion and exclusion criteria.

The research team obtained the data for their analysis from the websites and annual reports of NSE-listed service companies between 2014 and 2023. Accounts Payable and Receivable were used to determine WCM, whereas Return on Capital Employed was used to measure financial performance. Considering all of this, the empirical model that was estimated for the study was as follows:

$$ROCE = f(ACPAY, ACREC) \quad \text{eq. 1}$$

$$ROCE_{it} = \delta_0 + \delta_1 ACPAY_{it} + \delta_2 ACREC_{it} + \varepsilon_{it} \quad \text{eq. 2}$$

The implicit (Equation 1) and explicit (Equation 2) versions of the study's regression model are displayed below. Where AP and AR are the accounts payable and receivable terms in days, ROCE is the return on capital employed, ε_{it} is the error term, and δ is the regression coefficient of the variables. WCM observations of AR and AP are the independent variable, and financial results are the dependent variable.

Panel data were gathered for Indian companies that are listed on stock exchanges from 2014 to 2023. The data analysis was done using a panel data estimate method that incorporated both

Fixed and Random Effect Models. Statistical techniques including descriptive, inferential, and diagnostic were applied throughout the analysis. The Variance Inflation Factor (VIF), heteroscedasticity, minimum and maximum values, kurtosis, Pearson correlation, and regression using the Fixed Effect Model and Random Effect Model were among these techniques. According to the a priori hypothesis, if the WCM measurements improve by one unit, service organizations in India can predict a similar one-unit rise in their financial performance. On the presumption that WCM measurements have been becoming better over time, this prediction is made.

5. Results

Table 1: Descriptive Statistics

Statistics	ROCE	AP	AR
Mean	2.510	389.55	167.83
Median	4.575	185.39	95.065
SD	16.288	66.091	90.656
Min.	-92.690	0.000	0.510
Max.	45.560	289.6	866.990
Kurt.	20.011	20.482	6.9616
Skew.	-3.373	4.0136	2.0992
Obs.	138	138	138

Source: Author Source, 2024

Table 1 provides a summary of the descriptive statistics for ROCE as well as the two independent variables (AP and AR) for the sample of listed service businesses that were conducted in India from 2014-2023. It was discovered that AP had the greatest mean, which was 389.55, followed by AR, which had 167.83, and their respective medians were 185.39 and 95.065. Since the WCM measures were presented in days, this is to be expected. Therefore, according to this finding, all other factors being equal, the average number of days for payable and receivable accounts for the listed service companies in their inventory are 390 days (AP) and 168 days (AR).

The dispersion was greatest for AP (66.001), while it was at its lowest for ROCE (16.288). According to the standard deviation, the

financial performance indicator varied by over 16% on average throughout the period of analysis. The minimum for AP is set at zero, while the minimum for AR is set at 0.51. This indicates that the number of days it would take some listed service firms to pay their inventories is zero, while the number of days it would take to receive receivables is twelve.

In addition, the values of skewness for the WCM measures of AP (4.013) and AR (2.099) are both positive, except for ROCE (3.373), which has a negative value. This finding suggested that all the WCM measures went in the same direction, except for ROCE, which moved in the opposite direction of the WMC measures that were investigated in this study. In addition, the kurtosis values for ROCE (20.011), AP (20.482) and AR (6.9616) all had a kurtosis value that was larger than 3, which is a sign of a leptokurtic distribution. A leptokurtic distribution is a distribution that has the potential to raise the possibility of a tremendously poor performance by service organizations in India.

Table 2: Pearson Correlation Result

Statistics	ROCE	AP	AR
ROCE	1.000		
AP	-0.082	1.000	
AR	-0.190	0.768	1.000

Source: Researcher Compilation, 2024

Table 2 presents the results of the analysis of the correlation between the dependent and independent variables about the service companies that are publicly traded in India. All the WMC measures, including AP (r = -0.082) and AR (r = -0.190), were shown to have a negative correlation with performance measures (ROCE), as the investigation's findings demonstrated. According to these findings, the Return on Capital Employed (ROCE) for publicly traded service companies in India has a negative correlation with WCM indicators (AP and AR).

Table 3: Result of the Variance Inflation Factor (VIF)

Parameters	VIF	1/VIF
AP	1.43	0.302
AR	1.43	0.302
Mean VIF	1.43	

Source: Researchers’ Compilation, 2024

Table 3 displays the results of the multicollinearity test that was conducted on the NSE-listed service providers that were included in the sample. Since the mean VIF (1.43), which is less than the conventional mean VIF benchmark of 10, the panel dataset satisfies one (1) of the axioms of panel linear regression. This is because the fact that there is no multicollinearity disadvantage in the model of WCM and service providers' performance in India implies that there is no multicollinearity disadvantage. In addition to this, there was not a single correlation coefficient that was greater than 0.8 (Gujarati, 2003; cited in Okoro & Ekwueme, 2021 and Okoro & Ihenyen, 2020), which indicates that no two variables were perfectly related with one another.

Table 4: Breusch-Pagan/Cook-Weisberg Test for Heteroscedasticity

F-Value	65.33
Prob. F	0.000

Source: Researchers’ Compilation, 2024

According to the findings of the statistical study, the Breusch- Pagan/Cook Weisberg F-value is 65.33 and there is a probability that is more than F, which is 0.000. According to this conclusion, which is significant at the 0.05% level, there does not appear to be any evidence of heteroskedasticity in the variables that were investigated. In addition to this, it is quite likely that the panel dataset does not demonstrate unequal variance. This result also satisfies an additional tenet of the linear panel regression methodology.

Table 5: Impact of WCM Measures (AP and AR) and Financial Performance (ROCE) of the Publicly Listed Service Companies

Estimator(s)	Fixed Effect (FE)		Random Effect (RE)		
	Variable(s)	Coefficient	Prob.	Coefficient	Prob.
AP		0.002 (0.870)	0.388	0.030 (1.190)	0.236
AR		-0.025 (-2.270)	0.025	-0.026 (-2.350)	0.019
Constant		5.895 (3.140)	0.002	5.638 (3.020)	0.003
F-value		3.470			
F-Probability		0.034			
R ² (within)		0.053			0.052
R ² (between)		0.080			0.028
R ² (overall)		0.045			0.046
Wald Ch ² (3)					6.470
Prob. Ch ²					0.039
Hausman Test		Chi2(2) = 9.41		Prob>Chi2= 0.000	

Source: Researchers’ Compilation, 2024

Table 5 illustrates the financial performance (ROCE) and WCM metrics (AP and AR) of publicly traded service companies in India. According to the findings of the RE, the coefficient for AP is 0.0308, which indicates that the changes in ROCE brought about by the sampled service companies in India's AP will amount to around 3.08% (rise). In addition, the AR value of (-0.0266) will result in changes in ROCE of around 2.66% (a reduction); this condition is comparable to the one that was reached in the FE result.

In addition, the findings of the t-test performed on AP indicated that this component has a positive and minor influence on ROCE (t = 0.87; prob. = 0.388). On the other hand, it was demonstrated that AR has a negative and significant effect on the ROCE of publicly listed service businesses in India (t = -2.27; probability = 0.025).

The overall coefficient of determination (R²) for FE is calculated to be 0.0454, whereas the overall coefficient of determination (R²) for RE is calculated to be 0.0464. This indicates that the WCM measurements, taken as a whole, were responsible for approximately 4.64 percent of the variance in ROCE. The findings of the Hausman test indicate that FE is superior to RE in terms of

effectiveness ($\text{Prob} > \text{Chi}^2 = 0.000$). As evidenced by $F = 3.470$ and $\text{prob. Chi}^2 = 0.039$, WCM (AP and AR) had combined major impacts on the financial performance (ROCE) of publicly listed service organizations in India. This was the case since WCM was responsible for both ACs.

In conclusion, the findings suggest that service providers in India could potentially gain financial benefits from increasing the number of days that it takes debtors to repay their debts. It is consistent with the findings of Abbas and Isiaka (2021) and Akir and Kucukkaplan (2020) to find that WCM influences financial performance.

6. Conclusion and Recommendations

When it comes to the bottom line, it is realistic to predict that the practices of a company regarding the management of its working capital will have a significant influence on the success of any modern corporation that comes into possession of a significant amount of cash on hand. Because the procedures that an organization uses to manage its working capital are directly tied to the firm's ability to make profits, this is the case. Although this may be the case, certain businesses have only a very small amount of cash invested in their working capital. This may or may not affect the financial outcomes of the company, depending on the circumstances. Because these two points of view are opposed to one another, the purpose of this research was to determine whether the efficient management of working capital plays a role in the financial success of publicly traded service firms in India.

In the simplest terms, the efficiency with which publicly traded companies in India manage their working capital is an essential variable that organizations achieve. Businesses that can properly manage their working capital often see improvements in their bottom lines, as well as gains in their profitability, decreases in their operational

expenses, and overall improvements in their financial standing. Consequently, for Indian businesses to achieve long-term growth and profitability, they must apply successful procedures to manage their working capital. This is to ensure that they can reach their goals.

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Beyond Pilgrimage: Evaluating Hospitality Facilities around the Takht Sri Damdama Sahib

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Accepted: 10.04.2026

Published: 30.04.2026

Page No. 72 – 75

DOI: 10.5281/zenodo.19909597

Abstract

In developing economies like India, religious tourism plays a pivotal role in regional economic development. This case study focuses on understanding the ecosystem of hospitality around the Takht Damdama Sahib situated at Talwandi Sabo village in Bathinda district of Punjab, which is a place of attraction for visitors. The case study examined the hospitality facilities, including capacity, pricing, and booking mechanism and other facilities, of 10 hotels situated near Talwandi Sabo village. The findings indicated the dominance of budget and mid-range hotels with wide availability of basic amenities but limited workforce, poor standardisation of services, and lack of digital platforms for booking as major challenges to be addressed. This case study will provide valuable insights regarding the sustainability of hospitality sector around the pilgrimages.

Keywords: Pilgrimages, Hospitality, Takht Sri Damadama Sahib, and Religious Tourism

1. Introduction

In recent years, there has been a notable increase in tourism to religious destinations globally, encompassing a variety of religious traditions, and this trend has emerged as a significant catalyst for economic development. Nevertheless, the body of work in this field is somewhat constrained. The primary elements influencing tourism for religious purposes include the growth of specific religious traditions, the variety of tourist

motivations, the advancement of media coverage regarding religious sites and events, and the active collaboration between religious and secular authorities. It is essential to develop effective strategic plans aimed at promoting tourism in religious destinations, which will contribute to the economic development of these regions. Historically, individuals' journeys were predominantly influenced by religious motivations. The initial individuals who embarked on journeys were pilgrims, undertaking travel to various locations with the intent of engaging in spiritual worship (Hvizardova, 2018).

Takht Sri Damdama Sahib, located in Talwandi Sabo, holds significant importance due to the literary contributions of Guru Gobind Singh Ji during his stay in 1705. It is at this site that Guru Gobind Singh prepared the revised and authentic version of the Adi Granth, culminating in the final edition known as Sri Guru Granth Sahib Ji, regarded by Sikhs as their Eternal Guru¹.

¹ <https://www.goldentempleamritsar.org/top-religions-of-the-world/sikhism/five-takhts/takht-sri-damdama-sahib.php?>

Over a year, he added new teachings to the original Sikh scriptures compiled by Guru Arjan Sahib, which previously included the wisdom of all preceding Sikh Gurus along with verses from Guru Tegh Bahadur. The final edition of the scriptures produced at Damdama Sahib is referred to as the 'Damdama Sahib Bir'. During this period, many

converts embraced Sikhi and joined the Khalsa. The term 'Damdama' translates to a resting place, highlighting the location's significance as a sanctuary after Guru Gobind Singh's defensive battles against Mughal oppression. This period was marked by tragedy, as two of his sons were martyred, leading the Guru to seek refuge at Talwandi. The current structure of Takht Sri Damdama Sahib, built in the 1970s under Sant Seva Singh's supervision, features a spacious hall with high ceilings, two pavilions, and a 2-meter-high marble platform serving as the sanctum for the Guru Granth Sahib. The hall is adorned with geometric and floral glass designs and topped with a prominent gold-plated dome and khanda at the apex. Recognized as the fifth Takht on November 18, 1966, following recommendations from a sub-committee appointed by the Shiromani Gurdwara Parbandhak Committee, its designation as Guru Ki Kashi emphasizes its spiritual and educational significance. A further affirmation of this status came during the tercentennial celebrations of the Khalsa, when the Government of India officially recognized Takht Sri Damdama Sahib in April 1999. Throughout his time here, Guru Gobind Singh issued Hukamnama to the Sikhs, reinforcing the area's status as a prominent Takht. After composing Zafarnama, he successfully battled at Muksar before resting at Talwandi Sabo, where his orders for Sikhs further solidified the site's legacy as a spiritual headquarters.

Damdama Sahib serves as the headquarters for the Nihangs. There exist 10 Gurudwaras and three tanks. The three tanks are Nanksar Sarover, Akalsar Sarover, and Gurusar Sarover. The initial named tank is linked to Guru Nanak Dev Ji, who reportedly visited this village in 1510 A.D. during his second Pad Yatra to Rajputana. The Akalsar Sarover is linked to Guru Gobind Singhji, and a sip of its water is thought to provide protection from

diseases and afflictions. The Gurusar Sarover is believed to have been excavated under the directives of Guru Teg Bahadurji.

2. Research Methodology

In alignment with the study's requirements, primary data were gathered from 10 hotels located in proximity to Sri Damadama Sahib through a structured questionnaire. This questionnaire encompassed inquiries related to various structural aspects of the hospitality sector, as indicated in Table 1. The selection criteria for the hotels stipulated that they must be within no more than 5 kilometers, adhering to the purposive sampling method.

Findings

Table 1 indicates the details regarding the nature and facilities offered by them.

Table 1: Details of Hotels

Sr. No.	Type of hotel	No. of rooms	No. of employees	Charges per day (Rs.)	Facilities provided	Mode of booking
1	Budget	<10	<5	Below 1000	AC room, free wi-fi, parking facility	Walk-in, phone
2	Budget	<10	<5	Below 1000	AC room, free wi-fi, parking facility, restaurant	Walk-in, phone
3	Mid-range	10-20	<5	Below 1000	AC room, free wi-fi, parking facility, restaurant	Walk-in, phone
4	Mid-range	<10	<5	Below 1000	AC room, free wi-fi, parking facility, restaurant	Walk-in, phone
5	Mid-range	<10	<5	Below 1000	AC room, free wi-fi, parking facility	Walk-in, phone

Sr. No.	Type of hotel	No. of rooms	No. of employees	Charges per day (Rs.)	Facilities provided	Mode of booking
6	Mid-range	<10	5-10	Below 1000	AC room, free wi-fi, parking facility, restaurant	Walk-in, phone
7	Mid-range	<10	<5	Below 1000	AC room, free wi-fi, parking facility	Walk-in, phone
8	Luxury	<10	5-10	1000-2000	AC room, free wi-fi, parking facility	Walk-in, phone
9	Luxury	10-20	<5	1000-2000	AC room, free wi-fi, parking facility	Walk-in, phone, online booking app
10	Luxury	<10	<5	1000-2000	AC room, free wi-fi, parking facility	Walk-in, phone

Source: Authors' compilation

3. The Local Hospitality Ecosystem

As a result of the fact that seven out of ten hotels fell into either the budget or the mid-range categories, with room rates reaching up to INR 2,000, the hospitality industry is concentrating its efforts on the factor of affordability. An organization of the sectors in this manner displays the degree to which individuals or tourists in such locations are sensitive to pricing. It is also worth noting that the bulk of the hotels have fewer than ten rooms, which is a strong indication of the restricted ability of the hotels to accommodate guests. Also, none of the hotels has more than ten employees at any given time. If the workforce is restricted in this manner, it has an impact on the maintenance, professionalism, and quality of service. When it comes to the services that are provided, virtually every company provides air-conditioned rooms, parking facilities, and free

wireless internet access. Additionally, some hotels also have restaurants, which provide an additional value to the property by giving the convenience of having access to sustenance. It may come as a surprise to learn that nine out of ten hotels continue to rely on conventional booking methods, such as walk-in registration and telephone reservations.

4. Strategic and Operational Challenges

This case study brought to light several operational and strategic difficulties throughout the organization. Although there are limited accommodations available, it is possible that they will not be sufficient to accommodate travelers during busy seasons. In addition, the limited availability of online bookings makes it difficult to arrange trips for guests and reduces the visibility of hotels on various web platforms. The management of customers will be significantly more difficult if there are restricted personnel.

From the point of view of the management of the hospitality industry, Takht Sri Damdama Sahib is a market that is both big in volume and low in cost. It is reasonable to anticipate that demand will remain consistent because of the religious significance of the item; nonetheless, the absence of a digital system and the lack of up-to-date technology would be key problems.

5. Conclusion

Considering the pilgrimage culture, the hospitality sector near Takht Sri Damdama Sahib focuses on providing affordable accommodation facilities, as the purpose of visiting such places is religious. Although the sector offers basic amenities at affordable prices, there is a need for digital integration along with professional services. Along with improved service quality, the enhanced adoption of new technology and coordination among stakeholders will assist in the sustainable

development of such a pilgrimage without compromising the spiritual ethos.

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Managing Menstrual Safety and Hygiene after Fire Disasters: A Qualitative Study of Women and Girls in Korail Slum, Dhaka, Bangladesh

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Accepted: 10.04.2026

Published: 30.04.2026

Page No. 76 – 82

DOI: 10.5281/zenodo.19910309

Abstract

Fire disasters are an ever-present danger in urban slum areas of Dhaka, particularly impacting women, and girls by heightening their pre-existing vulnerabilities in menstrual safety and hygiene management. This study aims to examine the experiences of women and girls between 15-49 years of age in menstrual hygiene management in the aftermath of fire disasters in Korail Slum, Dhaka. A qualitative research study was conducted, based on 22 in-depth interviews of women and adolescent girls, along with 6 key informant interviews of NGO workers, community leaders, health workers, and disaster workers. The thematic findings of this study indicate that fire disasters have a severe impact on the menstrual hygiene management of women and girls in Korail Slum, resulting in considerable discomfort, distress, and dignity loss. Gender issues were also identified as an important factor in the menstrual hygiene management of women in the aftermath of fire disasters in urban slum areas of Dhaka. Although women have employed coping strategies in their menstrual hygiene management in the aftermath of fire disasters in Korail Slum, the findings of this study indicate that the support of institutions in menstrual hygiene management is scarce.

Keywords: Fire disaster, Urban Slum, Menstrual Hygiene Management, Women and Girls

1. Introduction

Menstrual safety and hygiene management (MSHM) is an important public health and human

rights issue, mainly for women and girls living in resource-constrained environments. For proper hygiene during menstruation, it is essential for women and girls to have access to safe and affordable menstrual materials, water, proper sanitation facilities, privacy, and information. [1]. In the context of Bangladesh, the growing problem of urbanization has resulted in the formation of informal settlements, commonly referred to as slums, where the provision of water, sanitation, and hygiene facilities has remained inadequate [2]. Research has shown that in slum areas of cities, the needs of women and girls in terms of managing their menstruation have remained a challenge, including the lack of sanitary facilities, inadequate provision of sanitary materials, lack of private toilet facilities, and social stigmas attached to the discussion of the topic. [3] Vulnerabilities during and after disasters strike are more pronounced. Bangladesh, being geographically ill-fated as a disaster hotspot with a myriad of flood, fire, and cyclone threats, [4] ranks high in global disaster risk. In the urban slums of Bangladesh, particularly the Korail Slum in Dhaka, fire disasters are frequent as the slum has a high risk of fire due to the absence of adequate housing, the presence of narrow roads, and the risk of fire to the wiring [5] Disasters cause interruptions to the normal functioning of a community, and during this time, the critical services that services the community, such as water, sanitation, and housing, are often damaged and this increases the degree of vulnerability in the MHM [1]. Research from humanitarian and emergency responses indicates

that menstrual needs have often not been integrated into disaster responses and recovery due to the lack of consideration of food, shelter, and medical care [6]. Women and girls have had to resort to unsafe practices, such as the extension of use of menstrual materials or limiting movement to maintain privacy [7]. Korail Slum, which is one of the biggest slums in Dhaka, has witnessed various fire incidents that have a significant impact on women and girls. The destruction of homes, property, and sanitation facilities during such incidents has a substantial impact on the daily practices of women and girls in managing menstruation. It is important to comprehend the experiences, perceptions, and coping strategies of women and girls in managing menstruation during the aftermath of fire disasters to develop effective disaster preparedness and response strategies. In this context, the current study focuses on menstrual safety and hygiene practices of women and girls in Korail Slum, Dhaka, during fire disasters using qualitative research approach. The main objectives of the study are-

To investigate the experiences of women and girls in managing menstruation in the aftermath of fire disasters in Korail Slum.

To identify the meaningful issues of women and girls concerning the menstrual safety and hygiene maintenance in post-disaster fire setting.

To understand the approaches that women and girls use in managing menstruation whenever there is a breach of water, sanitation, privacy, and menstrual supplies.

To evaluate the availability and sufficiency of support systems for disaster response in relation to menstrual needs in the aftermath of fire disaster.

2. Literature Review

Slums in urban areas have been a major challenge to MSHM, given the high levels of poverty, poor housing, and inadequate water,

sanitation, and hygiene facilities. A study carried out in Bangladesh revealed that women and girls in slum areas do not have access to private sanitation facilities, clean water, and proper facilities for the disposal of menstrual waste [3]. In addition, the poor economic status of the population in the slums means that they cannot afford sanitary materials, with most using cloths that may pose health challenges if they are washed or dried in unhygienic environments. [8] In slum areas of Dhaka, socio-cultural factors also influence menstrual experiences, with menstrual stigma and silence acting as a barrier to discussing issues, hence limiting women from seeking support. [3] Disasters often have the effect of increasing gender inequalities, particularly for women and girls [9]. Research into humanitarian responses has consistently highlighted the lack of consideration for menstrual hygiene needs during disaster preparedness and response, with emergency responses often prioritizing food, shelter, and medical supplies over the specific needs of women and girls [1]. Research conducted during emergency and displacement situations has consistently highlighted the barriers to menstrual hygiene management due to the lack of privacy, inadequate water supplies, and poor sanitation facilities [6]. Women and girls have been observed to employ coping strategies for menstrual hygiene, including the extension of the duration of the menstrual product used, reduced mobility, or staying indoors to ensure privacy, which often compromises their health and dignity. [7],[10] Observes urban slum fires are a common phenomenon in Dhaka because of high population density, flammable materials used in house construction, and dangerous electrical connections.” Although research on fire disasters focuses on the loss of housing and economic resilience, gender-related health requirements, especially menstrual hygiene, are neglected Few

studies focus on women’s experiences, strategies, and perceptions in post-fire situations using a qualitative research paradigm. This study will fill the research gap by exploring menstrual hygiene management among women and girls in Korail Slum, Dhaka, in the context of fire disaster

3. Theoretical & Conceptual Framework

This study is informed by Feminist Political Ecology and Social Vulnerability Theory to examine menstrual safety and hygiene management among women and girls in Korail Slum, Dhaka, following fire disasters while Feminist Political Ecology (FPE) focuses on the gendered aspects of resource access, decision-making, and environmental risks, underscoring the ways in which social and political factors shape women’s experiences [11]. FPE, grounded in feminist and political ecology theories, contends that environmental disasters and crises are not experienced equally by all groups; instead, their effects are shaped by gender, class, and social location [12]. Social Vulnerability Theory highlighting disaster aspre-existing inequalities, which make groups more vulnerable, such as women, children, and the poor in urban areas [13].

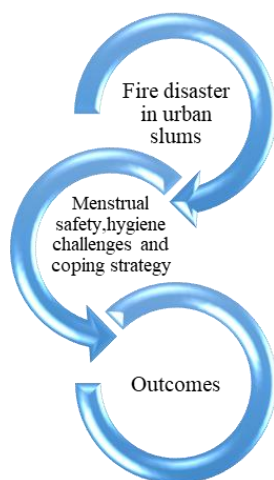


Figure 1: Conceptual Framework Developed by the Researcher

4. Methodology

4.1 Study Area and population

The study was conducted in Korail Slum, one of the largest informal settlements in Dhaka City. And the area particularly vulnerable to fire disasters and provide a relevant context for examining post-disaster menstrual safety and hygiene management among women and girls. The data was mainly collected by the respondents of bou bazar, Nouka ghat, jamai bazar area.

Sampling Technique	Sample Size	Description
In-Depth Interview (IDI)	22	Girls & females lives in Korail slum (Bou bazar, Noukaghat, Jamai bazar) area.
Key Informative Interview (KII)	6	NGO worker, Community health specialist, Community leader

4.2 Methods and Sampling

The study used the purposive method for the sampling design, which is widely used in IDIs and KIIs. Women or adolescent girls that had experienced the consequence of fire disaster in the study setting in Korail Slum, Dhaka, and who were either menstruating or at menstruating ages, were targeted for the research study. For KIIs, the participants were chosen based on their professional roles in the targeted study setting.

4.3 In-Depth Interviews (IDIs) guidelines

The interviews lasted for approximately 30 to 45 minutes and took place in a safe and private environment.

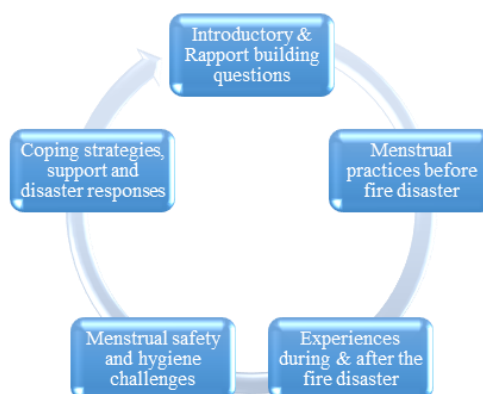


Figure 2: Guidelines for In-depth Interviews (IDIs)

4.4 Key Informant Interviews (KIIs) guidelines

Key Informant are those people who have in-depth knowledge about the selected area. Here the researcher selected 6 key informant who have vast knowledge about the selected area. 6 KIIs are selected including community health worker, NGO worker, community leader etc. Here are the guidelines for key informant interviews-

- Informant profile consisting institutional affiliation
- Fire disaster and community vulnerability
- Menstrual hygiene management in disaster response
- Gender and policy gaps
- Coordination and resources

4.5 Data Analysis Techniques

For analysing data, the researcher follows Braun & Clarke’s thematic analysis diagram which includes familiarization with data, generating initial codes, searching for themes, reviewing themes, defining, and naming themes and producing the report. As the researcher used qualitative data, so it’s regarded the best techniques for data analysis.

5. Data Findings

The study is based on qualitative findings collected through 22 in-depth interviews (IDI) with women and adolescent girls in the 15-49 years’ age group, along with 6 key informant interviews (KII) with NGO workers, community members, health workers, and disaster response workers in the Korail Slum, Dhaka city. The findings reveal the nexus of the fire disaster with the existing vulnerabilities or structural inequalities in the experiences of the women and girls in menstrual hygiene management. The discussion is further supported with existing literature and interventions based on theoretical perspectives.

Table-1: Demographic Profile of the Respondents

ID	Method	Age	Description
P01	IDI	15	Student
P02	IDI	38	Female shop keeper
P03	IDI	21	Housewife
P04	IDI	24	Housewife
P05	IDI	27	Garments worker
P06	IDI	24	A single mother
P07	IDI	35	Store keeper
P08	IDI	17	Student
P09	IDI	29	Housewife
P10	IDI	30	Kitchen assistant
P11	IDI	18	Student
P12	IDI	33	Small entrepreneur
P13	IDI	45	Housewife
P14	IDI	48	Housewife
P15	IDI	16	Student
P16	IDI	21	Garments worker
P17	IDI	18	Students (drop out)
P18	IDI	19	College drops out
P19	IDI	32	House maid
P20	IDI	40	Cleaner
P22	IDI	38	Domestic worker
P23	KII	33	NGO worker
P24	KII	42	Community health specialist
P25	KII	28	NGO worker
P26	KII	48	Community leader
P27	KII	39	Disaster response personnel
P28	KII	42	Disaster management official

Thematic analysis from the data collected through in-depth interviews with 22 females and adolescent girls aged between 15-49 years and 6 key informant interviews revealed some salient, interconnected themes related to managing menstrual safety and hygiene after fire disasters. This is in order to give credibility to these assertions, quotes from the participants are provided.

Theme 1: Pre-Disaster Menstrual Practices and Baseline Conditions

Before the fire disaster, women and girls managed menstruation within already constrained

environments characterized by shared sanitation facilities, limited water supply, and restricted privacy. An adolescent student shares her experience before fire disaster-

"Life was not easy before the fire, either, but I had a routine. I knew where I could wash up, and where I could change." (IDI, P01, Age 15).

Before the fire disaster, at least there existed toilets that an individual would share with other family members.

"Before the fire, at least there was one toilet where I felt safe. There was a selected washroom to do the activities of washing before going to school." (IDI, P15, Age 16).

A health worker of the renowned NGO "Joyeeta" shared his bitter experience to work in slum before fire disaster stated that-

"Menstrual hygiene was already fragile here, even before any disaster." (IDI, P25, Age 28).

Theme 2: Disruption of Menstrual Safety after Fire Disasters

The sudden loss of menstrual materials and safe spaces intensified women's vulnerability, particularly for those menstruating during or immediately after the fire. 21-year women who is professionally a garments worker shared the horrible experience of the fire disaster. The researcher saw tears in his eyes when he shared-my small savings burned. I have no money to buy pad and I must keep one dusty clothes whole day long" (IDI, P16)

After the fire disaster maximum peoples of this slum area must live under a plastic shed or outside. All the family member must share a single plastic shed. An adolescents girls stated that-

"We slept outside after the fire and there was no place to change. My brother and my father also live in the same place. Sometimes my private area is started to itching and I must manage place to change that was very difficult to find." (IDI, P17, Age 18).

A disaster response personnel shared his real experience that-

"In the emergency phase, menstrual needs are often overlooked. Although a limited number of NGOs address menstrual needs, their capacity and resources remain insufficient to meet the demands of women and girls in slum settings." (KII, P27, Age 39).

Theme 3: Structural Vulnerabilities and Living Conditions

Post-fire menstrual challenges were deeply embedded in broader structural vulnerabilities, including overcrowding, poverty, and the informal status of the settlement. Temporary shelters lacked gender-segregated spaces, making safe menstrual management nearly impossible for many women.

"So many people in one place—how can a woman manage her period with dignity?" (IDI, Woman, P20, 42 years)

A community leader of this area gives his statement and make clear that-

"It's not like that we don't understand women's issue but this is an informal settlement, proper sanitation is never permanent." (KII, P26, Age 48).

Theme 4: Coping Strategies and Women's Agency

Despite severe constraints, women demonstrated resilience through adaptive coping strategies.

"Others women in the slum helps me due this time and some NGO supply Pads sometimes" (IDI, P06, Age 24).

A 19-year College dropout girls states- *"I stayed inside to solve the problem at that time and stop continuing college for that"* (IDI, P18)

Theme 5: Institutional Response and Persistent Gap

Although some humanitarian assistance was provided, menstrual hygiene support remained

inconsistent and insufficient. Relief efforts largely prioritized food and shelter, with limited attention to menstrual needs.

“We find relief but no Pads while pad is also essential like food but maximum institution have no concern regarding this.” (IDI, P12, Age 33)

6. Discussion

This study examined menstrual safety and hygiene management among women and girls aged 15–49 years in Korail Slum, Dhaka, following fire disasters. Drawing on 22 in-depth interviews and 6 key informant interviews, the findings reveal that fire disasters intensify pre-existing structural and gendered vulnerabilities, resulting in compromised menstrual health, dignity, and safety. In line with the disaster sociology literature, the results show that fire disasters do not give rise to new problems, instead, they worsen the situation of poverty, congestion, and poor infrastructure in terms of WASH. Already before the fire events women had limited privacy and shared sanitation which limited their menstrual practices. When shelters and toilets were destroyed, routine activities were disrupted making menstruation a severe crisis.

Women applied all kinds of coping strategies including the use of improvised material and informal networks of support. Although the practices are a sign of resilience and agency, systemic gaps in preparedness and response to disasters are also manifested. Institutional responsibility should not be replaced by such strategies. Lastly, the results show that there are still institutional and policy loopholes. Even though some few NGOs tried to cater the menstrual needs, their ability was low to accommodate the demand. Lack of harmonized practices that would incorporate menstrual hygiene management into the emergency response on the fire disaster supports the need to have gender-responsive disaster management planning. To promote equity, health, and dignity of

women and girls during disasters in disaster prone slums, it is necessary to integrate menstrual hygiene into governance of disasters in cities.

7. Conclusion

This paper has indicated that fire crises have a massive impact on the pre-existing structural and gendered insecurities of menstrual safety and hygiene among women and girls in urban slums. The results indicate that the lack of proper WASH facilities, menstrual stigma, and institutional ill preparedness affect the wellbeing, dignity, and health of women in the post-disaster stages. Although women adopt coping strategies and rely on informal support networks, these measures cannot substitute for gender-responsive disaster management. Integrating menstrual hygiene management into urban fire disaster preparedness, relief responses, and policy frameworks is essential to ensure equitable, dignified, and inclusive disaster response for women and girls.

8. Acknowledgement

The author would like to express sincere gratitude to all the individuals who helps in this study and this study is entirely original and has not been submitted to or published in any other journal or platform prior to this submission.

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Integrating CSI with CSR: A Systematic Literature Review and Case Study Analysis

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Accepted: 10.04.2026 Published: 30.04.2026 Page No. 83 – 97 DOI: 10.5281/zenodo.19910417

Abstract:

Corporate social responsibility (CSR) and corporate social innovation (CSI), both assist organisations in tackling social issues, but the interrelation of these two paradigms is yet a topic of debate in the literature. This paper aims to find the connection that exists between CSR and CSI, and specifically to answer whether CSI is an update to CSR, a replacement for CSR, or a different concept from CSR. A combined systematic literature review and case study method have been used. From the thematic analysis based on a systematic literature review, it was found that for creating shared value and sustainable advantage, CSI should relate to CSR, as a significant element of CSR. This strategic interrelation has also been demonstrated by real-world cases. This assists policymakers and management by providing more strategic insights about the social dimension of business which is more sustainable and strategically advantageous.

Keywords: corporate social responsibility; corporate social innovation; strategic CSR; systematic literature review; case study

1. Introduction

The term corporate social responsibility means the contribution of businesses toward the employee and for the local community. CSR has been regarded as a key term that integrates the demands of stakeholders into a company's operations, policies, and decisions. It has become an important strategic technique, which enhances the business reputation

or goodwill (Tabares, 2020) and provides a competitive advantage (Porter and Karmar, 2006), thus contributing towards overall sustainable development. In parallel to CSR, the paradigm of social innovation has emerged, focusing on every kind of idea and solution that has the potential to generate social value and, as a result, offer solutions to the numerous social issues that plague the entire world. The term "social innovation" refers to innovative concepts, business models, goods, and services that address existing sustainability issues and forge new social collaborations among local bodies, organisations, and their stakeholders. At the local, regional, national, and global levels, social innovation is increasingly regarded as a sound strategy for resolving some of society's most challenging issues in an innovative way (European Commission, 2012).

When applied to the business world, social innovation has resulted in the paradigm of 'Corporate Social Innovation' (CSI), which entails seeking novel approaches to the numerous social and environmental issues affecting the entire globe while simultaneously generating economic benefits for businesses. The term is corporate social innovation, was firstly coined by Kanter in 1999. However, Kanter explains CSI as an advanced form of CSR. But there are lots of debates in the literature about the relationship between the two concepts. Especially most of the CSI literature highlights their differences, for instance, studies conducted by (Popoli, 2016; Popoli 2017; Jali et al., 2017;

Portales, 2019; Canöz and Çerçi, 2019) solely centred on the distinctions between CSI and CSR. But the core approach behind the both paradigm is to tackle the social issues. As like CSI, CSR projects are also for social benefits so they can be categorized as CSI projects, or when CSR practices are being implemented with an innovative approach it becomes CSI. However, social innovation has a broader scope; it can be implementing without CSR. For instance, in the SMEs context social innovation is termed as social enterprises, there are a huge number of start-up's that come up with innovative solutions for any social problems, as the term CSR is not so much defined in the SMEs context but the core idea and mission of start-ups (as social enterprises) of this era itself fulfilling their social responsibility. However, the interconnection between CSR and CSI can't be ignored. The core argument of the literature which differentiates CSR and CSI is that CSR is a philanthropic or a mere charitable practice. But the core dimensions of CSR are (Philanthropic, economic, legal, and ethical) so, we can't rely on the argument that CSR is a mere philanthropic term, as it also includes economic dimensions. The idea of CSR propounded by Carroll (1979) consists of an integrated view, where the business' responsibility is to provide benefits to society as well as earn profits. CSI also has the same view where businesses provide innovative solutions for any social problem that will create advantages for both the business as well as society (Drucker, 2014; Popali 2017). Because of these mutual approaches, publications also struggle with the idea that CSI can be either a strategic method for driving CSR (Nazari et al., 2022) a type of CSR (MacGregor et al., 2007), a tool for achieving CSR (Harazin and Kosi, 2013), an innovation-driven by CSR, or a combination of CSR and innovation (Sanzo et al., 2015; Garcia-Piqueres and García-Rumos, 2022; Shan and Ling, 2020). It is true that, when

companies consider the competitive advantages as an important driver for their CSR initiatives, then CSI is a more advantageous term than CSR. But the understanding of these two concepts is still underdeveloped, as literature still has various opinions regarding it. This paper seeks to fill the identified gap and advances in the CSR and CSI literature. It adopts a systematic literature review and qualitative case studies to address the following research questions.

- 1) How has the CSR and CSI concept evolved?
- 2) How CSI is integrated with CSR?
- 4) Whether CSI is a new version of CSR or CSR and CSI are different concepts?
- 5) How can the management use CSI or CSR as a strategic tool?

However, lots of previous research (Nazari et al., 2022; Popali, 2017; Rozakowaska-Menkes, 2018) has dealt with similar kinds of research questions, but there is no clarity about the CSR/ CSI integration. Even those who define their relation, are only based upon literature review, but this study conceptualizes these terms and then tries to quantify the integration between them, and the outcome of this integration is exemplified with various case studies.

2. Methodology

This qualitative study is based on mixed method research, in the first stage we conduct a systematic literature review (SLR), then based upon the thematic analyses of SLR, some real word case studies were identified to exemplify the conceptual framework developed through this study. Theoretical case study method is used, based upon the secondary data available on reports and websites of the organisation. Even some unstructured interviews of industry experts (such as CSR managers and professionals working in the area of sustainability and ESG) were also conducted, for

getting their opinion about the CSR and CSI relationship.

We use SLR because it is the most appropriate research method for identifying the body of relevant scholarly literature, as well as for a critical evaluation and synthesis of an emerging yet already diverse research area. The Scopus database was selected for its comprehensive business journal coverage stretching over 50 years, its reliable search algorithms, its user-friendly interface, and its frequent use in systematic reviews. One another database Google Scholar was also used, to get a comprehensive base for the conceptual understanding. The keywords as “corporate social responsibility” OR “CSR” OR “social responsibility in business” AND “corporate social innovation” AND “corporate social innovation” OR “social innovation” OR “sustainable innovation”.

A total of 329 articles were searched out of which 242 were from the Scopus database and 87 were from Google scholar. 13 articles were from other than the English language and 23 duplicate records are removed. The titles and abstracts of 295 articles were screened, out of which 133 papers were selected for full-paper analysis. Thereafter 85 articles were removed; the final 49 articles were selected for the review, as they fulfilled the inclusion criteria for getting the answers to research questions. The exclusion criteria were articles published other than English language and, which are not related to the keywords and did not contribute to an understanding of CSR and CSI. The time period for the articles published was not fixed in inclusion criteria, as the term “Corporate social innovation” was first coined in 1999, so all articles related with CSI are of 1999, or later years. However, in the first decade it is quite a new term, and the research analysing the integration of CSI with CSR emerged mainly after 2010. So, the maximum number of articles was published after 2010. But for the year

2023, only articles published before March 2023 were included, as the papers are collected in March 2023.

Figure 1: Identification and selection of Articles

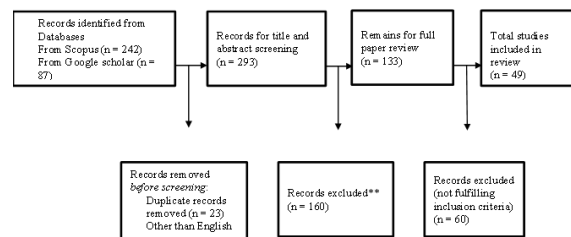


Figure 1: Identification and selection of Articles

3. Thematic analysis

3.1 What Corporate Social Responsibility (CSR) means?

The concept of CSR has varied and numerous meanings since it emerged. In the initial stage, CSR is a pure charity or voluntary activity. Later in the '90s when businesses start considering the stakeholders' view, defensive CSR was used, to gain the trust of society and the government (Popoli, 2017). At that time, it is treated as a responsibility of the organization towards society, as businesses use resources of the society so they have some obligation towards it. The well-known Carroll's pyramid (Carroll, 1991) also defines CSR as a combination of businesses' philanthropic responsibilities to act as good citizens, seek ethical responsibilities towards society, and follow legal responsibilities to obey the law while fulfilling economic needs to maintain profitability. But CSR is not only an obligation; it is also an important strategic tool (Porter and Kramer, 2011), as contribution towards society and the environment also positively influences the relationship with stakeholders. This view forms the stakeholder theory, which emphasizes that companies should integrate the interest of all stakeholders with the profit-making objectives (Fredrick et al., 1992; Freeman, 1999). CSR also enhances the image and reputation of a company. Companies are now aware

that CSR practices can change how they interact with local communities and add value through partnerships with community organizations (Porter and Kramer, 2002). Various types of social, environmental, and financial outcomes can be influenced by CSR strategies, companies with a high CSR level; for instance, can enhance their value-creation strategies (Porter and Kramer, 2011). So, Carroll's obligatory CSR now has become a "shared value" concept of Porter, which means the new business models for resolving social and environmental issues create economic value for the company as well as social and environmental value for the communities in which it operates (Porter and Kramer, 2011). Even the origin of stakeholder theory also emphasizes the strategic aspect of CSR (Freeman, 1999). This view of CSR requires a proactive approach (Popali, 2017) where the aim of CSR is not only the obligation and a defensive technique but a proactive involvement to improve social and environmental issues and gaining competitive advantage from it (Porter and Karmar, 2006). They also state that the success of the company and community are interdependent. When a business tries to solve social or environmental issues, it generates various marketing or financial opportunities for the business as well. This integration between social and economic objectives requires some more strategic and innovative solutions, and from here the journey of CSI starts, as CSI is a concept that is more strategic and provides more sustainable and innovative solutions to social problems.

3.2 What Corporate Social Innovation (CSI) means?

CSI is the application of the social innovation paradigm to the business world and the encouragement and assistance of businesses in rethinking their innovation processes whether in new products, processes, business approaches, or

managerial cultures; or in favour of solutions with positive social impacts. Kanter (1999) who coined the term 'CSI' contended that organizations ought to involve social issues as their learning research centre for recognizing neglected needs and for creating arrangements that make new business sectors. He defined CSI as a new way of thinking about innovation, a partnership between private industry and the public interest that results in change that is profitable and lasts for both. Ceggarra-Navarro et al. (2016) also assert that social innovation is the innovation that is good for society as well as for business. Paunescu (2014) defines CSI as a new form of innovation that integrates both social and economic development; social goals for society and economic goals of businesses (Cegarra-Navarro et al., 2016). Collaboration and integration are the key features of CSI, which involves deeper collaboration across functions within the organization as well as external parties (Jaykumar, 2017; Altuna, 2015). They also define CSI as products or services that are created to satisfy a social need and offer the opportunity to establish new social relationships or collaborate. These social relationships help in achieving competitive advantages (Mirvis et al., 2016; Jaykumar, 2017). This view of CSI leads to strategic investment that engages companies in societally relevant research and development and applying all its assets to the issues at hand to co-create something new (Mirvis et al., 2016), modify (Varadarajan and Kaul, 2018), or improve (Nazari et al., 2022) the existing products, procedure, or practices. The literature defines CSI as a separate innovative activity, product, or practice which solves social problems more sustainably and innovatively than before. But its meaning in relation with CSR is missing. After analysing the development of the CSR concept, the more effective form of CSR requires innovation with it which forms the CSI concept (MacGregor, 2007). But literature

differentiates CSR from CSI as the former means contribution in the form of manpower, money, or resources for philanthropic intent, whereas social innovation typically entails collaborating with external parties and functions within the company to co-create something novel that offers a long-term solution to social issues (Ekelhof, 2022). Dionisio and Vargas (2020) argue that CSI is a broader term than CSR as it integrates both internal and external functions to enhance effectiveness. Some studies (Harazin and Kosi, 2013; Jaykumar, 2017) state that CSR is an important driver of innovation even social innovation. It can be implemented with the help of CSR as a strategic element (Harazin and Kosi, 2013; Lopez- Fernandez and Rajgopal, 2018). While Mahlouji and Anaraki (2009) state that when managerial creativity and sustainable approaches are linked with CSR then it shapes SRI (socially responsible innovation). Mirvis and Googins (2018) define two types of CSI projects funded by R&D or funded by CSR budget. They also contend that the use of social innovation is important to drive business growth, meet CSR and sustainability goals, and/or simply engage employees in social activities. So there is no uniform definition of CSI and its relationship with CSR also has various aspects. The industry experts working in the area of CSR, ESG, or sustainability are also not clear about the relationship between CSR and CSI. Three out of five CSR professionals don't even know about the term CSI. One expert states that "CSI is a larger circle and CSR is a subset of it". Another one said that "Social innovation is used by many companies as an integral part of CSR initiatives, yet CSR is legal compliance but CSI is voluntary activity". That's why CSR and CSI are very overlapping concepts.

Table 1: Key theories related to CSI

Studies	Theories	Context
Belyaeva et al. (2020), Ekelhof	Stakeholder theory	CSI works as a strategic technique not

Studies	Theories	Context
(2022), Mirvis and Googins (2018), Reinlie (2017), Roszkowska-Menkes (2018)		only to collaborate internally but also with external parties or stakeholders for better impact.
Gonzales-Gemio et al. (2020), Mahlouji and Anarki (2009), García-Piqueres and García-Ramos (2022); Turker and Ozmen (2021); Sanzo et al. (2015)	Resourced based view	With the help of CSI scarce and idle intangible resources can be modified into profitable opportunities.
Belyaeva et al. (2020); Vrabcová and Urbancová (2023) García-Piqueres and García-Ramos (2022); Jali et al. (2017)	Knowledge-based view	CSI consists of new ideas, seeking new knowledge, and integrating and distributing knowledge for better social solutions.

Source: Own compilation by Authors

Like CSR theories, there are also various types of theories that explain the meaning and context of CSI. The foremost important base for social innovation or even innovation is the knowledge-based view/theory in which CSI is considered as a source of creativity and knowledge generation. Although knowledge creation and CSI exists together, as knowledge is also an important resource for corporate social innovation (Jali et al., 2017), and CSI also generate knowledge in form of new ideas and practices (García-Piqueres and García-Ramos, 2022). In CSI, a significant portion of the knowledge exchanged is tacit knowledge, which results from shared connections and encounters between organizations (Mirvis et al., 2016). Knowledge is the

real payoff of many CSI investments (Mirvis and Googins, 2018). Some authors (Gonzales-Gemio et al., 2020; Mahlouji and Anarki, 2009; García-Piqueres and García-Ramos, 2022) highlighted how CSI helps in generating resources by concerting intellectual or intangible resources into tangible benefits. This forms the resource-based view of CSI. Another important theory of CSI is stakeholder theory. It is the mostly used common theory in both CSR and CSI literature. It emphasizes on the aspect that management must implement those strategies which include the benefits of all who directly or indirectly have a stake in the company (Freeman, 1999). CSR helps companies to achieve this, but the mere CSR prospects lead to social objectives only, innovative solutions are necessary for the benefit of all stakeholders. CSI serves as an innovative solution for this, the core of which is the integration of the interests of all stakeholders including partners, customers, and society with the company’s profit-making objectives.

3.3 Key debates in the literature:

CSR and CSI are interrelated concepts	
Cegarra- Navarro et al., 2016 Spen & Chiara, 2012; Martins and Terblanche 2003; Sanzo et al., 2015; Garcia-Piqueres and Rumos, 2022; Shan and Ling, 2020	Innovation with CSR is CSI
Harazin and Kosi, 2013; Turnker et al, 2022; Jayakumar, 2017; Vrabcová and Urbancová, 2023	CSR Driven innovation is CSI
Yousfi et al 2021; Altuna (2015); Nazami et al 2022; Trabbes, 2020; Nazari et al., 2022;	CSI as Strategic CSR
CSR and CSI are different concepts	
Popoli, 2017, Portales, 2019; jail et al 2017; Tabares, 2020; Dionisio and Vargas, 2019; Bertola et al 2020;	CSI has wider scope than CSR
Acharya and Patnaik, 2018; Canöz and Çerçi, 2019;	CSI replacing CSR

CSR and CSI are interrelated concepts	
Nazari et al., 2022; Shan and Ling, 2020; Popoli (2016)	

- **CSR v/s CSI:** The existing literature differentiates CSR and CSI. The first difference between the two concepts is CSR is an outside activity, whereas CSI integrates both internal and external activities of the business (Popoli, 2017). Tabares (2020) concluded that CSR is related to the triple bottom line, but CSI is closer to SDGs. However, SDGs are also based upon the three dimensions of sustainability (economic, social, and environmental), which in itself is a triple bottom line. Portales (2019) differentiates CSR and CSI from a socio-cognitive perspective, and when the socio-cognitive process is indulged with CSR then it becomes CSI. Mirvis and Googins (2017) recognized that “CSI has developed over the past two decades, building on traditional corporate social responsibility (CSR) activities in ways that embed social impact more directly in corporate strategies, activities, and partnerships” which re-enforces the distinctions between the two ideas. Another argument for the difference between CSR and CSI is that CSI has a more comprehensive meaning (Jail et al., 2017), it is a cross-disciplinary concept nourished by multiple disciplines (Tabares, 2020). CSI is a consolidation of all concepts, which is integrated within itself as well as other concepts such as CSR, corporate innovation, responsible innovation, sustainable innovation, and social enterprises (Dionisio and Vargas, 2020). Whereas, CSR is related with the

social responsibility or obligations of businesses towards the society.

- Corporate innovation and CSR: Corporate innovation and social innovation both are the two different kind of ‘innovation’. Corporate innovation provides a better solution to unmet needs. On the other hand Social innovation is also a type of innovation that consider the social objective with the better solution, which is required to maintain a balance between social and economic objectives (Cegarra-Navarro et al., 2016). Martins and Terblanche (2003) states that CSI is emerged from corporate innovation, in which efforts are given to society with the innovation. This social orientation in innovation is termed as ‘CSR’ which enhance the effectiveness of companies’ innovation (Spena and Chiara, 2012). However, in the initial decades, CSR and innovation are not interrelated used by companies (Crets and Celer, 2013). But now their correlation whether CSR with innovation (Cegarra-Navarro et al., 2016) or innovation with CSR (Spena and Chiara, 2012) enhances the competitiveness of corporates (Sanzo et al., 2015), and this combination is called corporate social innovation (Garcia-Piqueres and Rumos, 2022). Shan and Ling (2020) analyse the dimensions of corporate innovation and social responsibility and state that CSI is the advanced version of corporate innovation and social responsibility. They also found some influencing factors of CSI, which guide companies, to design their CSI by bringing innovative solutions to social problems.
- CSR-driven innovation: Authors like (Rexhepi et al., 2013; Renile, 2017; Turker and Ozmen, 2021) identified CSR as an important driver of innovation. But it is an important topic of debate, whether CSR drives innovation or social innovation. Because, authors like Cegarra-Navarro et al. (2016) differentiate innovation and social innovation are different concepts, where innovation is related to economic or strategic dimensions, and social innovation has a significant relationship with social innovation. Authors like (Harazin and Kosi, 2013; Jayakumar, 2017; Turker and Ozmen, 2021; Vrabcová and Urbancová, 2023) identified that CSR drives social innovation. On the other hand, Crets and Celer (2013) state that CSR is a driver of innovation, not social innovation, they argue that social innovation may or may not be a result of CSR. They argue that social innovation can be introduced through, social enterprises or open innovation where organizations come together with NGOs, government, or community organizations in partnership to solve social and environmental issues. García-Piqueres and García-Ramos (2022) also states that the positive effect of CSR on innovation depends upon the different type of innovation and CSR dimensions, they also empirically found that economic CSR has a more positive relationship with innovation, and environmental CSR has very lessor impact on CSR. Rexchepi et al. (2013) and Renile (2017) analyze CSR and Innovation from two different perspectives ‘CSR-driven innovation’ and ‘innovation-driven CSR’.

CSR-driven innovation where CSR leads to innovation, for instance, if a company wanted to make a product that was better for the environment and society, which led to product innovation. It's also possible to have innovation-driven CSR, in which the innovation has a social process but no social purpose. Rexhepi et al. (2013) also argue that innovation and corporate social responsibility are fundamental business competencies. The European Commission (2006) asserts that CSR has the potential to boost a company's competitiveness and contribute to its development toward sustainability, but this requires innovation (MacGregor, 2007). That's why authors like Nidumolu et al. (2013) contend that CSR is viewed as a principal driver of innovation, to develop sustainable solution of creating effective social impact.

- **Strategic CSR and CSI:** Companies are using CSR as a strategic tool to integrate and manage both internal and external environments, as it enhances the reputation of the companies and creates a positive image in the minds of customers. This form of CSR is called 'strategic CSR' (Porter and Kramer, 2011), which is very much related with CSI (Yousfi et al., 2021). This is also termed as "doing well while doing good" and can be achieved with social innovation (Tabares, 2020). Nazari et al. (2022) termed this idea as corporate social investment (CSI), they found that by involving various company segments and stakeholders, businesses must pursue a strategic concept that results in long-term social change. Altuna et al. (2015) also assert that for-profit

organizations engage with social innovation to make strategic CSR in practice, as it enables the integration of CSR in business strategies. The strategic CSR perspective also leads to the stakeholder theory perspective (Roszkowska-menkes, 2018). As the firm-centric view has been replaced by a network-centric view, because of the interdependence of stakeholders and the company. CSI can improve the relationship among businesses, stakeholders, society, and communities (Dionisio and Vargas, 2020). Chen et al. (2021) also found that the adoption of social innovation into CSR initiative positively influence the perception of employees. Therefore the implementation of CSI in CSR leads to strategic CSR (Yousfi et al., 2021). Strategic CSR also emphasizes on shared value concept which requires innovative solutions, that create value for both society and business, and CSI is a more strategic and innovative approach that involves developing novel products, services, and business models that yield economic value while also generating benefits for society and the environment (Nazari et al., 2022). That's why strategic CSR is very much related with CSI, and shared value is the common factor in both concepts.

- **The new version of CSR:** When we discuss the move from mere CSR to strategic CSR, then there are also studies (Acharya and Patnaik, 2018; Canöz and Çerçi, 2019; Nazari et al., 2022; Shan and Ling, 2020) that explained the move from CSR to CSI. For instance, Popoli (2017) states that CSI is an evolution of CSR, as

it takes CSR towards a far more inclusive role for helping to improve the working with the external environment such as economic, social, organizational, political, and cultural conditions. Canöz and Çerçi (2019) concluded that CSR still exists but there is a remarkable move towards CSI. It replaces the charitable work of CSR with sustainable social change (Nazari et al., 2022). In another study, Popoli (2016) asserted that CSI is a proactive responsibility of business, and it is not only replacing CSR but integrating the social benefit of CSR with profitability. Osburg, (2013) also asserts that social innovation is not a progressive form of CSR; rather, it is an essential driving force in achieving corporate sustainability. Mirvis and Googins (2017) acknowledged that CSI has evolved over the past two decades, building on traditional CSR activities in ways that embed social impact more directly in corporate strategies, activities, and partnerships, highlighting the distinction between the two concepts. It has been suggested by Mirvis and Googins (2018) that businesses should shift from philanthropy to innovation by utilizing their corporate foundations and CSR funds, which were originally intended for charitable purposes, to engage employees in CSI and provide venture capital for social enterprises to increase their focus on social impact.

Source: Own compilation by Authors

The thematic review based conceptual framework literature indicates that when CSI is introduced as a CSR practice it will create value for both the company as well as society by enhancing the effectiveness of CSR. The ordinary meaning of CSR includes the dimension of Carroll’s pyramid (Philanthropic, Ethical, Legal, and economic), employee volunteerism (Mirvis and Googins, 2016), and contribution to the environment (García-Piqueres and García-Ramos, 2022). On the other hand, CSI provides innovative solutions (Kanter, 1999; Paunescu, 2014), creating social impact (Portales, 2019), enhancing knowledge creation (García-Piqueres and García-Ramos, 2022), integrating the interest of all parties with business (Jaykumar, 2017; Dionisio and Vargas, 2020), and eco-innovation (Rexhepi, 2013) for solving the environmental issues. When the features of both paradigms are combined or a company uses CSI as a part of CSR, it creates lots of sustainable advantages, such as enhanced collaboration and stakeholder engagement, providing an effective solution for all types of social or economic issues, and thus creates shared value by providing more strategic insight.

To test this model, we analyse some real-world cases in this context. We analyse five social innovation initiatives by renowned companies (Amazon, HUL, ITC, Usha International, and Mahindra & Mahindra). All these companies mentioned their selected CSI projects in their sustainability or CSR reports, as a part of their CSR practices. These projects have an innovative approach for solving one or more social or environmental problems; for instance, SMART Centres by Mahindra and Mahindra dealt with the employment issue, HUL Shakti and Usha Silai School are working for the upliftment of women



Figure 2: Conceptual framework showing the interrelation between CSR and CSI

from underprivileged sections, Amazon Saheli for the tinny women entrepreneurs and promote environmentally friendly handloom products, and ITC e-choupal for the betterment of rural households and farmers. With these initiatives, companies are not only serving society but also generating sustainable opportunities for their business; as mentioned in Table 2 all the selected case studies have an innovative approach to create sustainable social impact with a sustainable competitive advantage. That's why companies enjoy more opportunities when they include social innovation practices in their CSR, and thus creates shared value.

Table 2: Analysis of CSR-oriented CSI projects:

Company	CSI Project	Innovative Approach	Sustainable Social Impact	Sustainable Competitive Advantage
Amazon	Amazon Saheli	Encourage women entrepreneurs as well as promote recyclable handloom and handicrafts.	Empowered more than 80,000 female entrepreneurs by allowing them to sell their products on Amazon and promote the use of recyclable and environment friendly products.	Able to offer unique products to the customers by providing these women artisans and weavers direct access to buyers.
Mahindra and Mahindra	SMART Centres	Skills-for-Market Training (SMART) is a well-organized training program to provide skill and employability training to the youth from deprived sections, with the collaboration of various government or non-government organizations.	Contribute to the skill development program of the Indian government by training deprived and disabled persons, built on the vision of an educated, enabled, and empowered India.	Collaboration with other partners enhances the positive impact on the company's value chain.
HUL	Project Shakti	Empower women micro	Improve the living standards of	Penetrate the rural market in a

Company	CSI Project	Innovative Approach	Sustainable Social Impact	Sustainable Competitive Advantage
		entrepreneur called Shakti Ammas through imparting basic selling tenets with HUL brands, also spread awareness of hygiene in rural areas.	the rural populace by promoting greater awareness of health and hygiene, and provide opportunities for underprivileged women to generate income.	strategic way, which is feasible as well as cost-effective.
ITC	e choupal	Link farmers via the internet for procurement of agricultural products. offer an alternative to traditional mandies, and provides training of new farming techniques.	The largest internet-based intervention in rural India has developed into a network of services that cater to a wide range of rural requirements, including insurance and healthcare, retail, agree-extension, and other farm-related services.	Get direct access to farm produce and penetrate the rural market.
Usha	Usha Silai School	Provide opportunities for rural women for becoming entrepreneurs, through which they not only become self-reliant but also impart sewing and stitching skills to other rural women of their community.	Empowered rural women by making them self-independent, and thus ensures women-centric rural development.	Popularize the use of 'Usha' sewing machines among rural women (Arnold, 2011).

Source: Own compilation by Authors based on info available on companies' websites and reports

4. Discussion and Conclusion

CSI is the idea, project, product, or any practice done by the companies for the solution of any social problems. CSR projects are also for social

benefits so they can be categorized as CSI projects. However, CSI has more comprehended meaning (Jail et al., 2017). It is a cross-disciplinary concept (Tabares, 2023) nourished by multiple disciplines and consolidation of all concepts, which is integrated with itself as well as other concepts such as CSR, corporate innovation, responsible innovation, sustainable innovation, and social enterprises (Dionisio and Vargas, 2020). By analysing all the literature and case studies related to CSR and CSI it will not be right to say CSI is a new version of CSR or it can replace CSR, but it can be used as a dimension of CSR, which replace the social dimension of CSR with social innovation (Nazari et al., 2022). However, CSI can be used to modify the meaning of CSR, as the need for today's challenging world is to shift to more sustainable solutions than mere philanthropic benefits, so with the use of CSI companies can make their CSR initiatives more sustainable, as innovation provides the best sustainable solutions.

However, studies by Googins (2013) asserted that social innovation has never been integrated into CSR, as countless social innovation arises without integrating into CSR. But these arguments are not as it is true in today's context. Over last decade, the recognition of CSR as a driver for innovations has increased (Vilke, 2014). Now companies integrate their CSI projects with CSR, to get double the advantage of CSR and sustainability. The social innovation cases explained above are also part of CSR practices. But it doesn't mean that social innovation is only related to CSR or it is only a part of CSR. CSI is a cross-disciplinary concept. For instance, social enterprises whose main objective is to solve a social problem are also playing a significant role in achieving social objectives, through innovative solutions. Even 'for profit' organizations can use CSI without CSR, by including it in R&D and product innovation.

No doubt CSI has broader prospect, but it can be used as a part of CSR or as a separate activity. Although it can't be the replacement for CSR, when it is used as a part of CSR it can add more sustainable values to CSR. Even when CSI is funded by R&D, it must relate to CSR as CSR add more social value to it. In the case of SMEs, CSI must be linked with CSR because of limited funding. So, whether it is to implement CSR in an effective way, or CSI, the more advantageous and sustainable way is the integration of CSI into CSR. This study tries to conclude this simple relation between CSR and CSI, which can be examined empirically by upcoming research. Even in case of controversial industries CSI may be a game changer concept, while connecting with CSI. As CSI is "doing good while doing well", future researches can be carried out on the prospect of "doing well while doing bad" as coined by Miles and Angelis (2022), which may be possible with the integration of CSI in the CSR practices of controversial industries.

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A Structured Framework for Writing Research Papers: A Beginner's Approach

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Accepted: 10.04.2026 Published: 30.04.2026 Page No. 98 – 110 DOI: [10.5281/zenodo.19914521](https://doi.org/10.5281/zenodo.19914521)

Abstract

Research writing is crucial to academics and professional growth in the different areas of science, engineering, and humanities. Many new researchers tend to have difficulties in developing ideas, choosing strong methods, and presenting clearly. In order to resolve these obstacles, we offer a guiding framework designed for the novice researcher to weave through the entire research process from first ideas to first publication. The key steps adopted in this framework are locating a problem, analysing the previous literature, designing methods, collecting data, and writing the paper. By fragmenting intricate academic processes into simpler phases, the modality makes scholars' works more coherent, clearer, and better in general. We also highlight common mistakes, and give advice on best practices. As such our guide will assist you in writing a high-quality paper which gets accepted by a peer-reviewed journal or an international conference.

Keywords

Research Writing, Academic Writing, Research Methodology, Beginners, Framework

1. Introduction

Research is important to generate new knowledge and innovation in every discipline including computer science, engineering, medicine, natural and social sciences. It helps in problem exploration, hypothesis testing and generating new insights. These contributions are theoretical and practical for the officer. In a technologically oriented and data-driven world, you must conduct and

disseminate your research. Having analytical skills is essential for students, scholars, and professionals. While good research pushes forward academic fields, it also helps us make better choices in industry, policy, and society.

The importance of research writing is well-known, but it is not an easy job at all and is often hard, especially for inexperienced writers. Early-career researchers often encounter setbacks in various stages. Students may find it difficult to identify a good research problem, conduct thorough literature reviews, choose the right methods, and/or present coherently. Along the way, academic writing conventions (referencing, logical ordering, and consistency) can challenge many beginners. The lack of universal guidance adds more of a challenge, especially for certain fields.

Many a beginner will fail because they don't have a path that binds all parts of research to one another. Research can feel discordant when it happens. This often results in ambiguous methodologies, poorly constructed arguments, and ultimately compounds the difficulty of getting published in good journals or putting forth papers at conferences. Additionally, research publications are becoming more competitive. Being engaged is not just about original ideas – clarity and thoroughness, in addition to accepted standards. In the absence of guidance beginners will fail to do these things. Thus, what can we do?

We require a straightforward and formal step-by-step procedure for research writing to simplify the task. It's useful to think about a map: a

good framework takes you from your first thought to writing it, then revising, and publishing. It needs to be flexible enough to accommodate different research methods qualitative, quantitative, and mixed-methods while also providing clear and practical steps that beginners may follow.

The goal of our paper is to fill this gap. The present framework is an organized proposal for writing research paper especially for beginners. The process of research is divided into steps by a framework. This comprises refining your concept, outlining the issue, reviewing literature, designing methods, collecting, and analyzing data as well as writing and publishing. Organizing these steps into a clear structure helps your research progresses smoothly, stays consistent, and is complete.

Our work delivers four major contributions. To start, we show a general framework that works across fields. Many researchers find it a useful tool for their work. Additionally, we are providing a step-by-step guide that simplifies complex research so that beginners feel confident and capable. Also, we show you some common new researcher mistakes and offer practical ways to avoid them. We conclude with advice on journal selection, peer review, and revision throughout the publication process. It equips beginners to effectively communicate their research.

In general, our study intends to assist researchers. We provide them a systematic way to write research which improves their research work, make it clear and impactful.

- Check out a glimpse of what we offer.
- A framework applicable across all different areas.
- Instructions for beginner from scratch.
- Finding common errors and their solutions.
- Understanding the process of publication and peer review.

- Insights into publication and peer-review processes

2. Nature of Research Across Disciplines

In whichever area of study, research consists of basic rules that systematically produce knowledge. Research is a process of inquiry which tries to find out something new whether it be in the computer sciences, natural sciences, social sciences, engineering, or humanities. Further it tries to probe questions, solve problems, and add new knowledge to our existing knowledge. Diverse fields may use different tools, techniques, and focus. Nevertheless, the fundamental framework and reasoning behind research largely remain constant. To be knowledgeable about research and its types, a beginner must be able to. You can select the right methods and approaches for your studies with its assistance.

Research can largely be categorised into three major approaches.

- Qualitative Meaning
- Numerical.
- Blended approach research.

All these approaches serve different purposes and is useful for different types of research questions.

Qualitative research is about phenomena but utilizes non-numeric data. Then, why use the servomechanism? It enables us to understand human nature, behaviour, experience, perception, and social context. Commonly used qualitative research data collection methods include interviews, focus groups, observations, and analyses of texts or documents. For instance, social sciences could refer to the research through conducting interviews for public policy attitude whereas in humanities, it could signify analyzing literary texts for themes and meanings. The depth, context, and subjective view are affecting our common perception. This is

extremely useful when coming up with new ideas or describing experiences.

This method relies on numerical values and statistical analysis. You will find it everywhere, from science and engineering to economics, particularly when measurable variables and objective analysis are essential. Quantitative Research Collects Data in the Form of Surveys Using Closed Questions with Short Answers and Other Numerical Data. The main aim here is to experiment with ideas, observe patterns and eventually demonstrate how the variables are related. For example, in engineering or computer sciences, we may evaluate an algorithm's performance in terms of accuracy, efficiency, and time complexity. Quantitative research is exact, replicable, and allows for generalization. These are some of its benefits.

Qualitative and quantitative studies are included in mixed-method research as the name suggests. When one method does not suffice to understand a complex situation, it is a great help. incorporating numbers into narrative allows for checking of results and adds richness to analysis A study, for instance, might deploy surveys to collect quantitative data and subsequently conduct interviews to glean deeper insights regarding participant responses. As a result, it enhances both the reliability depth of the research

Research can also be classified based on purpose and contribution in addition to methodology. The creation of new knowledge is referred to as original research. We consider this to be the most valuable type of research as it pushes the field ahead directly. A review paper brings together and critically evaluates the findings of the researched work done already. They reveal patterns, discrepancies, and prospective paths. They make it particularly useful for novices who wish to grasp a research domain. An in-depth study of a case is an

investigation that estimates the specific & more familiar instance that surpasses the broader study.

Qualitative Research	Quantitative Research	Mixed Methods
What It Is Explores experiences and meanings	When to Choose It <ul style="list-style-type: none"> Understand 'why' or 'how' Open-ended questions Human experiences 	Combines qualitative and quantitative
When to Choose It <ul style="list-style-type: none"> Understand 'why' or 'how' Open-ended questions Human experiences 	Strengths <ul style="list-style-type: none"> Generalizable results Statistical analysis 	Strengths <ul style="list-style-type: none"> Comprehensive Validates findings
Strengths <ul style="list-style-type: none"> Rich data Flexible approach 	Limitations <ul style="list-style-type: none"> Smaller samples Subjective 	Limitations <ul style="list-style-type: none"> Time-intensive Complex

Figure 1: Classification of Research Approaches (Qualitative, Quantitative, Mixed Methods)

Though they differ in method and form, research shares a similar structure and process. This typically begins when we discover a research issue. After that, we explore the existing literature, select the right methodology, collect the data, analyze the collected data, and finally interpret the results. This approach will ensure the logic and transparency of the research. It is vital for beginners to keep these similarities in mind. It enables you to tailor general research ideas to your discipline and keep the top strong and clear.

3. Generating Ideas and Defining Problems.

A clear and meaningful problem is at the heart of every successful research study. A good research problem makes research relevant, original, and useful; guides the study; and determines appropriate methodology for the study. For novices, this phase is usually the hardest one. What is the reason? Due to the need of critical thinking, depth

knowledge in the areas (Computer Science) etc. An unfocused research design, weak methods and unclear results occur from a poorly defined problem. A clearly articulated problem outlines the course of the entire research process.

3.1 Sources of Research Ideas.

Generation of research idea is not haphazard. It relies on a process of exploration and observation. Identifying literature gaps is one of the most reliable sources. Examining the existing literature enables us to find research gaps and future directions for the topic. A particular study might restrict itself to one group, one methodology, or one dataset. This gives us the opportunity to explore or enhance those findings.

Real-world challenges also inspire us greatly. A lot of influential research stems from issues faced in industry, society, and everyday life. These issues can be tackled with creative solutions which can connect the theory with the practicality. Dilemmas touching on the health industry, the environment or tech efficiency can prompt worthwhile research ideas.

One way to develop ideas is through theoretical extensions, where researchers use existing theories and models. This might entail perfecting the theory, using it in a novel context, or integrating it with others to generate insights. This enables us to broaden the frontiers of academic knowledge.

Further, taking to consulting people, experts, attending seminars and making yourself aware of inter-disciplinary topics also enhances your idea generation. As a novice researcher, it is prudent to stay curious, watchful, and open-minded while selecting a research topic.

3.2 Issue Statement.

You have a research idea; now turn the idea into a clear problem statement. The research problem helps to pave the way for the study, and its

statement explains the study conducted. A good problem statement can get you quite far.

First and foremost, it should be clear and straightforward, without ambiguity or unnecessary complexity. Clarity makes it easy for the reader to follow the research. Second, it must be researchable, which means that it can be explored through adequate methodologies. If you cannot measure or analyze a problem, it won't give you much. Third, the problem must be relevant. It means the problem should concern something important in the field. Further, the problem should contribute to knowledge or practice already taking place in the field.

An effective problem statement has context, identifies a gap, or specifies a limitation that needs further investigation. An iterative process of refinement by expert mentor feedback of the beginner's problem statement, according to available resources and time frame, may be required.

3.3 Research Goals and Queries.

Identify your issue first. Afterward you set clear research aims and questions. Your study will be guided and structured by these. The research goals are the general aspirations of it. They express your goals in clear, measurable terms within a specified timeframe. Such efforts may lead you to seek ways to assess the performance of a system or analyze an event or a new model.

On the other hand, research questions are your objectives, articulated into questions you seek to answer. These aids enhance the effectiveness of your studies and show you the essential information. Good research questions are clear, focused, and consistent with your problem statement. In some types of quantitative research, you may express these questions as hypotheses which you can test statistically.

Research objectives and questions form your roadmap throughout the research process. Your methods, how you collect the data, and what you do

with it. For new researchers, it is important to ensure that your objectives and questions logically follow from your problem statement, and are achievable within the limits of your study.

4. Review of Literature.

The intellectual foundation of any research study is provided by the literature review. By examining published literature in each field such as Computer Science and other academic disciplines, it links what we know already with what you will add to knowledge. Do not merely summarize previous studies. An effective literature review evaluates, contrasts, and integrates all existing research to provide a context for your study. This section is important for new researchers because it gives you an idea about what has been done, missing and your work.

4.1 Reason of Literature Review

The literature review serves a variety of important functions.

First, it helps you understand existing work by getting you familiar with key theories, methods, and findings in your area. Building on what we already know is easier than starting fresh.

Secondly, it helps to identify research gaps. A close examination of earlier studies will reveal limitations, open questions and/or inconsistent efficacy. New study starts from these gaps and shows you are adding something new to the knowledge.

Third, the literature review prevents duplication. Your study will have less impact if you do repetitious work that does not offer new insight. By reviewing existing works, you can make sure your own research offers something different, better or a new way of thinking (Riel and Snyder, 2024; Eneome, Eberechukwu and Obiakor, 2025; Lian et al., 2025).

A literature review demonstrates that you have been briefed in the field in which you work.

4.2 Literature's Resources.

Selecting Appropriate Sources for a Successful Literature Review. Peer-reviewed journals are trusted because of their credibility and valid research. Sources that are thoroughly vetted by experts are the best sources. Scholarly papers provide relevant information for papers that are researched. Social media is an essential resource that enables you to discover cutting-edge innovations. It brings you new ideas and trends that may hit the journals in the months to come.

Books as well as Textbook provides the fundamentals and big ideas Beginner sources give you a sense of the big ideas before you read anything heavy. Besides these, you may also find many academic papers using digital databases and platforms such as Google Scholar and IEEE Xplore, SpringerLink and many more. Ensure you use topical and highly cited references; usefulness and quality at a premium (Haboussi et al., 2025; Vaswani et al., 2025).

4.3 A process of literature review.

Literature review process is systematic. The initial step is to utilize the appropriate database by using relevant keywords. Successfully searching for scientific literature requires using Boolean operators (AND, OR, NOT), filters, and citation tracking.

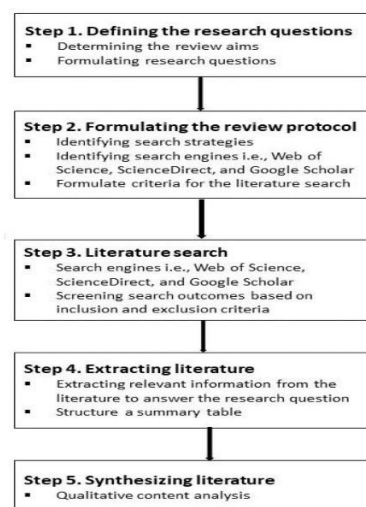


Figure 2: Systematic Literature Review Process

The next step is to filter for quality papers. It is important to check every source for relevance, credibility, publication venue and methodological rigor. As a rule, opt for peer-reviewed articles and frequently cited articles.

Table 1: Literature Review Matrix

Author	Year	Method	Key Findings	Gap
Study A	2023	Survey	High accuracy	Small sample
Study B	2024	Experiment	Strong validation	Limited scope

It's time to organize your findings once you have your research. Grouping papers according to their theme, methodology, or chronology can do this. Utilization of software tools like Mendeley or Zotero help enormously organize and cite reference sources (James et al., 2024; Duymuş, 2025; Lian et al., 2025). In addition to being organized, you should analyze the literature. This does not involve merely enumerating findings, but also evaluating, synthesizing, and interpreting studies in order to present more comprehensive insights. Compare the Studies (Paul and Rialp, 2020; Adeoye, 2024) Compare the different studies by noting similarities and differences in their methodology, findings, and conclusion. The authors identify trends, including emerging theories, dominant methods over time, and new themes spanning publications (Paul and Rialp, 2020; Heston, 2023). They assess their strengths (robust sample sizes, rigorous designs) and weaknesses (methodological biases, limited generalizability, or outdated data) (Adeoye, 2024; Aksakallı et al., 2024). For novices, this is even harder, with beginner writers often struggling to connect studies, interpret findings and synthesise evaluations rather than just summarise. While some researchers argue that a simple descriptive summary will suffice, especially for those pressed for time as it rapidly conveys key points, this misses the point of synthesising, which identifies gaps and pushes knowledge along. Tools such as literature matrices

can assist you in creating a table where you summarize your sources according to various themes, methods, strengths, and critiques.

Table 2: Key Steps in Analyzing and Evaluating Research Literature

Step	Action Example	Purpose
Compare	Note how Study A used surveys vs. Study B's experiments	Reveal methodological diversity
Trends	Track shift from qualitative to quantitative approaches	Show field evolution
Evaluate Strengths	Praise large-scale empirical validation	Highlight reliable evidence
Evaluate Weaknesses	Critique small samples or biases	Identify limitations

This analytical view differentiates a quality literature review from mere summary and gives credibility to your research (Paul and Rialp, 2020).

4.4 Identification of gaps.

Gaps in literature also lead to gaps in research design. Many researchers forget to include their literature review in their methodology section. These gaps indicate where research is deficient, contradictory, or lacking. It is possible that they occur due to lack of data, methods being outdated or any.

In order to identify gaps reading and thinking critically are essential. Inquiries that have not yet been addressed, discrepancies between findings and extra data, or areas where something may have been overlooked can expose opportunities for improvement. For instance, a limited study may have been done, showing we need to test further (“over 200 people in nine countries”) or the effect isn't small.

Clearly showing the gaps defines the contribution of your research. It helps to justify the importance of your work and show how it adds to knowledge.

5. Proposed Structured Framework.

We have devised an eight-phase framework that structures research.



Figure 1: Eight-Phase Structured Framework for Research Paper Development

Phase 1: The Research-idea Conception

Choose a research topic that is interesting and relevant to the discipline.

Inducing the Research Issue,

Phase 2: Specify the research problem and the aim precisely.

Phase 3: Review of literature.

Based on existing studies find the knowledge gaps.

Phase 4: Designing the Methodology.

Choose suitable research approaches based on the aims.

Phase 5: data collection and experimentation.

Perform experiments, surveys, simulations, or other similar techniques to collect data.

Phase 6: Analyzing and interpreting data

Analyze the data you have collected and put it into context.

Phase 7: involves manuscript drafting and structuring.

Compile results in well-organized coherent formal research paper.

Phase 8: Finalization and Submission for Publication.

Edit the article repeatedly and submit for peer-reviewed publication.

The systematic research framework described in the Introduction section enhances the quality of research from conception to dissemination. The framework will help beginners do this research easily. In fact, it will simplify the often-complex process of research writing into a systematic series of steps useful for producing quality academic work. The framework acknowledges that novice researchers may encounter challenges in recognising genuine research gaps, differentiating them from mere gaps in the literature, and determining how to translate their research gap into a viable research question. This systematic strategy prepares novice researchers with tactical students to formulate firm research questions which would lead to a meaningful contribution to their field (Islam, 2024). This distinction is important because often novice researchers cannot differentiate between research gap and research problem causing ambiguity in research questions and weakening conceptual frameworks (Kamal, 2026).

Adopting a systematic approach can help in making progress in a logical way. It also enhances your research.

6. Research Methodology

6.1 Method Selection

The choice of a right research method will depend on the objectives of the study. A careful examination of the different kinds of qualitative, quantitative and mixed-methods approaches to finding the appropriate methodological paradigm, following their epistemological and ontological structures do the research. For instance, when there is a relationship between two things like weight and

intelligence, then correlation test may be employed (Anik, Raaz and Khan, 2023).

6.2 Methods of Data Collection

Surveys are structured questionnaires that are generally distributed to a large sample for a more efficient collection of data. Generalizable insight afforded, but it suffers from respondent bias (Anik, Raaz and Khan, 2023).

Interviews: valuable qualitative data about the motivations and experiences of vulnerable communities. They facilitate exploration albeit being time-consuming and interviewer biased.

Observations are the systematic observation of behaviours of individuals occurring in natural situations as well as controlled settings. The behaviours are recorded as they occur to derive an authentic picture of reality without self-reporting. There are participant and non-participant types which raise ethical issues.

Experiments are specific manipulations of independent variables to see what happens in the dependent variable. Randomization reduces confounding but may be unrepresentative.

Simulations are helpful for testing a hypothesis in a complex environment that cannot be easily tested and cost effective (Anik, Raaz and Khan, 2023).

Method	Type	Advantage	Limitation
Survey	Quantitative	Large data	Bias
Interview	Qualitative	Depth	Time-consuming
Experiment	Quantitative	Causality	Artificial setting
Observation	Qualitative	Real behavior	Ethical issues

Table 3: Data Collection Methods Comparison

6.3 Tools and Techniques

Statistical Tools are computer programs or packages that facilitate any Statistical Analysis such as tests of hypothesis, regression, descriptive statistics etc. Researchers can easily handle and draw inferences from quantitative data. The authors (Anik, Raaz and Khan, 2023) provide examples of SPSS for user-friendly interface in social sciences, R for advanced statistical modelling, and Stata for econometric analysis.

Programming Languages are different coding environments used for data manipulation, automation, and bespoke analyses. They allow for scripting, making research reproducible and flexible beyond graphical interfaces. Python (through libraries, including Pandas and NumPy) is an example of a programming language that can fulfil the requirements for data handling. Another example is R, which can conduct statistical computing. Further, MATLAB supports numerical simulations and has engineering applications.

Specialized platforms for descriptive analysis of datasets, which allow for data exploration, visualization, and communication, usually used for qualitative and mixed evaluation research (for example, NVivo).

Software options include NVivo for the thematic analysis of text-based data; Tableau for interactive graphics and visualizations; and Excel for processing and creating pivot tables.

It avoids plagiarism by properly citing the sources. When a student uses an idea, they incorporate it into their own words and use quotation marks for direct excerpts.

You must ensure the integrity of data by collecting, recording, and reporting that data truthfully without making up, falsifying, selectively reporting, or misrepresenting it.

Manage Confidentiality: Respect your respondents' privacy by anonymizing sensitive

information, acquiring informed consent, securely managing information, and following applicable ethical guidelines (like the institutional review boards).

7. Analysis and interpretation of data.

The step data analysis and interpretation is an important one in the research process. That is to say, the collation is followed by a phase of analysis and interpretation. The application of suitable analytical techniques (quantitative, qualitative, or mixed) on the raw data gives results. In addition, contextually makes sense of the results. This establishes link between research objectives, theory/hypothesis, and existing literature. Proper Analysis Ensures Reliability and Validity Connecting the research to a wider set of implications and avoiding generalisation and misattribution.

7.1 Fundamental Elements.

Statistical tools for hypothesis testing, correlations, regressions, and descriptive statistics are used for quantitative analysis to quantify relationship and significance.

Qualitative analysis refers to a method of analysis involving thematic coding, content analysis or narrative synthesis to identify recurrent patterns, themes, and meanings that come from texts made.

We use charts and tables in data visualization to present results and make them easy to understand.

Summarize the results in relation to the research questions, discuss the limitations of the findings, compare the results to past studies, and discuss the theoretical or practical contributions of the results.

In this stage, data is converted into theoretical knowledge that forms the basis of credible conclusions and recommendations. In the process of data analysis (i.e., participant confidentiality and data integrity); ethical

considerations are essential and must be stringently guaranteed (Romero-Carazas et al., 2024; Tahir, 2024).

7.2 Analysis Techniques.

Statistical analysis refers to the use of statistical tools and techniques for the processing of quantitative data. These include descriptive statistics (i.e., means, frequencies), inferential tests (i.e., t-tests, ANOVA, chi-square), correlations, regressions, and multivariate analyses, to test hypotheses, quantify relationships, and assess level of significance. It ensures objectivity, reliability, and generalizability but assumes data normality and may overlook contextual nuances (Anik, Raaz and Khan, 2023; Romero-Carazas et al., 2024; Tahir, 2024).

A method of thematic analysis can be used to identify, analyse, and report patterns (themes) within data. This process consists of six phases: familiarisation, coding, generating, reviewing, defining, and reporting themes. An extensive and deep exploration of experiences and meanings is possible, but it is also subjective, potentially very time-consuming, and may suffer from researcher bias (Romero-Carazas et al., 2024; Tahir, 2024).

Presentation of Result

Tables are structured grids that organize data into rows and columns. They are used to present numerical summaries, comparisons, and more detailed data.

Graphs are visual representations using line graphs, scatter plots, area graphs, etc, that can show relationships, trends, and changes over time.

The charts can include bar charts for categorical comparisons; pie charts for proportions; and histograms for distributions.

7.3 Interpretation.

The results must be clearly explained and connected to the research objectives.

8. The Layout of a Research Paper

A standard research article includes

The abstract must be concise (150-250 words long) describing the purpose, research methods, main results, and conclusions of the research. It helps a reader to get an overall view of the paper and its contribution to the research field.

The introduction of the overview manages the research problem and objectives includes the significance and research questions or hypothesis as well as provides the outline of the paper.

Surveys existing studies, theories, and gaps to put the present research in context and support the need for the current research, uses reliable secondary sources such as databases and literature surveys (Anik, Raaz and Khan, 2023)

The methodology is a research design (quantitative, qualitative, or mixed-method), sampling, data collection methods, instruments and analysis techniques for replication and validity (Tahir, 2024).

Results are objective presentation of findings by means of tables, graphs, and statistics with no interpretation. It highlights the pattern, relationship, and significance of data analysis (Romero-Carazas et al., 2024; Tahir, 2024).

The discussion part of this section interprets the results in relation to the research questions. Also, compare results to previously published research. Discuss limitations, implications, and future research. Lastly, discuss ethical aspects such as the integrity of the data (Romero-Carazas et al., 2024).

In the conclusion section, the main findings are presented, along with the contributions made, the recommendations provided, and the directions for future research.

- Writing Ideas.
- Avoid technical terms.
- Maintain the logical flow.
- Do not make it repetitive.

9. Citing Your Sources.

9.1 Referencing and Citation.

Citations and referencing are an important part of academic writing, as they give credit to the original author, strengthen the credibility of the paper, help readers verify the information and prevent plagiarism. The proper way to cite maintains decorum and the amalgamation of existing scholarship (Anik, Raaz and Khan, 2023).

The most used social sciences citation style is APA. uses author-date in-text citations (eg, Smith, 2023) and alphabetical reference lists.

MLA is the format most used in humanities. It uses author-page citations (like Smith 45) and provides a Works Cited page.

The IEEE style is the most common style in engineering and technical fields. The style is a system of numeric superscripts in the text which are linked to numbered references.

9.2 Imagery.

Mendeley is a free reference manager that does PDF organization, bibliography creation, and team library sharing.

Zotero is open-source software that captures sources from web pages and can use multiple styles. It integrates with word processors.

9.3 Preventing Plagiarism.

Reword content in your own words, very rarely quote directly with citations, and always check with something like turn it in. Ensure the accuracy and integrity of references.

10. Common Mistakes by Beginners

New researchers formulate a vague, too broad, saccharine section like “Every day millions of people walk the streets of Buenos Aires. It is an amazing Plaza. There are so many different restaurants...”⁴. Problem title and explanation the needless vagueness results in loose objectives and justifications, and much difficulty in forming precise research question/hypothesis. To avoid, state the issue, what the context is, and why it matters.

A literature review is weak when it fails to survey the existing studies comprehensively, identify the gaps, and engage with the prior work critically. It leads to repetitions and unsupported claims without adequate theoretical backing. Use dependable sources organized thematically or chronologically.

A poor structure such as disorganized sections and illogical flow, or missing key components (e.g., no clear methodology) confuse the reader. Use a standard outline and organize logically with headings/subheadings.

Failing to take the right citations may involve incorrect referencing and non-citation of sources. Utilize one citation style (e.g., APA) and a tool, such as Zotero, to keep accurate.

Language errors like grammatical issues, awkward phrasings, redundancy, or inconsistent terminology affect the readability. Check for grammar mistakes, write in clear academic language, and seek peer feedback.

Table 5: Common Mistakes and Solutions

Mistake	Impact	Solution
Unclear problem	Weak research	Define clearly
Poor review	No novelty	Use quality sources
Wrong citation	Ethical issue	Use tools like Zotero

When you avoid these mistakes, your paper will improve exponentially. Moreover, awareness and use of various citation styles such as APA, MLA, and Chicago are important to maintain academic integrity, as well as to incorporate new knowledge into the existing academic discourse (Barasa, 2024; Garg, 2024). Citation management tools like Zotero to not only help researchers format their references properly. They also enable users to integrate different sources into their work seamlessly. In the process, researchers collect, sort, and share research materials reasonably effectively.

Further, they help you avoid common mistakes (Nikolov, 2023; Meer, 2025). Omitting this aspect will make the paraphrased sections look like fabrication (Habiba and Shadek, 2024).

11. Publication Process

11.1 Journal Selection

Scholars must choose journals that are related to their paper's topic, scope, methodology, audience, impact factor, acceptance rate, and indexing database. Please provide the text that you would like me to paraphrase.

11.2 Submission

It's essential to respect the journal's formatting guidelines, author guidelines, word limitations, reference style, submission process via online portals, etc. It can send out a custom cover letter. It helps avoid desk rejection.

11.3 Peer Review

Each paper assigned to independent experts for a blind peer review of the originality, soundness, validity, clarity, and contribution will take about 1-6 months

11.4 Revision

Make sure to integrate the reviewers' comments, change the content, support your claims, clarify the ambiguities, and provide a point-by-point response letter detailing the changes made and re-submit it as soon as possible for reconsideration.

12. Conclusion

The research writing framework outlined in this paper is broad and contains organized frameworks for beginners. A beginner's guide to research shows how to create new ideas, define a problem statement, conduct a literature review, design a research methodology, objectively analyse results, discuss interpretation, and navigate the publication process successfully. The framework improves the clarity, rigor, and impact of academic work by emphasising clear expression, logical construction, proper

referencing (using a referencing tool such as Zotero) and avoiding common pitfalls (vague objectives, plagiarism, etc.). You can use it in different fields and disciplines. It increases reproducibility, ethics, and credibility. It helps novice researchers obtain quality papers that contribute to existing research. In conclusion, this adaptable resource provides emerging scholars with valuable tools to translate ideas into publishable outputs, addressing gaps in novice research practices.

13. Future Scope

Future studies can use technologies to make futures studies more academic. Essential sectors contain the consolidation of artificial intelligence devices to mechanise scripting, rectifying, and blueprint generations mechanisms; improvement of mechanised literature Review systems that efficiently synthesize colossal research sources and pinpoint research voids; and production of cooperative frameworks producing real-time co-authorship, resource allocation, and interdisciplinary teamwork. The promise of enhancing efficiency, accessibility, and quality of the research work.

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A Comprehensive Review of Lung Disease Detection Using Machine Learning and Deep Learning Techniques

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Accepted: 10.04.2026

Published: 30.04.2026

Page No. 111 – 121

DOI: 10.5281/zenodo.20020870

Abstract

Respiratory diseases, such as pneumonia, tuberculosis (TB), chronic obstructive pulmonary disease (COPD) and COVID-19, are among the world's major causes of illness and death. Timely and precise diagnosis plays a pivotal role in patient outcomes; nevertheless, conventional diagnostic processes are limited by subjectivity, resource availability, and the requirement for skilled professionals. The emergence of integrating machine learning (ML) and deep learning (DL) in the diagnosis of lung diseases has introduced a new paradigm that may improve diagnostic accuracy, shorten the diagnostic process, and broaden access to health care, especially to those in remote settings. This review paper provides an overview of the research using ML and DL techniques for the diagnosis of lung diseases, focusing on chest X-rays and computed tomography (CT) scans. This review examines popular datasets, feature extraction techniques, classification models, convolutional neural network (CNN) models, and transfer learning methods. It also explores image preprocessing techniques, data augmentation methods, and performance metrics. The research highlights the challenges in this field - lack of labeled data, class-imbalance, and interpretability of the models - and suggests future research opportunities. The work is primarily an analysis of the literature, and it does not include any original experiments or clinical studies.

Keywords: lung disease diagnosis, machine learning, deep learning, convolutional neural network, transfer learning, chest X-ray, CT scan.

1. Introduction

1.1 Background of Lung Diseases

Lung diseases are a major global health issue in the 21st century. The World Health Organization (WHO) lists lower respiratory tract infections as one of the world's top four causes of death, resulting in more than four million deaths per year (WHO, 2022). Tuberculosis alone accounted for the deaths of around 1.6 million people in 2021, and COVID-19 has led to a global health burden not previously experienced in modern history since its onset in late 2019 (Dong et al., 2020). COPD, a progressive lung disease marked by airflow limitation, affects over 300 million individuals worldwide and often goes unnoticed until later in the disease course (Global Initiative for Chronic Obstructive Lung Disease [GOLD], 2022). These figures highlight the need for effective, scalable, and early detection techniques.

1.2 Need for Early Detection

Timely diagnosis of lung-related diseases enhances patient outcomes and decreases the financial burden on health care. Research shows that the five-year survival rate for early-stage lung cancer, detected before metastasis, is greater than 55%, whereas late-stage lung cancer survival rates are below 5% (Siegel et al., 2021). Likewise, early diagnosis of pneumonia and TB allows for early antibiotic treatment, thereby decreasing disease spread and death rates. But the lack of radiologists - especially in developing and middle-income countries - and the subjectivity of visual interpretation present significant challenges to early

diagnosis (Patel et al., 2019). The need for computer systems that can help clinicians in making a diagnosis is therefore important to public health.

1.3 Machine Learning and Deep Learning

Artificial intelligence (AI), including traditional machine learning and the more recent deep learning technique, has shown extraordinary promise in medical imaging applications. Machine learning techniques such as Support Vector Machines (SVM), k-Nearest Neighbors (kNN), and Random Forests can learn to classify radiomic features with moderate accuracy on relatively small datasets. Deep learning models, particularly CNNs, can automatically identify hierarchical features from pixel data, removing the need for feature engineering and producing state-of-the-art results on large-scale medical imaging datasets (LeCun et al., 2015; Rajpurkar et al., 2017). Classical models such as VGG16, ResNet50, InceptionV3, and DenseNet121 have been effectively fine-tuned for lung disease classification with transfer learning methods, achieving diagnostic performance that in some cases equals or exceeds board-certified radiologists.

1.4 Review Purpose

This article is a systematic review of peer-reviewed articles indexed in databases such as IEEE Xplore, PubMed, Scopus, and Google Scholar published from 2015 to 2024. The authors have not undertaken any experiments, datasets, or clinical studies. The paper aims to provide an overview of the current state of the art, assess the methodological strategies, identify the gaps and future scope of applying ML and DL techniques for lung disease detection. The rest of the paper is organised as follows: Section 2 offers a clinical overview of major lung diseases and traditional diagnostic techniques; Section 3 reviews of the benchmark datasets and the challenges faced; Sections 4 and 5 describe classical ML and deep DL approaches

respectively; Section 6 covers image preprocessing; Section 7 compares model performance; and Section 8 concludes with a discussion of limitations and future work.

2. Background of Lung Diseases and Diagnosis

2.1 Classification and Characteristics of Major Lung Diseases

Acute inflammation of the lung parenchyma, most commonly due to bacterial, viral or fungi infection. The most frequent pathogens are *Streptococcus pneumoniae* and Influenza A. Lobar consolidation, interstitial infiltrates, and ground-glass opacities (GGOs) are typical CXR findings. The variability of its radiological features makes its classification challenging (Wang et al., 2017).

Tuberculosis is one of the world's oldest and most persistent infectious diseases, with a primary focus on the lungs. CXR findings in TB include upper lobe consolidation, cavitation, and hilar lymphadenopathy in the presence of *Mycobacterium tuberculosis* infection. The radiological appearance of TB lesions is like other lung diseases and requires laboratory confirmation for diagnosis; however, automated diagnostic tools have been proven effective in resource-poor environments (Jaeger et al., 2014).

COVID-19 pneumonia, due to SARS-CoV-2 virus, can be seen with bilateral peripheral GGOs, crazy-paving pattern, and consolidation on CT. The global pandemic of COVID-19 prompted the need for automated tools to diagnose SARS-CoV-2 pneumonia and differentiate it from other viral and bacterial infections (Ai et al., 2020).

COPD is an inflammatory lung disease with irreversible airflow limitation due to emphysema and chronic bronchitis. CT findings include hyperinflation, bullae and thickening of the airway walls. Lung cancer, including adenocarcinoma, squamous cell carcinoma and

small cell types, requires early detection and differentiation of lung nodules to facilitate surgical resection.

2.2 Diagnostic Imaging Modalities

Chest X-ray (CXR) is the most widely used imaging technique in clinical practice for its affordability, ubiquity, and speed. But CXR has poor three-dimensional resolution and a high degree of superimposition, making it difficult to identify subtle abnormalities. CT offers better anatomical resolution and cross-sectional images, allowing detection of small nodules, interstitial and vascular abnormalities, but with increased radiation and scan time. Positron emission tomography (PET)-CT and magnetic resonance imaging (MRI) are used for specific clinical purposes, such as mediastinal staging and pleural disease, respectively (Litjens et al., 2017).

The clinical use of these imaging techniques is time-consuming, requires expert interpretation and is prone to variability. These challenges have sparked interest in the development of AI-based diagnostic systems that offer reliable, objective, and efficient image analysis.

3. Datasets and Challenges

3.1 Benchmark Datasets

The development of large-scale, annotated medical image datasets has played a key role in driving improvements in AI-based medical diagnosis of lung disease. The National Institutes of Health (NIH) ChestX-ray14 dataset (Wang et al., 2017) comprises 112,120 anteroposterior CXR images with 14 different thoracic diseases, and is the most popular benchmark dataset. The Shenzhen and Montgomery County TB datasets (Jaeger et al., 2014) are CXR images annotated for tuberculosis screening. The Kaggle RSNA Pneumonia Detection dataset, sourced from the Society for Thoracic Radiology, includes more than 30,000 CXR images, and has been widely used for pneumonia

classification and localization. The COVID-19 Radiography Database (Chowdhury et al., 2020) is a multi-class CXR dataset that includes COVID-19, viral pneumonia, and normal images, while the LIDC-IDRI dataset offers CT images for the detection of pulmonary nodules.

Table 1: Summary of Benchmark Lung Disease Datasets

Dataset	Disease Focus	# Images	Format	Access
NIH ChestX-ray14	14 Pathologies	112,120	PNG	Public
Shenzhen TB Set	Tuberculosis	662	PNG	Public
Montgomery TB Set	Tuberculosis	138	PNG	Public
Kaggle RSNA	Pneumonia	30,000+	DICOM	Public
COVID-19 Radiography	COVID-19	21,165	PNG	Public
LIDC-IDRI	Lung Nodules (Cancer)	1,018 CT scans (~100k+ slices)	DICOM	Public (with agreement)
JSRT Dataset	Lung Nodules	247	IMG (grayscale)	Research / Restricted

Table 1. Comparative overview of publicly available benchmark datasets utilized in lung disease detection research.

3.2 Dataset Challenges

Despite the availability of these databases, there are common challenges in research. Class imbalance is a common issue in medical imaging, where the number of pathological cases is significantly lower than that of non-pathological cases, making models trained on such distributions prone to overestimate their accuracy (Johnson & Khoshgoftaar, 2019). Limited sample sizes are an issue in CT studies due to the expense of image

acquisition and privacy concerns. Moreover, labeling inconsistencies due to inter-radiologist variability result in label noise, which may hinder model training and testing. Domain shift, where models trained with data obtained from one CT scanner or institution do not generalise to other acquisition protocols, is a major limiting factor to translation (Raghu et al., 2019). Finally, CT data is three-dimensional, which introduces computational challenges not present in CXRs.

4. Machine Learning Techniques

4.1 Feature Extraction Strategies

Traditional machine learning approaches for medical image classification involve the extraction of hand-designed feature representations before classification. These can be broadly construed as textural, morphological, and statistical. Textural features, such as those obtained from the Gray-Level Co-occurrence Matrix (GLCM), Local Binary Patterns (LBP) and Gabor filters, describe spatial intensity distributions of abnormal tissue. Morphological features capture shape information of the segmented regions (lesions or lung regions), whereas statistical features capture global or local statistics of the pixel intensity distribution of the image. Other features that have been used for lung image analysis include the Histogram of Oriented Gradients (HOG) and the Scale-Invariant Feature Transform (SIFT), which can be used to describe nodule shapes (El-Baz et al., 2013). Dimensionality reduction techniques, such as Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA), are often used before classification.

4.2 Support Vector Machines

Support Vector Machines (SVMs) are a family of supervised classifiers that find the hyperplane that best separates two or more classes in a high-dimensional feature space, while providing the greatest margin between the classes. SVMs are especially well-adapted to binary classification

problems in high-dimensional low-sample sizes. The kernel trick allows SVMs to fit a nonlinear hyperplane using radial basis function (RBF), polynomial or sigmoid kernels. Several recent studies have reported high classification accuracy for TB screening with GLCM (84-92%) and pneumonia detection with HOG descriptors using SVMs. But SVM classifiers are not suitable for multi-class problems, or when the features have different distributions (Cortes & Vapnik, 1995).

4.3 k-Nearest Neighbors and Decision Trees

The k-Nearest Neighbors (kNN) classifies a new instance by computing the majority label of its k nearest neighbors in the training data using a distance function like Euclidean or Minkowski distance. Although intuitive and straightforward, kNN is inefficient at inference, dependant on the choice of k, and prone to the curse of dimensionality in high-dimensional spaces. Decision trees recursively split the feature space based on information gain or Gini impurity, and produce easily interpretable rules for classification. Ensemble variants such as Random Forests and Gradient Boosting Machines significantly improve the model's performance by reducing variance (bagging) and sequentially correcting the errors (boosting) respectively, and have demonstrated high accuracy in radiological classification problems (Breiman, 2001).

5. Deep Learning Techniques

5.1 Convolutional Neural Network Architecture

Convolutional Neural Networks (CNNs) are a type of feed-forward artificial neural network selectively designed for spatial processing. Convolution, activation, pooling and fully connected layers are the building blocks of a CNN. Convolutional layers employ learned sets of filters to the input feature map, extracting local spatial features via weight sharing and translational

equivariance. The Rectified Linear Unit (ReLU) activation function adds nonlinearity without suffering from the vanishing gradient issues of sigmoid and tanh units. Max-pooling layers successively downsample spatial dimensions while retaining feature responses. Fully connected layers combine global feature responses and generate class probability scores using a Softmax function (LeCun et al., 2015).

Figure 1: Convolutional Neural Network Architecture for Lung Disease Classification

Input	Conv +relu	Pooling	Conv +relu	Flat ten	Fc+softmax
224×224×3	Feature maps	Downsampling	Deep features	Feature vector	Class output

Figure 1. General CNN architecture pipeline from raw image input to disease classification output. Arrows indicate forward propagation through successive processing stages.

5.2 Landmark Deep Learning Models

The VGGNet of Simonyan and Zisserman (2014) is a deep network with 16-19 weight layers using 3×3 convolutional filters that has been widely fine-tuned for pneumonia and TB classification and has reported 93-96% accuracy on benchmark tasks. He et al. (2016) proposed ResNet50, which uses residual skip connections to overcome the problem of degradation in very deep networks, allowing training of networks with 50-152 layers and superior performance in multi-class thoracic disease classification. InceptionV3 (Szegedy et al., 2016) uses factorized convolutions and inception modules to efficiently build feature maps in parallel without compromising representational power, and has shown strong performance when applied to TB classification. DenseNet121 (Huang et al., 2017) uses dense connectivity, where each layer receives feature maps from all preceding layers and has achieved state-of-the-art performance on the NIH ChestX-ray14 benchmark with an area under the

receiver operating characteristic curve (AUC) of more than 0.80 for 14 thoracic diseases.

5.3 Transfer Learning

Transfer learning involves transfer of representational knowledge learned by a deep neural network through pretraining on a large-scale dataset (typically ImageNet (Deng et al., 2009), a collection of 1.2 million natural images) and fine-tuning the network for a particular medical imaging task. Such an approach is especially valuable in medical imaging, where the available labeled training data is limited in comparison to the number of parameters of deep neural networks. The main transfer learning approaches are featuring extraction, where the pretrained convolutional layers are frozen and only the classification layer is retrained; and fine-tuning, where all or a subset of layers are retrained with a lower learning rate. Research has shown that transfer learning consistently yields significant improvements in accuracy over training from scratch on small medical imaging datasets, with 5-15% improvement in accuracy being reported (Tajbakhsh et al., 2016).

5.4 Hybrid and Ensemble Models

Hybrid models that combine CNN feature representation with recurrent neural networks (RNNs) or attention-based mechanisms have also been applied to capture temporal information in longitudinal imaging studies, and to enforce spatial attention on salient regions of interest. The use of squeeze-and-excitation and transformer-based models (including Vision Transformers or ViTs) has also proved beneficial in modelling global spatial dependencies in high-resolution CT scans. Ensemble learning, which combines predictions from multiple individually-trained models, further reduces variance and enhances model calibration, and has been used in several successful lung disease detection challenges to deliver state-of-the-art performance (Rajpurkar et al., 2017).

Table 2: Comparative Performance of Deep Learning Models for Lung Disease Detection

Model	Architecture	Accuracy (%)	Parameters	Dataset	Disease
VGG16	16 Layers CNN	94.5	138M	NIH CXR	Pneumonia
ResNet50	Residual Net	96.2	25M	COVID-19 DB	COVID-19
InceptionV3	Inception Mod.	95.8	23M	Shenzhen	TB
DenseNet121	Dense Connect.	97.1	8M	NIH CXR14	Multi-class
MobileNetV2	Lightweight	93.7	3.4M	Kaggle	Pneumonia
EfficientNetB4	Compound Scal.	97.5	19M	RSNA	Nodule Det.

Table 2. Summary of reported accuracy values for major deep learning architectures across diverse lung disease datasets. Results are sourced from literature and are approximate.

6. Image Processing and Preprocessing

6.1 Image Enhancement

Medical images are often degraded by noise, poor contrast, and other scanner-specific artifacts, which require systematic pre-processing before feeding them to the model. Contrast-Limited Adaptive Histogram Equalization (CLAHE) is commonly used for local contrast enhancement of CXR images to boost detection of subtle lung infiltrates and nodular opacities while avoiding global image saturation (Pisano et al., 1998). Gaussian and median filtering are used for noise reduction, while histogram normalization ensures consistent image intensity distributions across different scanners and acquisition techniques to reduce domain shift. Bone suppression (removing bony structures from CXR images) has been shown to enhance the detection of pulmonary infiltrates

obstructed by rib and clavicular bones (Suzuki et al., 2006).

Figure 2: Image Preprocessing Pipeline for Lung Disease Detection Systems

Raw image Dicom/png	Resize & normalize 224x224 px	Enhance CLAHE	Segment Lung region	Augment Flip/rotate	Model input Ready data
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Figure 2. Schematic representation of the sequential image preprocessing pipeline, from raw DICOM/PNG acquisition through normalization, enhancement, segmentation, and augmentation.

6.2 Lung Segmentation

Lung field segmentation highlights the areas of interest in the lungs by removing extraneous thoracic structures, such as the cardiac silhouette, mediastinum, and diaphragm, thus enhancing the signal-to-noise ratio of subsequent feature extraction or deep learning processing. Traditional methods include thresholding, region growing and graph-cut, while deep learning models - such as U-Net and its extensions - have set new standards for automated lung segmentation (Ronneberger et al., 2015). U-Net's contracting and expanding architecture with skip connections allows for accurate detection of boundaries even with limited training data, making it well-adapted to medical applications. Volumetric segmentation of CT scans with 3D-UNet allows for volumetric measurements of lung nodules and extraction of quantitative radiomic features.

6.3 Data Augmentation

Data augmentation is a crucial strategy for enlarging the apparent size of small training sets and avoiding overfitting in deep learning models. Common geometric augmentations of medical images involve horizontal and vertical flipping, random rotation (usually ± 15 degrees), scaling, translation, and elastic deformation. Random variations in image intensity (brightness and contrast

jitter, Gaussian noise) also contribute to intra-class variations. A more advanced approach to augmentation is through generative adversarial networks (GANs), where synthetic pathological images are generated to complement real image data; several studies have reported accuracy gains of 2-5% with GAN augmentation for rare disease classes (Frid-Adar et al., 2018). Mixup and CutMix policies, originally designed for natural image classification, have also been applied to lung image classification with promising results.

Figure 3: End-to-End System Flow for Automated Lung Disease Detection

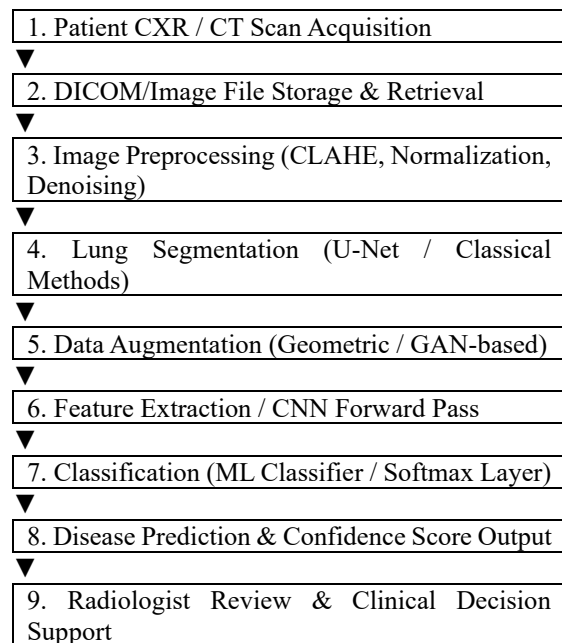


Figure 3. End-to-end system architecture for automated lung disease detection, from image acquisition through preprocessing, feature learning, classification, and clinical decision support.

7. Performance Evaluation and Comparison

7.1 Evaluation Metrics

Performance analysis of lung disease classifiers requires the consideration of several performance metrics, as no single statistic is suitable to fully describe the classifier's performance in all aspects relevant to clinical practice. Accuracy - the fraction of correctly predicted cases among all cases

- is an intuitive measure but can be misleading in the presence of class imbalance, where a simple majority-class predictor might yield very high accuracy. Precision (positive predictive value) represents the fraction of positive predictions that are true positives (i.e., true pathological cases), while Recall (sensitivity) represents the fraction of true positive instances that are detected. The F1-score, defined as the harmonic mean of precision and recall, is a balanced metric that is appropriate for imbalanced data. The Area Under the Receiver Operating Characteristic Curve (AUC-ROC) measures the discriminative power of a classifier over all possible decision thresholds, and is considered the preferred metric for binary medical classification problems. Other metrics such as Specificity, Negative Predictive Value (NPV) and the Dice Similarity Coefficient (for segmentation problems) are also used in the literature we review.

7.2 Comparative Analysis of Approaches

Table 3: ML vs. Deep Learning Performance Comparison

Criterion	SVM	KNN	Decision Tree	CNN (DL)
Accuracy	Moderate-High	Moderate	Moderate	Very High
Data Requirement	Low-Medium	Low	Low	High
Feature Engineering	Required	Required	Required	Automatic
Interpretability	Moderate	High	High	Low
Training Time	Fast	Very Fast	Fast	Slow
Scalability	Limited	Limited	Moderate	High
Best Use Case	Small datasets	Simple tasks	Structured data	Image data

Table 3. Comparative analysis of classical machine learning algorithms and deep learning frameworks across key performance dimensions for lung disease detection.

Table 4: Reported Performance Ranges by Methodological Approach

Approach	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
SVM (Hand-crafted)	82–88	80–86	79–85	79–86
KNN	75–83	73–82	72–81	73–82
Random Forest	84–90	83–89	82–88	82–89
Basic CNN	88–93	87–92	86–91	87–92
Transfer Learning	93–97	92–96	91–96	92–96
Hybrid DL Models	95–98	94–97	94–97	94–97

Table 4. Summary of accuracy, precision, recall, and F1-score ranges reported across the reviewed literature, categorized by algorithmic approach.

The benchmarking results in Tables 3 and 4 demonstrate a clear hierarchy in performance between deep learning methods, especially transfer learning and hybrid approaches, and classical ML classifiers across all benchmarking metrics, when applied to large imaging datasets. Transfer-learned CNNs typically attain classification accuracies in the 93-97% range, whereas SVM and Random Forest classifiers typically achieve 82-90% accuracy. But this performance gain comes with the assumption of adequate training data; in low-data regimes (less than 500 labeled images), traditional ML approaches with strong feature engineering can match or outperform undertrained CNNs. Rajpurkar et al. (2017) showed that a DenseNet-based model outperformed the average radiologist on the National Institutes of Health (NIH) CXR14 data set measured by the area under the curve (AUC) metric, suggesting deep learning has the potential to be a clinical decision support system, rather than just a benchmark system.

8. Challenges, Future Directions, And Conclusion

8.1 Persistent Challenges

Despite the significant advances highlighted in this review, several challenges remain that hinder the transition of AI-based lung disease detection systems from research to clinical settings. The lack of large, diverse, and accurately annotated medical imaging data sets - and regulatory limitations on cross-institutional data sharing - limits model generalisability and external validity. Class imbalances, particularly for rare lung diseases, are a common problem that requires the application of sampling techniques, cost-sensitive learning, or data augmentation approaches. The lack of interpretability of deep neural networks - the "black-box" issue - presents a major hurdle to clinician acceptance and regulatory approval; while gradient-weighted class activation mapping (Grad-CAM) and integrated gradients can provide post-hoc saliency maps, they don't explain the decision-making of these models (Selvaraju et al., 2017). Domain shift due to variability in imaging equipment, protocols, and demographics presents a challenge to model generalization and requires domain adaptation or federated learning strategies. In addition, ethical issues related to algorithmic bias, privacy, and liability in AI-assisted diagnoses need to be addressed (Obermeyer & Emanuel, 2016).

8.2 Future Research Directions

The review of literature suggests several valuable research opportunities. Federated learning (distributed model training across multiple sites in a privacy-preserving manner) presents a scalable approach to address data scarcity and domain shift while preserving privacy, and has been applied to lung nodule detection in initial studies (Roth et al., 2020). Unsupervised and semi-supervised learning, leveraging large quantities of unlabeled data to learn generic representations, is an attractive alternative to supervised learning approaches that may suffer from limited training data in clinical practice. The

incorporation of multi-modal data - for instance, combining imaging features with clinical metadata, electronic health record data and genomic data - has the potential to significantly enhance diagnostic performance and prognostic value compared to imaging-based models alone. Vision Transformers, which employ global self-attention, can be used as a complementary approach to CNNs to learn long-range spatial relationships in high-resolution CT images. Lastly, the need for uniform assessment and validation of diagnostic systems, prospective clinical trials, and regulatory procedures is crucial for the safe and equitable use of AI-based diagnostic solutions in clinical practice.

8.3 Conclusion

This paper has provided a systematic review of machine learning and deep learning algorithms for detection and classification of major lung diseases, such as pneumonia, tuberculosis, COVID-19, COPD, and lung cancer. This is a literature review based solely on analysis of published peer-reviewed studies, and has distilled evidence across benchmark datasets, feature extraction methods, classification algorithms, CNN architectures, transfer learning techniques, and image preprocessing approaches. The results of this review confirm that deep learning (especially transfer-learned CNN models like ResNet50, DenseNet121 and EfficientNet) consistently outperforms classical machine learning algorithms in diagnostic accuracy across large-scale image data, while also confirming that classical ML approaches hold many advantages in small data and interpretability-constrained settings. Critical issues of data availability, class imbalance, domain shift, and model interpretability must be comprehensively resolved with innovative approaches to federated learning, self-supervised learning, and explainable AI for safe and equitable clinical translation of AI-powered pulmonary diagnosis. It is hoped that this

review will provide a useful guide to researchers and clinicians tackling the interdisciplinary challenge of leveraging AI to benefit global pulmonary health.

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AI-Based Early Detection of Neurological and Mental Disorders using Multimodal Deep Learning

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Accepted: 10.04.2026

Published: 30.04.2026

Page No. 122 – 133

DOI: 10.5281/zenodo.20020928

Abstract

Early diagnosis of neurological and mental health disorders is a pressing issue in the current healthcare system, especially in underdeveloped areas with limited access to advanced diagnostic tools and healthcare professionals. Diseases like Parkinson's, depression and stroke often present with early signs that are difficult to spot through conventional medicine. In this research, we propose the use of a new multimodal deep learning model with which non-invasive as well as economically affordable prediction of disease can be done timely with the use of speech along with facial micro-expressions. Our work exploits Convolutional Neural Networks (CNN) for spatial feature extraction from facial images and Recurrent Neural Networks (RNN/LSTM) for temporal speech feature modelling. A fusion strategy is employed to combine multi-modal features for enhanced model accuracy and reliability. The goal of this strategy is to identify people at different risk levels to catch it early and keep an eye on their health for a long time to come. In addition, the system's ability to lessen the need for expensive diagnosis tests proves it can be used in the real world, especially in rural areas. We also discuss the issues of privacy, dataset collection, and generalisation. The method has the potential to revolutionize preventive health by facilitating scalable, affordable, and smart health diagnostic and monitoring systems.

Keywords:

Artificial Intelligence (AI); Multimodal Deep Learning; Neurological Disorders; Mental Health

Disorders; Early Disease Detection; Machine Learning in Healthcare; Medical Data Analysis; Healthcare Informatics; Predictive Modeling; Clinical Decision Support Systems.

1. Introduction

Mental and neurological disorders such as depression, Parkinson's disease, schizophrenia, and autism spectrum disorders are a serious burden on global health, impacting millions of people from all walks of life. Disorders such as depression, anxiety, and addictions impact cognitive, emotional and behaviours. It can be rewritten as it causes deterioration in the quality of life and huge social and economic costs. The accurate and timely diagnosis of a disease can greatly facilitate an effective treatment. In many cases, common traditional diagnostic methods mostly rely on the clinical judgement, self-report from the patient, and observation which can delay and misdiagnosis (Ren et al., 2025). New technologies in artificial intelligence (AI) have recently developed into a useful health care tool and offer new objective, data-driven techniques for detecting and diagnosing diseases. The utilization of machine learning (ML) and deep learning (DL) models allows for the evaluation of complex data sets with high density of dimensions to assist in detecting a pattern which is often hard for humans to detect (Sharma et al., 2025). These developments have not only made it easier but helped develop automated systems to detect early symptoms of mental and neurological disease more accurately. A promising avenue in this field is multimodal deep learning, which fusion of

multiple types of data including voice, facial expressions, behaviour, and physiological measures. Speech analysis detects subtle variations in pitch, tone, and rhythm, which can be indicative of mental health disorders. Likewise, facial expressions are informative of emotional states and neurological disorders. For example, decreased facial expressivity (hypomimia) is known to be an early symptom of Parkinson's disease, and can be detected using machine learning methods applied to video-based facial expressions (Moshkova et al., 2026). Merely integrating more and more data does not necessarily increase the effectiveness of an AI-based diagnostic tool. Past results indicate that multimodal solutions provide better detection accuracy than single-modality ones. According to Sharma et al. (2025), all systems demonstrated remarkable efficacy in identifying mental health disorders. The capacity of these systems for modalities was also enhanced by later developments in deep learning architectures such as convolutional neural networks (CNNs), recurrent neural networks (RNNs), and transformers. Even after so much progress, challenges remain about privacy, interpretability, diversity, and clinical validity. Applications that deal with sensitive subjects such as mental health need to have the AI systems in place to ensure privacy, ethics, and explainability. Overcoming these barriers will allow for the secure and effective transfer of diagnostic technology into practice. The purpose of this review paper is to discuss the various artificial intelligence-based approaches for predicting neurological and mental disorders at an early stage using multimodal deep learning techniques especially voice and facial analyses. This paper reviews recent developments, approaches, challenges, and future research opportunities to show the potential of multimodal AI systems for disrupting early diagnosis and healthcare process.

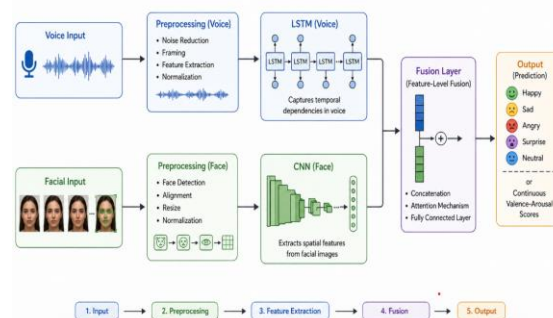


Figure 1. Overall System Architecture

2. Overview of Neurological and Mental Disorders

Neurological and Mental Disorders
Neurological and mental disorders are a wide variety of conditions affecting cognitive, emotional, and behavioural processes. The combination of biological, psychological, and environmental factors makes these conditions hard to diagnose and treat (Eryilmaz Baran & Cetin, 2025). These disorders should be identified early as the lack of timely diagnosis can lead to severe disability and poor quality of life.

2.1 Types of Disorders

Depression

Depression is a widespread psychiatric illness characterised by long-term sadness, inability to feel pleasure, sleep problems, and impaired thinking. It hampers one's daily living and may lead to suicide ideation in extreme cases. (Ren et al., 2025) The traditional diagnosis tends to rely on subjective measures which might not always be reliable and often ignores some symptoms.

Parkinson's Disease

Parkinson's disease is a motor-dominated neurodegenerative condition. It is characterised by early symptoms such as tremor, stiffness and mask-like facial expression (hypomimia). Early signs of the disease frequently manifest in facial changes and can be used to identify the disease early (Moshkova et al., 2026).

Alzheimer's Disease

Alzheimer's disease is a neurodegenerative condition that causes deterioration in memory, cognitive function, and reasoning skills. In general, it affects the elderly and impairs their daily functioning. In its early stages, it becomes difficult to characterise this disease due to the gradual onset of symptoms with the confusion of normal ageing (Eryılmaz Baran & Cetin, 2025).

Schizophreni

Schizophrenia is a serious mental illness. A person suffering from this often hallucinates, disorganized thinking and speech, and diminished assertiveness. A person suffering from this condition does find it hard to think properly and function normally. Schizophrenia can also lead to social withdrawal and anhedonia. Anhedonia refers to the inability to enjoy pleasure. So, we see that schizophrenia is a serious illness that does affect almost all aspects of a person's life.

Schizophrenia is not a personality disorder. It is different from the same and does not affect a person's character but rather the ability to think clearly and communicate. Schizophrenia is also a disorder that does not have a single cause. It is a combination of traumatic experiences, genetic factors, brain biochemistry, and environment.

A major misconception about the disease is that people suffering from it are violent. This is not the case. It is true that many people find it worrying to have a person suffering from schizophrenia around but most people with the disease do not pose any violence. But the stigma around violence continues. This stigma prevents many people from seeking help.

There are different types of schizophrenia. The first one is paranoid schizophrenia. This type is common and the person suffering from it has Schizophrenia is a severe mental disorder that can cause hallucinations, delusions and disorganized

thinking and behavior. It also involves negative symptoms of emotional flattening and lack of social engagement. It is difficult to diagnose (Eryılmaz Baran & Cetin, 2025) and induces severe effects on perception and behaviour.

Autism spectrum disorder (ASD)

Autism spectrum disorder is a neurological disorder that affects communication, social skills, and behaviour. Individuals with ASD may display repetitive behavior, challenges with social communication and interaction, and atypical responses to sensory inputs. According to Al-Shqeerat et al. (2026), identifying it early will allow for early intervention and better outcomes.

2.2 Signs and symptoms of early dementia.

The early signs of neurological and mental illnesses may differ from one individual to another and from one condition to another but often involve subtle changes. Often it appears to affect mood, speech, facial expressivity, memory and social interactions. As an example (Sharma et al., 2025) speech norms and behaviour cues have been found to be early predictors of mental health diseases. Similarly, decreased facial expressiveness is an early symptom of Parkinson's disease (Moshkova et al, 2026).

2.3 Diagnostic Challenges

Even after progress in medical research, it is challenging to diagnose brain and mind disorders. Normal diagnostics are subjective based on interviews, questionnaires, and observation. These methods might present some inconsistency, and they may also miss out on the early signs of disorder (Ren et al, 2025). Furthermore, the complexity and variability of these disorders and overlapping symptoms complicate diagnosis (Sharma et al., 2025). More critically, there has been a lack of availability of large and consistent datasets for developing diagnostic models. Due to privacy and

consent-related issues, the data usage gets restricted. Furthermore, several diagnostics systems are not clinically validated and are not transferable to various populaces, thus they present challenges in implementations (Al-Shqeerat et al., 2026).

2.4 Review of Existing Studies

Thanks to the continuous development of artificial intelligence and deep learning methods, there have been considerable improvements in the early diagnosis of brain and mind diseases. The studies in recent years (2020-2026) have investigated different unimodal and multimodal approaches based on voice, face, behaviour, and physiology. This section discusses some major research papers, highlighting their approaches, data, and results. Sharma et al. (2025) proposed a machine learning technique for detecting mental health problems using voice and behavior at an early stage. They used feature extraction methods from speech and behavior that classified it using machine learning models. According to researchers, the use of multimodal has a higher performance rate than unimodal approaches and high-level accuracy. Al-Shqeerat et al. (2026) introduced a multimodal deep learning method that integrates speech and behavioral data. Their approach incorporates Conv-BiLSTM, transformer embeddings, and a novel classification model called BioNeuroFusionNet. They tested their system on multimodal data and reported very high accuracy (98-99% on several performance measures). According to the findings of this study, multimodal fusion using deep learning has the potential to detect developmental and psychological disorders. The paper by Moshkova et al. (2026) proposes a video-based system in the domain of facial analysis for detecting Parkinson disease. Using the geometric features of facial landmarks, a support vector machine (SVM) model is used. Through a dataset of patients and controls, the system achieved balanced accuracy of 76% that

suggests facial biomarkers can be used for early detection. Eryılmaz Baran and Cetin (2025) review the diagnosis of mental disorders with AI, especially the multimodal approach. The study concluded that integrating voice, expressions and behavior improves system performance. The researchers noted how essential deep learning methods are for spotting complex patterns within and between different data sources. In short, the studies we reviewed suggest that multimodal systems consistently improve over traditional and unimodal systems by drawing on the information available from multiple data sources. Although unimodal approaches (such as facial recognition or voice recognition) can yield important conclusions, combining unimodal approaches results in better accuracy, robustness, and generalisation.

2.5 Methods and Performance

This table presents selected studies in terms of their methods, data and results:

Study (Year)	Approach	Data / Modalities	Techniques	Performance
Sharma et al. (2025)	Machine learning	Speech + Behavioral data	Feature extraction, ML classifiers	High accuracy (better than unimodal)
Al-Shqeerat et al. (2026)	Multimodal DL system	Voice + Behavioural data	Conv-BiLSTM, Transformer, BioNeuroFusionNet	~98-99% accuracy
Moshkova et al. (2026)	Facial recognition system	Video-based facial data	Landmark extraction, SVM	~76% balanced accuracy
Eryılmaz Baran & Cetin (2025)	AI review	Multimodal data	ML & DL approaches	Increased robustness & accuracy

2.6 Comparative Analysis of Methods and Performance

The following table summarizes key studies based on their methods, datasets, and performance:

Author (Year)	Methodology	Dataset / Modalities	Techniques Used	Accuracy / Performance
Sharma et al. (2025)	ML-based detection	Voice + Behavioral data	Feature extraction, ML classifiers	High accuracy (improved over unimodal)
Al-Shqeerat et al. (2026)	Multimodal DL framework	Speech + Behavioral data	Conv-BiLSTM, Transformer, BioNeuroFusionNet	~98–99% accuracy
Moshkova et al. (2026)	Facial analysis system	Video-based facial data	Landmark detection, SVM	~76% balanced accuracy
Eryilmaz Baran & Cetin (2025)	AI-based review	Multi modal data	ML & DL approaches	Improved robustness & accuracy

The results show that compared to unimodal models, multimodal deep learning models are much better. Models that incorporate both voice and behavioral data are the most accurate, usually reaching about 99%, as they capture additional features.

Yet, many of the studies are done on relatively small datasets and/or controlled settings, which may limit generalizability. Comparing results directly is also made difficult by differences in metrics. Regardless of the constraints indicated, the supporting trend is coherent with a recommendation of multimodal AI systems to facilitate early detection.

3. Multimodal Data Sources for Detection

The recent trend of multi-modal data analysis can be employed for the early detection of neurological and mental disorders using heterogeneous data. Multimodal systems utilize several complementary kinds of information such as voice, facial expression, behavior, and physiology.

Unlike any traditional system which depends only on one type of information, the multimodal system overcomes various limitations and results in a more accurate and robust diagnosis (Sharma et al., 2025). These numerous data sources provide understanding related to various aspects of human behaviour and neurological functions based on underlying disorder.

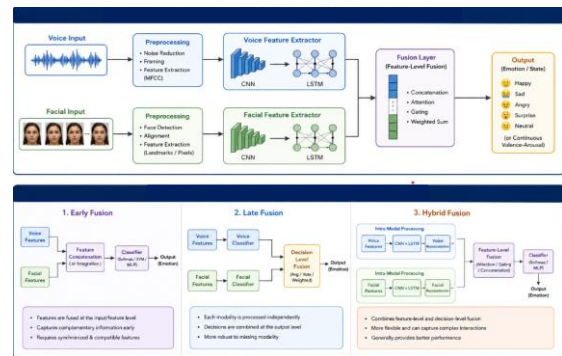


Figure 2. System Architecture & Multimodal Function Types

3.1 Analyzing the Voice

Many mental health disorders can be diagnosed from human voices through their speech patterns that can infer various emotional and cognitive states, including anxiety and depression. Atypical features of speech such as pitch, tone, rhythm, jitter, shimmer, and Mel-Frequency Cepstral Coefficients (MFCCs) are used to detect abnormalities associated with depression, anxiety, etc. (Sharma et al., 2025). With the help of these characteristics, machine learning models can pick up subtle variations in speech that are hard to perceive clinically. Speech analysis is a preferred feature extraction method because it is non-invasive, cost-effective, and can be easily recorded with common mobile devices. Additionally, the existing speech-based systems enable constant surveillance and real-time assessment of patients, making it possible for early intervention (Al-Shqeerat et al., 2026).

3.2 Facial Analysis

Facial expression analysis has important applications in the study of human emotional states and neurological disorders. Facial expressivity is

typically detected through facial landmarking, action unit recognition and geometric feature analysis. Reduced facial expressivity (hypomimia) is an early sign of Parkinson’s disease that can be automatically detected with facial movement (Moshkova et al., 2026). Facial analysis systems apply computer vision and deep learning to detect micro-expressions and facial movement dynamics. Being objective and reliable, they generate analyses that differ from subjective manual annotations.

3.3 Alternative Modalities.

Apart from these, things like EEG, behavioral cues and text also contribute significantly in the multimodal detection systems. Analysis of EEG data enables researchers to examine the biological causes of brain disorders and helps in distinguishing schizophrenia from depression. The data on human behavior like activity, sleep, and socialization offers context for mental health (Sharma et al., 2025). Moreover, you can use methods of natural language processing (NLP) on textual data available on social media or clinical interviews or psychotherapy sessions to infer your emotional states and detect mental disorders. This multimodal approach enables the system to have a deeper appreciation of the intricate and multi-dimensional nature of mental health problems (Eryilmaz Baran and Cetin, 2025).

3.4 The Significance of Multimodal Approaches.

Multimodal integration aids in improved diagnosis accuracy & effectiveness. Multimodal systems utilize information from multiple modalities to disambiguate and enhance predictions. According to research, multimodal systems that combine voice, behavioural, and physiological data outperform uni-modal systems (Sharma et al., 2025). Moreover, multimodal systems may also lead to adaptive and personalised healthcare solutions that take into account the patient’s global health. This overall view

allows for early recognised, monitoring and intervention for better outcomes and quality of life. AI-based early detection systems of neurological and psychiatric diseases require deep learning (DL) methods for the processing of multimodal data. Unlike traditional machine learning methods, deep learning models can extract features automatically from data of high dimensionality. This enables them to effectively process multiple types of data such as voice, face and behaviour (Sharma et al., 2025).

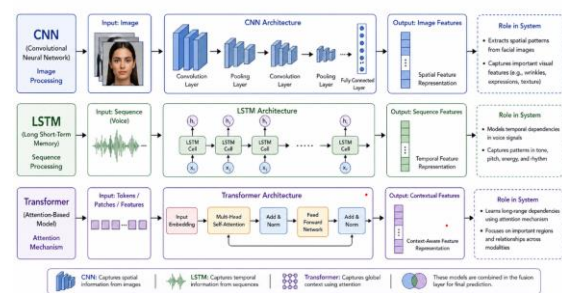


Figure 3. Deep Learning Models Flow

4. 4.1 CNNs or Convolutional Neural Networks.

CNNs are generally applied to image and video and thus suits facial data to detect neurological disorder. By learning spatial features like edges, textures and facial patterns, CNNs detect subtle changes in people’s faces. To detect the disease, CNN-based and landmark-based approaches are used for facial-based detection of Parkinson’s. They are applied to facial movement. The aim is to identify low expressivity (Moshkova et al., 2026). CNNs have been shown to be efficient in extracting visual features and are often utilized in multimodal approaches.

4.2 Recurrent Neural Networks and Long Short-Term Memory - RNNs and LSTMs

Recurrent neural networks (RNNs) and Long-short term memory (LSTM) networks deal with time series data. The use of these models is common for the processing of speech signals and behavioural patterns. LSTM architecture can be used to extract important features from speech like

pitch, tone, rhythm, etc. This shows that LSTMs can learn long-range dependency. This is important for identifying mental health from speech. According to Sharma et al. (2025), RNNs and LSTMs are regularly used alongside CNNs in multimodal systems to facilitate sequential data processing.

4.3 Transformer-Based Models

Transformers are now a popular way to model long-range dependencies and multimodal data. Transformers use attention mechanisms that highlight relevant features from the input and help in feature extraction. In applications with multiple modes, transformer embeddings are used to extract relevant features from speech data and nonverbal multimodal data so that classification is better and more robust. Studies have shown that the accuracy of any other deep learning model is enhanced significantly when used in conjunction with transformer-based models (Al-Shqeerat et al.2026)

4.4 Hybrid Models

Hybrid approaches of deep learning combine the strengths of CNN, RNN and transformer models, which have complementary strengths. Hybrid models combine different methodologies and provide solutions for multimodal problems involving different types of data. A CNN may be used for facial feature extraction, an LSTM for acoustic feature extraction, and a transformer for feature interaction. Recent models such as BioNeuroFusionNet have been used to achieve high classification accuracy for developmental and mental disorders (Al-Shqeerat et al., 2026).

4.5 It is important for multimodal analysis to understand deep learning.

Deep learning models have proven to be much superior as compared to traditional machine learning approaches in capturing complex non-linear interactions amongst modalities as also within them. They automatically learn features from data eliminating the need for feature engineering and

improving scalability. Deep learning models can be used in multimodal healthcare applications to combine multiple sources of data for beneficial diagnostic and early detection. Recent studies reveal that deep learning-based multimodal systems are more effective and robust than traditional systems (Sharma et al 2025).

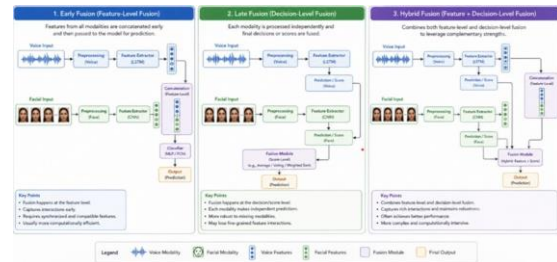


Figure 4. Multimodal Fusion Strategies

5. Multimodal Fusion Strategies

Multimodal fusion is a vital and crucial component of AI systems related to the early diagnosis of neurological and mental disorders, as it allows for different types of data (voice, facial expressions, body movements, physiological data) combination. Multimodal fusion improves the robustness, dependability, and precision of diagnostic systems by bringing together complementary information from various modalities (Sharma et al., 2025). Systems can learn complex patterns that are hidden to individual-modality data through suitable fusion techniques.

5.1 Early Fusion (Feature-Level Fusion)

Early fusion (feature-level fusion) fuses the features extracted from different modalities into a single feature vector to train any machine learning or deep learning model. The model can quickly learn multimodal connections, resulting in higher levels of interaction among the modalities. An example shows combining audio features (pitch, MFCCs) and facial features (facial landmarks) into a single feature vector that captures the state of the patient. Studies have shown that multimodal feature fusion at the input layers assist the model in better capturing the connection between the psychological signals

and physiological signals (Eryılmaz Baran & Cetin, 2025). Nonetheless, challenges arise with early fusion owing to the high dimensionality and heterogeneity of the data, along with the need to synchronize the data.

5.2 Late Fusion (Decision-Level Fusion)

In late fusion (also called decision-level fusion) the decisions or predictions of multiple independent models trained on different modalities are aggregated. Each modality is processed independently. The final answer is obtained by combining the individual answers, such as majority voting, weighted average, ensemble learning and so on. This approach is flexible as many models can be customized to process various modalities. To clarify, you can use speech models to get the voice data while you could use computer vision models to get the facial data. Afterwards, all outputs are integrated together to generate a prediction. According to Sharma et al. (2025), the application of the approach is demonstrated in the use of weighted voting methods to combine predictions of different behavioral data and voice data models for high classification accuracy. A late fusion approach is helpful when data format or sampling rate differ across modalities.

5.3 Hybrid Fusion

Combining feature-level and decision-level fusion allows hybrid fusion to take advantage of both methods. In this setting, we can have decision-level combinations of some streams while feature-level combinations of others. Through this type of multi-layer fusion, the system design is scalable. Techniques which hybridise various techniques have been shown to enhance the models' generalisation and robustness, particularly when it comes to clinical settings.

5.4 Significance of Multimodal Fusion

Next-generation multimodal systems are using hybrid fusion methods to achieve better

performance by combining low-level features and high-level decision patterns. Multimodal fusion is important to improve the effectiveness. Current AI-based systems use similar speech and behavioural features as AI-based diagnostic systems. Multimodal fusion techniques allow the integration of different modalities such as speech and facial expression to provide more information about a patient. This improves the detection performance, reduces false alarms, and makes the systems more robust. Furthermore, with the help of multimodal fusion, models can also adapt for diversity in various data sources across individuals, enabling personalised medicine. According to recent research, the detection of neurological and mental disorders will be better accomplished using multimodal data fusion instead of single-modality-based data (Sharma et al., 2025). The design of fusion methods, therefore, is essential to create robust and translatable AI systems.

6. Challenges, Future Perspectives and Conclusion

6.1 Challenges

Despite significant advancements in multimodal artificial intelligence systems for the early diagnosis of neurological and psychiatric disorders, many challenges limit their use in clinical practice. The accessibility and quality of data pose a significant obstacle. Multimodal systems require extensive and well-annotated collections of synchronised audio-visual-behavioural-physiological data. Nevertheless, acquiring these datasets can be challenging due to privacy and ethical considerations, as well as data collection issues (Al-Shqeerat et al., 2026). Another problem is the data variability and variety. The various formats, sample rates, and noise levels associated with different sources make them difficult to blend. Moreover, enhanced lighting, recording gear, and other environmental factors can alter the quality of

facial and voice data, resulting in dampened performance. It is equally essential to interpret the model. Deep learning algorithms are often referred to as black boxes because the clinicians cannot understand how they arrive at decisions. The trust and acceptance of AI in healthcare may be impacted resulting from this. Moreover, runoff datasets can raise fairness and bias issues, which could cause the risk of misprediction on subpopulations (Sharma et al., 2025). The standardization and clinical validation is also an important issue. The models are generally tested on small datasets and idealized settings that may not reflect clinical practice. It is difficult to evaluate and compare models owing to absence of standardized evaluation protocols and benchmarks.

6.2 Future Directions

Efforts should, therefore, address the foregoing challenges to improve reliability and effectiveness of multimodal AI systems. One possibility for future research is the creation of large multimodal datasets with diverse populations and use cases. The creation of partnerships between researchers and health care and policymakers can enable safe data sharing. Another future direction is developing approaches to Explainable Artificial Intelligence (XAI). Explainable AI has the potential to provide intelligible and transparent decision-making, which can enhance clinicians' trust and ultimately foster the adoption of AI models into clinical practice. The advancement of technologies such as edge and real-time computing can enable the deployment of AI models on mobile and wearable devices. This can help in continuous observation and predictions of disorders in the real world, facilitating health care especially in remote and resource-limited settings (Al-Shqeerat et al., 2026).

Additionally, upcoming systems need to devise methods that personalize the models to the patient. Personalized AI learning algorithms along

with data specific to a patient might refine diagnosis and treatment. Ultimately, it is important to investigate new classes of deep learning models, such as the use of transformer-based models and multimodal attention, to better combine diverse data sources. This may lead to an improvement in accuracy for multimodal systems. The review suggests that multimodal techniques enhance performances by integrating information from multiple types of data and sources. The overall performance and reliability of any system can be improved by using image preprocessing, feature extraction and multimodal fusion techniques. The discovery of subtle features associated with disease in early stages, through deep learning models, has resulted in a better diagnosis.

The analysis shows that multimodal approaches are more effective than traditional or single-modality systems by exploiting complimentary information. The way of preprocessing the image, extracting the features, and fusing the modalities help in system performance improvement and increasing reliability. Moreover, the use of deep learning models has led to the recognition of rare patterns linked to early-stage disease, resulting in more accurate diagnosis.

Despite this, the successful application of these systems requires overcoming issues including data availability, model interpretability, and clinical validation challenges. Further research in explainable AI, real-time monitoring and personalized healthcare will be important for future developments.

Overall, multimodal systems: the future of early diagnosis of neurological and mental disorders powered by Artificial Intelligence (AI) can improve patient outcomes and reduce global burden.

7. Challenges and Limitations

While there have been significant advancements in AI-driven multimodal systems for

early diagnosis of mental and neurological disorders, there are several challenges and limitations that prevent their effective use in clinical practice. These include technical, ethical, and clinical considerations and need to be overcome to guarantee the performance and ethically sound use of these systems.

7.1 Privacy and Ethical Issues

A fundamental challenge is data privacy and security. Multimodal systems use personal data, such as audio recordings, facial images and user behaviour, and present ethical and legal issues. Breaches of such data can lead to privacy violations. Moreover, consent and regulatory compliance with privacy laws are challenges in large-scale data collection (Al-Shqeerat et al., 2026).

7.2 Insufficient Diverse and Large Datasets

The training and evaluation of deep learning algorithms require large high-accuracy datasets that are diverse. However, such data are limited in the field of neurological and mental health due to privacy-related problems and the difficulties of collecting multimodal data. According to Sharma and colleagues, this could lead to overfitting and restrict the model from transferring to other populations and settings.

7.3 Model Bias and Fairness Issues

When data cannot cover sufficient population data, model bias occurs. One more crucial problem of machine learning. Datasets can be less than perfectly representative, meaning that performance may vary by age, gender or ethnic group which could result in an inaccurate or unfair diagnosis. We must ensure that AI systems designed for safe use in the medical domain are fair and inclusive (Sharma et al., 2025).

7.4 Lack of Clinical Validation

Two important elements are evidence from clinical practice and implementation of AI-based models and systems. Due to the absence of clinical

trials on a large scale and consensus protocols, assessing the efficacy and accuracy of these systems becomes challenging. Accordingly, due to a lack of evidence many healthcare professionals may not fully use AI-based diagnostic systems (Eryılmaz Baran & Cetin, 2025).

7.5 Lack of Interpretability

Deep learning models are sometimes called “black-box” models due to their complex and often unintelligible algorithms. Interpreting this can be difficult for clinicians and leads to low confidence in AI systems. The importance of explainable artificial intelligence (XAI) has gained recognition in recent years. Interpretable models can certainly provide information related to decision-making and assist clinical decision-making (Al-Shqeerat et al., 2026). In sum, ethical issues, data availability, modeling bias, clinical validation and explainability affect the deployment of AI-based multimodal systems in the real world. To cultivate trustworthy, impartial, and clinically useful solutions for the prompt diagnosis of neurological and mental disorders, it is important to overcome these challenges.

8. Conclusion

This review paper provided a detailed overview of artificial intelligence (AI) approaches to early diagnosis of neurological and mental disorders based on multimodal deep learning. The research examined several aspects, including an overview of various major disorders, including depression, Parkinson’s disease, Alzheimer’s disease, schizophrenia, and autism spectrum disorder, the symptoms, early signs, and the challenges in their diagnosis. The paper discusses multimodal data like voice, facial expressions, behavior, and physiological data to provide a rich source of information about human cognition and behaviour. Analysis of speech features (pitch, Mel-frequency cepstral coefficient) and facial landmark detection were helpful in the detection of early signs of

disorder. Furthermore, Sharma et al. (2025) revealed that a multi-modal integration (MMI) can enhance detection performance and improve system reliability. The multimodal analysis technology includes enabling technologies deep learning models such as convolutional neural networks (CNNs), recurrent neural networks (RNNs), long short-term memory (LSTM) networks, transformers are being used extensively. These are considered more effective in modelling complex and non-linear relationships in high dimensional data. The performance of the system, especially the health industry, is improved by using hybrid models (Al-Shqeerat et al., 2026). The study reviewed prior studies and demonstrated that multimodal systems outperform typical systems. In certain methods, the accuracy reaches as high as 99%. The paper also highlighted importance of preprocessing methods, multimodal fusion approaches, and performance metrics in the reliable and efficient diagnostic systems. Nonetheless, still, there are various challenges that still need to be addressed like privacy, a lack of large-scale and diverse datasets, model bias, lack of clinical validation and interpretability. These challenges highlight the importance of ethical, explainable, and clinically validated AI systems to ensure their clinical applicability (Eryilmaz Baran & Cetin, 2025). The next steps entail the establishment of multimodal datasets, the formulation of modules for explaining AI systems, the use of mobile and wearable devices to monitor patients in real-time and the development of personalized health care systems. To integrate AI systems in clinical settings, it is essential to overcome these challenges. All in all, systems that make use of AI-based multimodal deep learning can completely transform the early detection of brain disorders as well as mind disorders. Timely and accurate diagnostic tests for these disorders that are scalable can help enhance patient care, reduce

health-care burdens, and build smart and accessible health-care systems.

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Interdisciplinary Pedagogies for Sustainable Education in Bangladeshi

Universities: Bridging Theory and Practice

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Accepted: 10.04.2026 Published: 30.04.2026 Page No. 134 – 146 DOI: 10.5281/zenodo.20021109

Abstract

The growing intricacy of global sustainability issues like climate change, environmental degradation, and socio-economic inequality calls for a shift in higher education from traditional disciplinary silos to interdisciplinary rather than merely multidisciplinary. This study investigates the contributions of interdisciplinary pedagogies to the promotion of Education for Sustainable Development (ESD) in Bangladeshi universities. Based on systems thinking, transformative learning theory, and sustainability competency frameworks, integrated teaching fosters holistic problem-solving skills among students. According to the research, effective pedagogical approaches to integrate environmental, social, and economic dimensions of sustainability include problem-based learning, experiential learning, place-based education, and team-teaching. Implementing active learning faces lots of obstacles. In many developing countries, this is due to institutional restrictions, like stiff departmental boundaries. Further obstacles include inadequate faculty training and limited incentives, as well as assessment systems that emphasize knowledge in a discipline. The framework also outlines recommendations for curriculum revision, faculty development, and policy support that institutions may employ to enhance the sustainability of universities. Accordingly, it is concluded that graduates should address

sustainability challenges and assist in the fulfilment of national and global development goals.

Keywords:

Interdisciplinary Pedagogy, Education for Sustainable Development, Systems Thinking, Transformative Learning, Sustainability Competencies, Higher Education, Bangladesh

1. Introduction

The early 21st century is defined by complex, interconnected global challenges that fundamentally threaten human well-being and planetary stability. Issues such as climate change, biodiversity loss, pervasive inequality, and resource scarcity demonstrate that traditional, siloed disciplinary approaches are insufficient for generating effective solutions. Addressing these challenges requires a paradigm shift in how knowledge is produced, disseminated, and applied—particularly within Higher Education Institutions (HEIs).

Recognizing this imperative, organizations like the United Nations Educational, Scientific and Cultural Organization (UNESCO) have strongly advocated for Education for Sustainable Development (ESD) [Leicht et al., 2018]. ESD aims to Teach students the knowledge, skills, values, and attitudes to address the environmental, social, and economic interconnections of sustainability. Higher education institutions are required to go beyond technical training by fostering critical thinking,

systems thinking and a commitment to action [Tejedor et al., 2022].

Considering the cognizance of Bangladesh to the climate impacts and rapid socio-economic change, the need for strong sustainable education is dire. Bangladeshi institutions should develop not only professionals but also citizens equipped to handle global sustainability crises and their local impacts. Therefore, they must prioritize institutionalization of sustainability principles at the university level [Shamsuddoha et al., 2012; Naomee, 2024].

Despite the global ESD call and the national criticality, many universities, including in Bangladesh, continue to teach sustainability subjects in a siloed disciplined fashion [Sánchez-Carracedo et al., 2021; Shamsuddoha et al., 2012]. This means issues related to the environment are only related to the department of environmental science. Issues in society are only related to sociology. Economic issues are only related to economics and so on. Such divide does not reflect the interdisciplinary nature of sustainability challenges. We see students often struggle to synthesize fields of knowledge and come up with holistic solutions.

Interdisciplinary Pedagogies are pedagogies which intentionally combine content and methods from two or more academic disciplines to tackle a common complex problem. As per Wals (2013) and Dlouhá et al. (2017), pedagogies such as problem-based learning (PBL), collaborative research projects and transdisciplinary engagement are theoretically well-suited for enabling systems-thinking and collaborative competencies that sustainability requires.

Nevertheless, while mainstream discourse recognizes the significance of interdisciplinary pedagogies, their frequent, consistent, and effective usage within the existing structures of Bangladeshi universities remains a gap. Barriers encompass the

strict structures of various disciplines, insufficient training in interdisciplinary teaching for the faculty and assessment system that favour depth in their discipline rather than breadth [Rasli et al., 2024; Uddin, 2023].

Importance.

This article is important for different players of higher education in Bangladesh and possibly in other developing countries having the same problems. Its value lies in providing action-oriented insights to address the long-standing discrepancy between the commitment to Education for Sustainable Development (ESD) and its practical, effective realization through interdisciplinary pedagogies [Naomee, 2024].

Education and Faculty.

In order to facilitate quality teaching, the study will provide faculty with reusable models (e.g., problem-based learning, transdisciplinarity, field-based, etc.) that effectively incorporate sustainability. It allows them to go from conceptual knowledge to practical use in classrooms.

The new curriculum will give insight into how teaching roles need to change wherein the teacher moves towards being less the expert on content and more the facilitator for complex and interconnected learning. This will build the teacher's capacity for inter-disciplinary teaching [Wals, 2013].

For those involved in curriculum design and planning.

We will explore how the findings will help in restructuring current curricula to add modules, courses, and programs on different interdisciplinary subjects on sustainability challenges on Bangladesh (like the climate resilient, disaster management, renewable energy use etc).

The aim of the article is to provide designers with an understanding of how to select and justify approaches in their design based on the

resources available in their institution, as well as on the pedagogical implementations and national goals [Naomee, 2024]. The article will engage with some current literature and the constraints of a local context. Mapping their design to any contemporary theory of learning will give designers options for realising their design.

For Organizational Heads and Lawmakers.

The findings of the study will be an evidence base for the senior management of universities and HEI policymakers to understand what institutional and administrative reforms will be needed to advance interdisciplinary teaching. This may include changing faculty promotion criteria, creating inter-departmental collaboration mechanisms and allocating resources [UGC,2020].

By encouraging effective sustainable education, the paper is expected to help Bangladesh universities enhance their relevance status with the national development priorities, and global commitments, like the SDGs, which is expected to help the universities improve their national and international rankings. (UGC, 2020; Rasli et al., 2024).

The sustainable development agenda

The article contributes to producing a new generation of graduates who, through interdisciplinary methods, will develop systems thinking and collaborative skills thereby helping them to not only understand sustainability issues but also design and implement holistic solutions in their future professional life. This will help improve Bangladesh's climate-resilient and sustainable path [Dlouhá et al., 2017].

Theoretical Foundations: Interdisciplinary Pedagogies and Sustainable Education

The article is based on three relevant theories including Systems Thinking, Transformative learning theory, and sustainability competency framework tools to analyse

interdisciplinary pedagogies for sustainable development education in the universities of Bangladesh.

1. What Is It and Scope

Interdisciplinarity

Interdisciplinarity is the academic mode of research, teaching, or practice that intentionally brings together, across disciplines, information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines to bear on a common problem [Klein. 1990].¹ In higher education. Interdisciplinary Pedagogy is understood as teaching and learning strategies that require students to connect, synthesize, and apply knowledge from different fields for a common goal; a major aim is to move beyond simple juxtaposition (multidisciplinary) towards genuine integration of disciplines [Pohl & Hadorn, 2008].²

Education Attainable/ Education for Sustainable Development (ESD).

Sustainability Education (SE; better known as Education for Sustainable Development (ESD) from UNESCO) is a process with a goal. It enables the learner to develop knowledge, skills, values, and attitudes to contribute to a sustainable future.³ It is not a subject, but rather a principle that is integrated into the curriculum of subjects. This on the interconnected environmental, social, and economic aspects of sustainability [UNESCO, 2017].

2. Theoretical Frameworks Relevant.

A. Systems Thinking/Complexity Theory.

Sustainability challenges are complex and systemic in nature.⁴ That is, they are not caused by one factor, but rather arise from non-linear interactions in human-environment systems [Meadows, 2008].

Systems thinking is essential because it helps to understand the relationship between various components rather than a component in isolation. For example, a change in the economic domain

affects the environment and society as well and, thus, we need the systems thinking framework to make sense of this. Interdisciplinary pedagogy plays a crucial role, as it necessitates that students examine challenges according to feedback loops, leverage points, and boundary-spanning concepts that are essential in systems thinking.



B. Theory of Transformative Learning

The Transformative Learning Theory (TLT) was developed by Jack Mezirow. TLT refers to the process of becoming aware of and critically assessing one's basic assumptions, beliefs, and expectations (frames of reference or meaning perspectives), resulting in a more inclusive, differentiating, and permeable perspective [Mezirow, 1997].

When it comes to sustainability, it is important to recognize that tackling the world's big issues requires more than just information. It requires change – in the way we view the world (e.g., move consumerist to conservationist worldview), and our values and behaviour. Determining what is relevant for sustainability is crucial in this process. Interdisciplinary methods of teaching and learning enable this shift by presenting students with radically contrasting disciplinary perspectives (e.g., a humanist critique of a solution that is purely technological). This in turn provokes discourse and

critical reflection which is essential in transformative learning [Sterling, 2011].

C. Competency Frameworks of Sustainability.

Present-day education for sustainable development (ESD) frameworks articulate learning outcomes in terms of sustainability competencies an integrated package of knowledge, skills, and attitudes necessary for addressing sustainability problems [Wiek et al, 2011]. These usually comprise analyzing complex systems in a versatile manner. A competency that foresees future scenarios, skill in assessing trade-offs, and ethics. Capacity to intervene in an organized way: Working With Other Team Members

Relevance means that all the competencies work with one another. For instance, the strategic competency of designing an intervention requires one to integrate economic-, engineering- and social perspective which can only be effectively nurtured through collaborative, interdisciplinary project work [Wiek et al., 2011].

3. Connection between interdisciplinarity and education for sustainability.

Sustainability problems consists of various disciplines: knowledge and belief. No one discipline will explain or resolve the combined crisis of poverty, pollution, and climate vulnerability.

To engage in successful SE teachers' pedagogy should facilitate movement beyond disciplinary boundaries.¹⁰ Interdisciplinary pedagogy provides the tools and frameworks (e.g., team teaching, integrated curricula) to move students beyond discipline silos, allowing them to.

Combine different kinds of knowing.

Delve into the demarcation of ideas and social use (transdisciplinary).

Develop comprehensive problem-solving skills for handling complexity and implementing change.

4. Model the idea

This study will take an Analytical Lens focused on the Theory Practice and Enablers/Barriers to structure the content analysis.

Conceptual Model: Interdisciplinary Pedagogy for Sustainable Education

Component	Description
Input (Theory)	Interdisciplinary Pedagogies (e.g., PBL, Fieldwork, Collaborative Research)
Process (Practice)	Implementation in Bangladeshi HEIs: <ul style="list-style-type: none"> Enablers: Institutional support, Faculty training, Curriculum flexibility. Barriers: Departmental silos, Assessment rigidity, Resource constraints.
Output (Outcomes)	Achievement of Sustainability Competencies: <ul style="list-style-type: none"> Systems Thinking Transformative Learning Strategic Action

This framework enables a structured assessment commencing with the rationale for an interdisciplinary approach, followed by an exploration of real-world obstacles in Bangladeshi universities, and concluding with an evaluation of its success in producing graduates who are capable of aiding national sustainable development goals.

Main Learning Strategies in Transdisciplinary Sustainability Education.

Effective implementation of Sustainable Education (SE) and Education for Sustainable Development (ESD) necessitates a shift away from traditional, lecture-based delivery to certain pedagogical approaches that are inter-disciplinary and learner-centered. These methods are imperative to developing necessary graduates' complex sustainability competences in Bangladeshi universities.

1. Engaged and Cohesive Learning Strategies

Strategies of this nature encourage students to work on difficult issues from the real world.

Problem-Based Learning (PBL) and Project Based Learning (PjBL): These are the core interdisciplinary strategies in which students collaborate to research and propose solutions to ill-defined complex sustainability challenges (e.g., urban water management; coastal erosion). In the context of interdisciplinary activity, a PBL (project-based learning) course could require students from the field of Engineering, Economics and Sociology to work together on a project to design a resilient low-cost housing system, which is technically feasible, financially viable, and socially acceptable. This is an approach used widely at Aalborg University [Aalborg University Journals].

Experiential and place-based learning: Learning occurs within the local context of sustainability in Bangladesh.

Place-Based Learning utilizes local environment, society, and culture, e.g., the flood plain of Bagura as a teaching resource.

Community-engaged learning encompasses students collaborating on real-world projects with local non-governmental organizations (NGOs), government departments or community groups; for example, the design of localized early warning systems or the assessment of microfinance strategies for climate-resilient development. It establishes a direct connection between the theory and its application in addition to the ethics behind it.

2. Merger of Institute and Curriculum

Thoughtful structural supports need to be put in place to break down silos.

Collaboration between professors from varying disciplines (e. g., Anthropology, Environmental Science) to develop and teach alike. Students are exposed to multiple disciplinary perspectives simultaneously to model the kinds of intellectual collaboration needed to get this done. The integration of curriculum, in which courses or modules are designed together to focus on a

common complex theme and not mere cross-listings of existing departmental courses, is required.

Making Sustainability Competencies a Building Block: Sustainability is not to be treated as an “add-on” course but as a cross-cutting theme in the existing core and elective subjects in the curriculum [Wiek et al., 2011]. To illustrate, a course in engineering design could include the normative competency (ethical assessment) while a course in economic policy could include systems thinking [Frontiers].

5. Methods and Evaluation for Change.

The methods of delivery and the evaluation of deep learning and perspective shifts are the focus of these strategies.

Utilization of Digital/Hybrid Modes: It enhances flexibility and collaboration in the post-COVID setting. Using digital tools, students can model complex environmental systems, take virtual field trips to far-off ecosystems or work on team projects with students at other universities. Hybrid models allow for the combination of online delivery of content with community delivery and engagement (SpringerOpen).

Assessment and Reflection: Testing facts isn't enough— assessments need to allow critical, interdisciplinary thinking. This assesses students' capacity to connect concepts from different fields, justify ethical choices, and reflect on their learning journey.

The main assessment methods are Critical reflection journals recording changes in self-agency (whether students believe they can act sustainably) and value orientation (changes in ethical perspective).

Integrated solutions within scenario analysis exercises.

To this end, Bangladeshi universities must produce graduates who possess some understanding

and versatility in knowledge and skills for a sustainable future.

Implementation in Higher Education Contexts: From Theory to Practice

To turn the theoretical promise of interdisciplinary pedagogies into a practical, sustained reality in Bangladeshi universities, significant structural, cultural, and pedagogical shifts will be necessary. The world experience provides critical lessons on the institutional enablers and barriers determining the success of interdisciplinary sustainability education.

1. Elements and Conditions of the Organization.

Interdisciplinary sustainability education will not be successful unless there is a strategic, top-down support which allows collaboration outside of traditional fields.

Sustainability leadership should come from high-level university leadership and not just be something added on, but rather a core one. This involves incorporating it into the strategic planning and encumbering resources. Movements for systemic change that work as a resoundant of community strength, so a commitment to depth learning is needed by a higher institution to insure the process.

To enable collaboration, universities should have formal, structural mechanisms (like research institutes) capable of reaching decisions (like committees). Foster trust and communication between departments, and UCL Press Journals.

Faculty Development and Incentives: Faculty Will Become Transformation Agents To co-teach effectively, experts in co-teaching must facilitate and design integrated curricula need be trained.

It is important that policies around promotion and tenure are modified to specifically acknowledge and reward teaching in interdisciplinary areas and collaboration research

contributions to counter the likely “transaction costs” for faculty [Rasli et al., 2024; Zhang, 2017].

2. Curriculum Formulation and Program Frameworks

Curriculum designers or developers ought to deliberately engineer interdisciplinarity into the curriculum.

One common successful way is to offer a dedicated interdisciplinary programme (e.g., Master’s in Climate Resilience), or specialized modules (e.g., Sustainable Urban Planning) that is team-taught by faculty from various disciplines (e.g., Engineering, Public Policy, Geography).

To broaden impacts, sustainability concepts should be integrated across existing disciplinary courses (e.g., life cycle assessment in an Engineering course or social equity in a business course). There must be a harmonisation of learning outcomes for specific sustainability competences [Wiek et al.2011].

3. Evidence from the Case: World Wide Studies.

Global higher education institutions have created interdisciplinary sustainability pedagogy successfully providing models that can be transferred.

Students work in groups to solve complex, real-world problems in Aalborg University's Problem-Based Learning (PBL) model. This framework automatically ties in knowledge from different fields (Engineering, Humanities, etc.) to generate solutions in alignment to the SDGs [HEInnovate].

The model of “Living Labs” is adopted by universities in different countries including the UK and USA, where the campus and local community of universities used as a “Living Lab”. As a part of this model, students, faculty, and staff from different disciplines work together to solve on-campus operational sustainability issues, such as, designing waste management system or calculating carbon

footprint etc., through practical implementation of their university learning, thus sustaining campus life without harming the environment.

Source: Emerald Publishing

In US Universities, some institutions like the University of Nebraska-Lincoln deployed systemic curricular reform, designed to move away from the ‘bolt-on’ to ‘built-in’ approach. This was done through whole-programme cross-department programmes to emphasizes systems thinking, and linking humans and ecology explicitly [1].

4. Obstacles Encountered in the Implementation Process

Despite its obvious benefits, interdisciplinary pedagogy is facing fierce resistance that universities in Bangladesh must prevent.

Barrier Category	Specific Challenge	Implication for Bangladesh i HEIs
Structural	Disciplinary Silos: Rigid departmental structures and administrative divisions (funding, scheduling) prevent cross-collaboration [Rebus Press; Taylor & Francis].	Makes cross-listing courses, co-hiring, and shared resource allocation extremely difficult.
Cultural/ Faculty	Faculty Resistance and Attitudinal Barriers: Lack of experience, specialized training, and a perceived devaluation of interdisciplinary work in promotion/tenure [UBC Blogs; Zhang, 2017].	Faculty may prefer to stay in their "safety" of mono-disciplinarity, viewing integrated work as unrewarded extra labour.
Cognitive/ Logistical	Communication and Definitional Ambiguities: Different disciplinary jargon, epistemologies, and values create communication barriers and make reaching consensus	Team-teaching can fail if instructors from different fields cannot agree on core concepts or

Barrier Category	Specific Challenge	Implication for Bangladesh i HEIs
	challenging [UBC Blogs; Design Research Society].	shared learning outcomes.
Resource	Resource Constraints: Lack of dedicated interdisciplinary funding, shared knowledge resources (textbooks, materials), and time for negotiating co-taught courses [Atlantis Press; Rebus Press].	Compounde d by budget realities in many public and private Bangladeshi universities.

6. Factors that facilitate success.

Surmounting these obstacles relies on strategic factors.

Aligning Teaching with Institutional Mission. Making sure interdisciplinary education is explicitly connected to the university’s mission, such as Bangladesh’s climate resilience plans.

Iterative Design refers to implementing interdisciplinary programs gradually, with continuous feedback loops, evaluation, and refinement instead of imposing a huge one-off change.

To ensure high student motivation and engagement key predictors of success [NWCommons] design projects centred around real-world, local sustainability issues.

A thoughtful balance in the creation of Communities of Practice is needed so that a formal, yet flexible CoP can hold space for teachers to exchange and develop ideas in a safe environment for interdisciplinary teaching [Menon & Suresh, 2022].

7. Lessons for Organizations.

Shifting to interdisciplinary sustainability pedagogy requires careful and comprehensive reform.

Change must be authorized from the top down but driven by enthusiastic faculty from the bottom up.

Students who have developed competencies such as systems thinking or collaborating skills should be able to offer and analyze relevant arguments. Besides that, they should find and use information effectively.

Make hires to help link disciplines and cross cultures. These boundary spanners can make a big difference.

Implement the Living Lab model: Use the university and its community as a site for experiential, problem-based, learning to make theory practice-driven.

Debate.

This paper attempts to analyze how interdisciplinary pedagogies are being used for education for sustainable development (ESD) and maps the theoretical foundations identified with documented practices particularly in the Bangladeshi university context. The synthesis of findings, the implications for HEI and ESD, and the limitations and future research of the study are discussed.

1. This synthesizes theory and practice.

Added Value and Alignment.

The practice evidence supports the core theoretical foundations strongly.

Rephrased:

The active learning pedagogies, especially problem-based learning (pbl) and experiential learning, are acknowledged as instrumental in promoting systems thinking (wals, 2013). When students work together from different disciplines to solve a real-world problem (waste management on campus), they inevitably map complex causal

relations and feedback loops, rather than analyse these linearly from their disciplines' perspective (Wiek et al., 2011).

The learning theory that encourages shifts in frames of reference to effect change in worldview is transformative learning theory (TLT). As Mezirow indicates, TLT is best triggered through practical, place-based, and community-engaged learning. In Bangladesh, direct connection with local communities and ecosystems forces students to examine their beliefs and values, which is the basic trigger for perspective transformation. (Sterling, 2011)

Competency Frameworks Integrated Assessment team-teaching and integrated project-based assessment contribute directly to the holistic development of sustainability competencies (Wiek et al., 2011). Evaluating group projects, utilizing critical reflection journals, and analyzing scenarios stimulate strategic competency demonstrates and interpersonal competency. This cannot be demonstrated in a traditional exam.

Theory Versus Practice Gap

Important gaps exist, particularly connecting to the Bangladeshi context.

Theorists' relatedness necessitates structural (UGC, 2020) collaboration to ensure interrelated practice. However, practices are often bounded by structural barriers imposed by their own disciplines (Rasli et al., 2024). It was noted that faculty do not have time or incentives to work across departments on curricular matters. As a result, their efforts tend to be reduced to simply cross-listing courses rather than true integration (Zhang, 2017).

With respect to the need to assess competencies, the continued use of assessments underlying knowledge recall by many HEIs, which favours depth over breadth of disciplinary knowledge, seems to actively subvert the very pedagogy the interdisciplinary courses rest on.

Many teachers are not trained to facilitate interdisciplinary learning and to use transformative pedagogies (Naomee, 2024).

8. Repercussions for Universities in Bangladesh.

The findings indicate several core implications for HEI reformation in Bangladesh.

Introduce modules covering specific national sustainability issues including but not limited to delta management and energy poverty. These modules need to be co-developed and co-taught and linked with the local environment ("Living Lab").

College professors and, more broadly, administrators in the academy are currently witnessing developments of a different kind. Essential faculty development programs on problem-based learning, systems thinking, and team-teaching must be mandatory.

An endorsement and resourcing of community-engaged learning and PjBL pedagogies across all relevant departments as a means of developing systems thinking.

Revise assessment systems to emphasize competency (skills and knowledge) rather than content recall (facts). This could include reflection portfolios, integrated project defense, and ethical case studies as examples.

Create platforms for sharing resources and managing curriculum design; Foster flexibility and collaborative academic culture between departments and institutions.

9. Impacts on Teaching for Sustainability.

Interdisciplinary pedagogy contributes unique value to the overall effectiveness of ESD.

Integrated Thinking and Systems Awareness: Students' grappling with a singular problem through multiple lenses helps make sense

of the world around them. The world is not a cold disjointed piece but an integrated system. This is something critical for the sustainable impact of design solutions (Wals 2013).

Enhanced Agency and Self-Efficacy: Involvement in real-world, local projects (experiential learning) helps students realize how their knowledge can lead to real-world change. This creates an essential feeling of self-agency – the belief they can play a part in a sustainable future (Sterling, 2011).

Students work together in interdisciplinary teams. Involvement in teamwork is now a key component of any lineup work. Teamwork is essential. Teammates face professionally just like it is always the case with stakeholders in the job market. Therefore, it trains students in interpersonal skills (Wiek et al. 2011).

10. Constraints and Analytical Thoughts.

Collaborating among different disciplines is important but risky.

A major warning is the risk of sacrificing disciplinary rigour for an ill-conceived breadth. A good synthesis of disciplinary concepts from the various fields is possible after a student masters the core concept in each discipline.

One major limitation is the difficulty of measuring whether something counts as an outcome, such as a prospective transformation or ethical development, and whether these outcomes can validly continue over time (Wiek et al., 2011). Many HEIs have current assessment methods that are insufficient for this.

"Interdisciplinarity" is not defined uniformly by various actors/strategists (contrast with multi- or trans-disciplinarity). This definitional ambiguity can create confusion in curricula implementation (Pohl & Hadorn, 2008)

11. Future Directions

To enhance the relationship between interdisciplinary theory and sustainable education practice in Bangladesh, more research is needed.

Longitudinal Impact Studies: Carry out longitudinal studies designed to track the employment outcomes, systems awareness, and sustainability action in professional life of graduates from interdisciplinary versus traditional programmes.

Conduct large-scale comparative analyses between public and private and/or regional and metropolitan universities in Bangladesh to identify location-specific barriers and successful enablers.

Research on Assessment Validity: In order to develop and validate valid assessment tools to measure interdisciplinary outcomes and transformative learning in the specific socio-cultural context of Bangladesh, focused research is needed.

Research that examines the effect of a specific policy (e.g., designated pool of interdisciplinary funding, requirement for co-teaching release time) on faculty engagement and the quality of instructional output.

Suggestions: Approaches to Connect Theory and Practice.

The subsequent set of recommendations will be provided for relevant stakeholders based on theoretical analysis and identification of barriers acting as hindrances to the implementation of interdisciplinary pedagogies for sustainable education in Bangladeshi universities.

1. For Teachers: Developing Cross-Disciplinary Sustainability Modules.

The shift must be made from content delivery to facilitated learning experience.

Start with real, local projects: Develop modules that start with a real, complex, local sustainability problem of Bangladesh (countrywide/region-wise eg arsenic in groundwater, climate-change-induced migration of

particular region). This acts as the central anchor for the entire module, asking students to draw upon knowledge from multiple disciplines (Wals, 2013).

One way to improve multidisciplinary of a group is to create groups in such a way that students come from different disciplines like engineering, social science, business etc. The final project should require the integration of these various outlooks for a feasible solution.

Integrating a structured activity like reflection journals or a weekly discussion forum will prompt students to think critically how participating in other disciplines challenges and transforms their own disciplinary assumptions (Mezirow, 1997). The aim of Transformative Learning is reinforced.

As far as it is feasible, the instructors should design and deliver the module together. This way they can demonstrate to the students how professionals within a discipline talk, argue with each other, and bring together their findings to norm professional sustainability practice.

2. Structural and policy recommendations for institutions

University leadership is key to breaking down silos and creating a conducive environment for interdisciplinary work.

Revise policies of promotion and tenure (UGC, 2020) to reward team-teaching and co-authored interdisciplinary publications, involvement in cross-department curriculum development, and community engagement projects, to incentivise interdisciplinarity in faculty evaluation. This tackles the problem of faculty resistance and absence of incentive (Zhang, 2017).

Encourage Cross-departmental Collaboration: Set up funded interdisciplinary Hubs or Centres for sustainability. These centers should be granted sufficient budget and administrative authority to manage inter-departmental student

projects, share resources, and co-hire/assign faculty across traditional departmental lines.

Faculty Development programs, which are essential for specialised interdisciplinary skills, such as facilitation of PBL, systems modelling, curriculum integration methods, and measuring non-cognitive, self-agency outcomes must be made mandatory as PD (Naomee, 2024).

Implementing a Living Lab Policy: The university campus and its immediate community shall both be designated as a Living Laboratory for the implementation of sustainability projects and the relevant operational data on campus (energy use, water, waste, etc.) shall be made accessible to the students and faculty for their problem-based learning and research (Shamsuddoha et al., 2012).

3. For Curriculum Developers: Alignment & Integration.

The fragmentation pattern in curriculum planning should make way for a holistic competency pattern.

Incorporate Sustainability Competencies Systematically: To achieve a more effective integration of sustainability into curricula, all universities should make use of internationally accepted frameworks (for example, Wiek et al., 2011) to map where each of the key sustainability competencies (transformative competencies, systems competence and strategic competence) will be taught across the general education curricula and assessed across the general education and professional education curricula. Sustainability should not be treated as an add-on course.

The curriculum of all degree programs in the early years of students should have new integrated core modules. For example, core modules like the “Grand Challenges of Bangladesh” to facilitate students’ understand of complexity and interlinked nature of sustainability through multidisciplinary materials.

The institutional guidelines should state that interdisciplinary courses must adopt a competency-based assessment mechanism for integrated learning outcomes, and that further reduction of conventional exam system would be essential. Developing a standard may be useful. Competency-based assessment mechanism can include portfolio review, project defence, peer review, critical reflection, etc.

4. Future Empirical Work for Researchers

There is a need for strong empirical research on the Bangladeshi context for effective implementation and evaluation of these strategies.

Longitudinal Impact Studies: Longitudinal studies to study the long-term effect of inter and mono-disciplinarity on graduates' professional success, problem-solving ability, and contribution to sustainability in their careers.

We aim to develop and validate instruments that will reliably assess systems thinking and perspective transformation (TLT outcomes) in Bangladeshi students, in accordance with the assessment practices of HEIs (Sterling, 2011).

Conduct empirical cross-institutional studies comparing the success rates of different implementation models, e.g., dedicated interdisciplinary departments vs. integrated core modules, to manage logistical barriers and grow faculty buy-in across different types of Bangladeshi universities (public vs. private).

12. Conclusion

This article has systematically examined the theoretical necessity and practical impediments of implementing interdisciplinary pedagogies for Sustainable Education (ESD) at Bangladeshi universities which could help to overcome the enduring gap between theory and practice.

An analysis of interdisciplinary pedagogies that include, among others, Problem-Based

Learning (PBL) and Experiential Learning show that such pedagogies have the suited theoretical foundation that is required for sustainability education. Education standards support a range of pedagogies encompassing experiential learning and field studies that provide holistic meaningful learning. These pedagogies uniquely foster systems thinking and facilitate transformative learning by challenging worldviews. They are the necessary mechanism for building and assessing crucial sustainability competencies. If they do not integrate all three domains of knowledge environmental, social, and economic graduates will be equipped with fragmented knowledge that will leave them unprepared to handle the complex, interrelated sustainability problems in Bangladesh.

However, these results show that while there is a strong theoretical potential here, the conversion of this interdisciplinary intent into practice is a tricky one. The effectiveness of the implementation is being hampered by serious obstacles such as: Fixed disciplinary silos and rigid administrative systems (Quazi Uddin, 2023), Lack of training and incentive of faculties to work across programmes (Zhang, 2017), Assessment systems not able to evaluate the holistic transformational outcomes of ESD (Wiek et al., 2011)

In essence, interdisciplinary pedagogies show promise, but they do not happen by themselves. Moving from theory to practice means designing institutions and pedagogies carefully. Universities in Bangladesh need to go beyond just espousing the idea of interdisciplinarity to implement effective policy measures such as rewarding joint work, reforming summative assessment to focus on competence rather than content and investing in faculty development. Through this means, Bangladeshi HEIs can cement their position as pivotal agents in national

endeavours towards climate resilience and sustainable developments.

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