

New Perspectives *on*

Learning, Leadership & Development



Prof. (Dr.) Pankaj Kumar Singh

Dr. Dilip Dutt Varshney

Mr. Ritu Rajan

NEW PERSPECTIVES
ON
LEARNING. LEADERSHIP & DEVELOPMENT

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EDITORIAL

It is with immense pleasure and a deep sense of academic fulfilment that we present the **Conference Proceedings of the International Conference on 'Transforming Learning, Leadership & Development in a Rapidly Changing World'**. This volume brings together a diverse collection of scholarly contributions from researchers, academicians, industry experts, practitioners, and research scholars who have explored innovative ideas and emerging trends shaping the future of education, leadership, technology, and human development.

The contemporary world is witnessing an unprecedented pace of transformation driven by technological advancements, globalization, artificial intelligence, digital innovation, and evolving societal expectations. These rapid changes demand not only the reimagining of educational systems but also the cultivation of adaptive leadership, interdisciplinary collaboration, and lifelong learning. Institutions of higher education play a pivotal role in preparing individuals and organizations to navigate these complexities while fostering innovation, ethical responsibility, and sustainable development.

The conference was conceptualized as an interdisciplinary platform to facilitate meaningful dialogue among scholars and professionals from varied domains. It encouraged participants to exchange research findings, share best practices, and deliberate upon contemporary challenges and opportunities across the broad spectrum of teaching-learning practices, institutional leadership, digital transformation, employability, research innovation, and interdisciplinary collaboration.

The proceedings encompass research papers representing diverse themes, including innovative pedagogical approaches, educational technologies, artificial intelligence in teaching and learning, institutional governance, leadership excellence, skill development, industry-academia collaboration, research methodologies, sustainability, and emerging interdisciplinary perspectives. Collectively, these contributions reflect the commitment of the academic community towards generating knowledge that is both theoretically enriching and practically relevant.

One of the defining characteristics of this conference has been its emphasis on fostering collaboration across disciplines. As the boundaries between traditional academic domains continue to blur, interdisciplinary research has emerged as a catalyst for addressing complex real-world challenges. The papers included in this

volume demonstrate how collaborative inquiry can generate innovative solutions, strengthen institutional practices, and contribute meaningfully to national and global development goals.

The editorial team sincerely appreciates the enthusiasm and scholarly commitment demonstrated by all authors whose valuable research contributions have enriched this proceedings volume. We also acknowledge the meticulous efforts of the reviewers, whose constructive feedback and rigorous evaluation ensured the academic quality and integrity of the published work. Their dedication to maintaining high scholarly standards has significantly enhanced the quality of this publication.

We were privileged to host an eminent panel of keynote speakers whose vast experience and insightful deliberations significantly enriched the academic discourse of the conference. We express our sincere gratitude to *Mr. Prem Singh, President – Group HR (Group CHRO), JK Organization*; *Mr. Atul Shah, National President, Indian Society for Training & Development (ISTD)*; *Mr. Himanshu Jesse Wadia, Director – Program Management, AI Innovation and Automation (Delivery & Operations), Amdocs UAE/Middle East Region*; *Mr. Nayan Parikh, Management Consultant, Nayan Parikh and Consultants, and IIM Alumnus*; and *Ms. Bhumika Shah, Data Solution Engineer, University of the Cumberlands, USA*. Their thought-provoking keynote addresses offered invaluable perspectives on leadership, human resource development, digital transformation, artificial intelligence, organizational excellence, and the future of learning. Their distinguished presence not only elevated the academic stature of the conference but also inspired participants to explore innovative approaches to teaching, research, leadership, and professional practice.

We further extend our heartfelt gratitude to the session chairs, reviewers, organizing committee members, faculty coordinators, student volunteers, and the university leadership for their unwavering support and dedicated efforts in ensuring the successful organization of this international conference. Their collective commitment transformed the event into a vibrant platform for intellectual exchange, interdisciplinary collaboration, and academic excellence.

It is our sincere hope that this proceedings volume will serve as a valuable resource for researchers, educators, policymakers, students, and professionals seeking deeper insights into contemporary developments in learning, leadership, and organizational transformation. We believe that the ideas presented herein will

inspire future research, encourage innovative educational practices, and contribute towards building resilient, inclusive, and future-ready institutions.

As we move forward into an era defined by continuous change and technological disruption, the responsibility of academia extends beyond the generation of knowledge to nurturing ethical leadership, fostering creativity, embracing innovation, and promoting sustainable progress. May this collection of scholarly work encourage continued dialogue, inspire collaborative research, and contribute meaningfully to shaping the future of education and society.

We thank every contributor and reader for being a part of this significant academic endeavour and hope that these proceedings stimulate new ideas, meaningful collaborations, and impactful research for years to come.

Editors

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INDEX

S. No.	Title Of Paper	Author	Page No.
1	The SCALE WITH SOUL® Leadership Model: A Conceptual Framework for Sustainable Performance and Organizational Outcomes	Sindhuja Rai	01-11
2	Emerging Business Technologies and B2B E-Commerce Adoption: A TOE-Based Conceptual Framework in Developing Markets	Neeraj Raghav Kumar, Dr. Swapnil Undale	12-16
3	Skill Enhancement for Employability in the Livestock and Poultry Sector in India	Dr. Ngangkham James Singh, Dr. Sushma Singh, Dr. Amit Kumar Maurya	17-22
4	Role of Aptitude Skills in Employability Readiness of Engineering Students in Indian Private Higher Education Institutions (HEIs): A Conceptual and Empirical Investigation	Anant Bhardwaj, Mani Saraswat	23-32
5	NEP 2020 and Outcome-Based Education in India: Transforming Higher Education for Lifelong Learning	Vijay Kumar, Anant Bhardwaj, Navin Kumar	33-45
6	Graduate Employability in Digital Era : Post Pandemic Impact of Hybrid Learning	Nidhi Gupta	46-55
7	Bridging Innovation and Commercialization: The Role of Intellectual Property Rights in Data-Driven and Technology-Enabled Research Practices	Navin Kumar, Abhishek Kumar Singh, Sikha Kumari, Vipul Kumar Singh	56-69
8	Innovative Pedagogies: Bridging Theory and Practice in Pharmaceutical Sciences	Dr Ashish Singhai	70-94
9	Enhancing Dental Implant Outcomes: The Impact of Magnetism on Osseointegration	Sonal Singh, Prof.(Dr.) Vishwa Deepak Singh	95-104

10	Bridging the Skill Gap through Industry–Academia Collaboration A Study of Engineering and Management Students in Indian Private Universities	Mani Saraswat, Anant Bhardwaj	105-114
11	A comparative study of Breath-holding capacity among Smokers, Athletes and Non- athletes.	Ayush Kumar Ojha, Dr. Manu Mishra	115-120
12	The Multi-Tier Deduplication Framework: Model for Effective Media Deduplication Using Partial Semantic Hashing with Convolutional Neural Network	Tanmay Sethi, Deepali jain	121-135
13	Neuro-Symbolic AI for Cross-Cultural Leadership Development: A Controlled and Explainable Framework for Future-Ready Systems	Shridhi Gupta, Riya Jain	136-152
14	Power of Group and Open Source: How Group Perception and Open-Source Contribution can End the Subscription Debt	Deepali Jain, Tanmay Sethi	153-163
15	Comparative Study of Pretraining Strategies in Transformer-Based Machine Translation: T5 vs MarianMT vs mBART for English-to-French	Riya Jain, Shridhi Gupta	164-175
16	Interpretable Deep Learning for Medical Diagnostics and Prediction: A Framework with Clinical Coherence Guarantees	Rashid Ali, Vishal Pal, Umesh Chandra Garjola, Shivangi Patel	176-186

The SCALE WITH SOUL® Leadership Model: A Framework for Sustainable Performance and Organizational Results

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ABSTRACT

In today's world of growing organizational complexity and increasing executive burnout, traditional leadership models that focus on external skills rather than internal harmony are falling short (Maslach & Leiter, 2016). This paper presents the SCALE WITH SOUL® Leadership Model, a framework developed by practitioners that connects a leader's inner alignment to lasting organizational success.

Based on qualitative evidence from more than 2,500 executive coaching sessions with founders and senior leaders in over 60 organizations across 14 industries, the model highlights five key areas: Self-Alignment (S), Clarity of Vision (C), Aligned Execution (A), Leadership Energy Optimization (L), and Organizational Leverage (E).

The findings, backed by anonymized participant stories and outcome data, indicate that inner alignment is essential for consistent performance, better decision-making, and lower burnout rates (Deci & Ryan, 2000; Seligman, 2011). Leaders who are aligned report profit growth of 60 to 90 percent and a results multiplier of 2 to 5 times while working fewer hours. This paper adds to leadership theory by connecting personal development with measurable organizational results and offers practical suggestions for leadership training, executive coaching, and organizational design.

1. INTRODUCTION

Leadership efficacy is more scrutinized in terms of the balance of speed, precision, and strength of modern organizations. A confluence of factors causing a global crisis of leadership and wellness is felt by founders and senior leadership, such as high ambiguity, complex stakeholder surroundings, and relentless decision-making.

The foundations of traditional leadership development models are the acquisition of skills and behavioral competencies. Their basis in transformational (Bass & Riggio, 2006) and servant leadership models (Greenleaf, 1977) makes them advance leadership models. However, they often fail to consider the internal psychological and cognitive conditions necessary to sustain leadership. The gap in literature has led to increased executive burnout, decision fatigue, and a disconnect between strategy and organizational execution (Maslach & Leiter, 2016; Sonnentag, 2018). This gap in literature is best described as the execution-alignment gap and involves leaders' strategic and technical competencies, which they are unable to apply to achieve performance.

This paper argues that leadership effectiveness encompasses inner alignment. Further, the SCALE WITH SOUL® Leadership Model, is the first of its kind to create a practitioner-based, evidence-aligned model to combine inner alignment of the leader with the outcomes of the organization. The inner alignment basis is described in section 3. Section 4 shows the complete model. Section 5 shows the model and data collection techniques, section 6 shows the collected data. The last three sections (7-9) cover potential implications, limitations, and conclusions.

2. LITERATURE REVIEW

2.1 Leadership Models and Their Limitations

According to Bass & Riggio (2006), transformational leadership encourages inspirational motivation and individualized consideration. This in turn improves follower performance. Based on Greenleaf (1977), servant leadership believes that growing and caring for followers should be the main priority of the organization. Avolio & Gardner (2005), and George (2003) state that authentic leadership values self-awareness and relational transparency.

Advancements in leadership theories still have their limitations. They focus only on behaviors. They also address leadership burnout and cognitive overload inadequately, if at all. They also do not have specific links between psychological states and performance. Currently, there is no known published framework that addresses identity coherence, energy optimization, and organizational leverage in an integrated system.

2.2. Burnout and Leadership Effectiveness

According to Maslach and Leiter (2016), leadership burnout impacts your cognitive capacity, engagement, and your ability to make sound decisions. The recovery paradox states that the individuals who feel the most stressed out are the least able to participate in recovery behaviors. This worsens the paradox, causing performance to further deteriorate (Sonnetag, 2018).

Chronic stress results in allostatic load, which is the burden a body bears from on-going chronic stress, impacting the ability of a leader to manage complexity (McEwen, 1998). Sustainable leadership cannot rely on just training resilience. It impacts systems that include both internal and external demands.

2.3. Leadership Identity and Inner Alignment

Studies are beginning to see how leadership identity, self-congruence, and intrinsic motivation determine the effectiveness and efficiency of different leaders (Deci & Ryan, 2000; George, 2003). From what is known regarding adult developmental theory, a leader changes their system of meaning to meet the growing complexity that comes within organizations (Kegan & Lahey, 2009). Under self-determination theory, when leaders operate in line with their internal values rather than with external validations, they have more character, and less anxiety, and their judgment is improved (Deci & Ryan, 2000). Research in positive psychology connects the sustaining of well-being and performance to alignment, autonomy, and meaning (Seligman, 2011).

Unfortunately, with all of this knowledge, there is still a significant lack of application. There is a shortage of identity-centered research being applied in ways that may positively influence an organization's performance. Because of this discrepancy, the SCALE WITH SOUL® model was created.

3. CONCEPTUAL FOUNDATION: INNER ALIGNMENT

The definition of inner alignment for the purposes of this research is as follows:

This construct consists of four overlapping components, called pillars, based upon over 15 years of practitioner-based research:

- **Value Congruence** - being true to what you value most.
- **Identity Coherence** - leading from a consistent, stable sense of self.
- **Cognitive Clarity** - clear and decisive thinking during periods of pressure.
- **Emotional Regulation** - responding reflectively rather than reacting.

Inner Alignment is not a fixed state but rather a developing capacity that can be developed within the context of a structured coaching intervention; reflective practice; and the use of behavioral accountability as the basis for developing capability through the use of the SCALE WITH SOUL® methodology.

"Inner alignment is the degree of coherence between a leader's values, identity, cognitive processes, and behaviorally based actions in the development and execution of quality and consistent decision making and sustainable effectiveness as a leader."

4. The SCALE WITH SOUL® Leadership Model

Built upon five connected components, the model makes up a total leadership operating system. Unlike traditional additive competency models where dimensions simply stack together, SCALE WITH SOUL® is designed as a systemic approach; meaning that the interaction of all the dimensions will augment one another (amplifying each other), so that if there is a problem in one of the components, the overall effectiveness will be inhibited.

Table 1 Key Performance Indicators of different dimension

	Dimension	Definition	Key Performance Indicators
S	Self-Alignment (The Foundation)	Internal coherence and identity building through values inclusion, personal strengths and the development of a leadership identity.	Level of clarity in the identification of one's personal values; level of decreased internal conflict; level of increased ability to make decisions.
C	Clarity of Vision	Aligning personal purpose with the purpose or direction of the organization from an expanded level of strategic thinking to encompass all options (bounded rationality).	Amount of strategic focus; consistent communication; reduced level of ambiguity for team members; and identification of available pathways for growth.

A	Aligned Execution	Transforming the vision into an ongoing basis of consistent prioritization	Ability to make decisions and execute quickly; reduced overall amount of work; measurable impact of the leadership on those with whom they have been assigned their leadership (peer leaders, subordinates/colleagues); successfully execute strategic priorities.
L	Leadership Energy Optimization	The management of one's cognitive and emotional energy as an asset to gain leverage as a strategic leader and produce allostatic overload.	Lesser burnout instances; sustainable performance enhancement; increased attention management; quality of recovery
E	Organizational Leverage	Building in systems/ processes, delegation and autonomy so that the impact is scalable and moves from individual success or result to the amplification through the organization.	Effective rate of delegation; team ownership ratings or results; reduced dependency on the leader; alignment of key stakeholder relationships.

5. THE CONTINUUM OF LEADERSHIP DEVELOPMENT

Based on field observations from over 2,500 engagements, there are four different types of leaders which show a continuum of development. Where leaders fall on this continuum has direct implications for their team's overall health, as well as for the business performance and personal sustainability of the leader:

Stage 1: The Individualist

The average profit for this stage is 10-30%, with micromanagement; resulting in high levels of stress and turnover. There is little to no personal time (<1 hour/day).

Stage 2: The Strategist

The average profit for this stage is 30-60%, with understanding the root causes; delegating responsibilities to other members on the team; and, having Limited amount of personal time (1-3 hrs).

Stage 3: The Achieving

At this stage, profits begin to scale toward 60-90%, self-leadership occurs; team member empowerment begins happening; and, sufficient time is available for personal use (3-5 hrs).

Stage 4: The Expert

Profits at this stage are likely to double (90-120%+ profits) and an efficient, high performing, and autonomous team exist. The business is also operating on some level of automated operation,

therefore, there is sufficient time available for personal use (5-7 hrs).

6. METHODOLOGY

6.1 Research Design

This research employs a qualitative research design that is both practice-based and theoretical in nature, which aligns with the methodologies of applied leadership and coaching research (Grant, 2014). Additionally, grounded theory was used to analyze and categorize themes related to coaching engagement; this approach allowed the researchers to identify patterns across many coaches' use of the SCALE WITH SOUL® model through qualitative coding (Glaser & Strauss, 1967).

6.2 Data Sources & Sample

Data were collected from three data sources, consistent with triangulated qualitative inquiry (Creswell, 2014). These sources include:

- **Coaching records** – Structured observation data from over 2,500 executive coaching engagements over 15 years
- **Cross-client patterns** – Common leadership behaviour across many organizations and their clients that have been coached by the researchers (14 different industries)
- **Participant Narratives** – Anonymized client testimonials (via structured reflection) following the experience of being coached.

Client Profile- Senior leaders in transition; founders and entrepreneurs; high potential professionals; leadership teams

Industries Represented: IT / ITeS; Banking; Pharma; Consulting; Education; FMCG; Government; Hospitality; Automotive; Telecommunications; Real Estate

Geographic Scope- India (primary), USA, Southeast Asia, Middle East, Global MNCs

6.3 Analytical Approach

Thematic analysis (Braun & Clarke, 2006) was used to complete a pattern-based analysis of the coaching records in terms of the dimensions of the coaching engagement, the outcomes achieved, and the type of interventions used. The client testimonials were coded against the five dimensions of the SCALE WITH SOUL® model to measure whether each dimension was valid and outcome specific. The narrative component of the client testimonials supports the findings from previous research in the coaching domain that demonstrate the efficacy of experiential or reflective research methodologies (Theeboom, Beersma & VanVianen, 2014).

7. OUTCOMES: DATA AND INSIGHTS ACROSS OUTCOME MODELS

The qualitative findings relating to the outcome models include descriptions of clients whose stories illustrate each outcome for several instances.

7.1. Self-Alignment (S) – Leader Identity & Presence

Most leaders come into coaching with a limited understanding of their identity, as reflected in the experience of impostor syndrome, misalignment between values and behavioral results, and limited confidence with making strategic decisions about their ability as a leader. Coaching focuses on providing leaders with a new understanding of their identities by reframing and aligning with their strengths (i.e., value-based actions), while incorporating the principles of authentic leadership (George, 2003; Avolio and Gardner, 2005).

Coaching Result: Increased confidence in being an effective leader, building an authentic presence as a leader, and reducing internal cognitive dissonance across leaders.

7.2. Clarity of Vision (C) – Strategic Thinking & Decision-Making

Leaders were demonstrating constrained strategic thinking, which corresponded to the concept of bounded rationality (Simon, 1957), meaning that leaders were only able to visualize strategies and decision options that were relevant based on current operational conditions within the business unit. Using a structured reflection protocol, leaders created a broader view of their strategic thinking and evolved their decision-making style from being reactive to being proactive about creating a new strategic leadership model (Kahneman, 2011).

Coaching Result: Improved quality of strategic decisions, identification of new growth strategies previously unidentified, & enhanced site communication clarity.

7.3. Energy Optimization (L) – Sustainable Leadership Performance

Leaders with severe burnout came into coaching were demonstrating negative performance patterns (Maslach and Leiter, 2016). Coaching with leaders focused on creating psychological safety, energy auditing frameworks, and accountability for emotional self-regulation.

Coaching Result: Increased cognitive clarity and resilience, sustained high performance capability, and created a balance between demand and energy exerted for fulfilling the role as a leader.

"I came in thinking I needed a better strategy. What I actually needed was to understand how my identity as a founder was limiting the business. That shift changed everything."

Shruti Jobanputra

Founder, Sharav Enterprises

7.4. Organizational Leverage (E) - Stakeholder Alignment and Scale:

Misalignment between leaders' intentions and organizations executions led to ongoing inefficiencies, conflicts among stakeholders, and diluted resources. The structured leverage framework enabled effective strategic prioritization and stakeholder influence that are consistent with Balanced Scorecard execution models (Kaplan & Norton, 1996).

Outcomes Observed: Increased stakeholder influence, improved efficiency of resource allocation, and quantifiable increases in organizational output relative to the time invested by leaders.

"Getting coached by Sindhuja was something every CEO must undergo. She helped me scale when I felt there was no other way out. Her insights were as if she was in my office everyday."

Rajeevsharan Kohli, CEO · Jaipur Wax Museum

7.5. Aligned Execution (A) - Insight to Impact:

There was a consistent identification by leaders of the translation gap between awareness of strategy and execution of operations. Coached interventions used execution discipline frameworks and structured accountability mechanisms that matched the execution theory of Bossidy and Charan (2002).

Outcomes Observed: Improved consistency of implementation, quantifiable leader impact, and the development of practical action frameworks usable after the coaching has ended.

"The program was truly transformational — not just professionally, but in every aspect of who I am. I'm scaling new heights, leading with conviction, and experiencing growth like never before."

Rajat Pendarkar, Deputy GM Technology · Multiplier

7.6. Quantifiable Outcome Indicators

While this research study is primarily qualitative, repeated patterns of the outcomes across the engagements logically point to the aggregated outcome indicators:

Table 2: Outcome Metric

Outcome Metric	Without Alignment	With SCALE WITH SOUL®
Profit Growth	10–30%	60–120%+
Results Multiplier	Baseline output	Working 2–5x less
Daily Self-Time	<1 hour/day	5 to 7 hours/day
Team Autonomy	High dependency / micromanagement	Higher team ownership; Working on an auto-mode
Burnout Incidence	High stress levels; cognitive overload	Sustainable performance optimization

Note: This outcome data showcases the aggregate of 2,500+ coaching engagements.

8. DISCUSSION

The results indicate that effectiveness in leadership is not only influenced by the external competencies of effectiveness, but is largely determined by the alignment between a leader's internal identity and their external actions. While previous studies have focused on explaining leadership behaviours, motivation, and burnout as separate entities (Deci & Ryan, the scale with soul is a model that links the domains of leadership behaviour, motivation, and burnout. When viewed as an integrated system working together, there is less stress on the individual components of leadership.

Additionally, as performance is a result of the functioning alignment systems that exist within the organisation, the interdependence of the five dimensions allows us to think about leadership as functioning at a systems level of leadership – sustainable performance is an emergent property of doing so, not simply as a sum total of each individual leader's competencies.

Lastly (we need this) the leadership development continuum addresses a missing gap in the leadership literature (i.e., there has been no structural model presented) mapping the willful, spontaneous leadership stages from individualistic, reactive leadership to expert, leveraged leadership including what interventions act as the catalyst between each stage of development.

The 'BE-DO-HAVE' sequencing (identity → action → outcome) reinforces this model's difference with other skills-first methodologies.

Individuals who lead through alignment produce results much greater than those of other leaders due to their having coherent intentions and ability to generate synergy in their activities through people and processes.

9. IMPLICATIONS

9.1 Leadership Development Programs

It is imperative that leadership programs provide for the development of an individual's identity and psychological alignment along with skill development (Avolio & Gardner, 2005). The SCALE WITH SOUL® framework provides a systematic structure in which to complete identity development prior to conducting skill development to assure that an individual has a solid internal foundation from which to add new capabilities rather than trying to add new capabilities onto an existing misalignment.

9.2 Organizations

Organizational sustainability is dependent upon organizational performance being created through systemic alignment and not by providing standalone enhancements in professional capabilities (Kaplan & Norton, 1996). Therefore, organizations who are investing in executive coaching should view disalignment in the individual and/or the organization as one of the root causes of a problem before concluding that it is due to a lack of technical skills. The Leadership Development Continuum is a diagnostic structure to create effective solutions based on the stage of development.

9.3 Executive Coaching

The use of coaching should tie the results achieved through coaching to both the individual and business (Grant, 2014; Theeboom et al., 2014). The SCALE WITH SOUL® coaching architecture provides a system for holding dual accountability to both personal and organizational goals at the same time. The current coaching literature does not identify this dual accountability with respect to founders and C-Suite leaders. Therefore, attention should be given to the individual identity coherence prior to effective implementation of the different initiatives related to the organization.

9.4 For Researcher

In terms of future quantitative research, emphasis is given to developing and validating instruments that measure inner alignment; conducting longitudinal studies tracking the effects of model-based interventions; and testing whether the instruments have cross-cultural validity. The outcome indicators discussed in Section 6.6 serve as potential candidate dependent variables for future quantitative research.

10. LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

The qualitative, practice-based nature of this project limits its overall scope. There are several significant limitations to the study, including the absence of a comparison group, the potential influence of social desirability on practitioners' self-reported testimonials, and the practitioner's relationship with the researcher, who is also the primary author. Because there is no formal quantitative validation for any of the data presented, the researcher urges that the outcome data be viewed only as directional rather than verified.

Future Research Highest Priorities:

- **Scale Development** - The development and psychometric validation of scales that measure inner alignment.
- **Empirical Validation** - Conducting randomised / quasi-experimental studies comparing model-based coaching to control conditions.
- **Longitudinal Studies** - Conducting longitudinal tracking of business outcomes throughout the various stages of the Leadership Development Continuum.
- **Generalisability** - Conducting assessments of the cross-industry and cross-cultural applicability of model-based coaching.
- **Physiological Markers** - Conducting neuro-biological investigations of the physiological correlates of states of inner alignment (e.g., cortisol and HRV) that could serve as objective measures of outcome.

11. CONCLUSION

SCALE WITH SOUL® Leadership Model is an evidence-based leadership theory/practice developed by an experienced practitioner. It is the first model to bridge the dual dimensions of Leader Development:

- (1) the Intrapersonal dimension (identity) and
- (2) the Organizational dimension (execution).

This creates a bridge between these two areas that has been missing in leadership development literature.

This leads to the conclusion that the key to good leadership is not just having a good heart and nice clothes, but also that the leader operates in some way from an aligned "inner self" to be creative and productive in their "outer" business world. The reality and truth of this research indicates that the way to achieve evidenced based leadership is through having leaders create

value (sustainable, scalable results) from their aligned "inner self," and not just having leaders create value by having a skill set to deliver.

As organizations face unprecedented levels of complexity, "the leadership qualities that help organizations succeed are those who develop a Leader Identity that will provide them with each of the qualities necessary to lead, because the more they develop a coherent and aligned Leader Identity, the more clarity, energy and leverage they will have as they operate in the world of their Leadership Role."

"The pathway to creating sustainable change for your business is through completing processes in a consistent manner, using proven methodologies, being a part of a primary support community, and being coached to lead through the deep transformational process that you are creating for yourself and others. The SCALE WITH SOUL® Leadership Model is not about a method, but rather is about a Leader Identity."

— **Sindhuja Rai, founder, Mpower**

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Emerging Business Technologies and B2B E-Commerce Adoption: A TOE-Based Conceptual Framework in Developing Markets

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ABSTRACT

Companies are rapidly adopting new business technologies and collaborating, sharing information and coordinating supply chains in many different ways. However, business-to-business (B2B) e-commerce is not yet very widespread in developing economies, particularly for small and medium-sized businesses (SMEs). Organisations operating in these kinds of environments have a mix of organisational, environmental and technological issues that impact upon their decisions around the adoption and use of new technologies.

The previous research on e-commerce use by firms has been often weak and without a solid theoretical framework that considers market dynamics. This study fills the gaps by explaining why B2B e-commerce is gaining popularity in developing economies using Technology, Organization and Environment (TOE) as a framework.

Previous studies that have examined adoption of e-commerce by business have been found to be inadequate and not strongly grounded in theory with reference to market dynamics. This study describes the growing popularity of B2B e-commerce in developing economies based on Technology, Organization, and Environment (TOE) framework.

The study provides guidance to managers and lawmakers who wish to accelerate B2B e-commerce growth to do so in the right way and in the right way in the long run.

Keywords—B2B e-commerce; emerging business technologies; TOE framework; developing markets; digital transformation

INTRODUCTION

Digital transformation is now a strategic priority for companies that want to be more efficient, resilient and competitive. B2B e-commerce has been able to handle buying, shipping, coordinating, and information sharing[1], [2], [3] with the emergence of new business technologies like cloud computing, big data analytics, artificial intelligence, blockchain, and digital platforms. B2B e-commerce can reduce transaction costs, increase transparency, and strengthen supply-chain relationships via automation and process integration.

The adoption of B2B e-commerce in developing nations is still unequal despite these possible advantages [4], [5] Businesses often have to deal with weak infrastructure, limited access to capital, a lack of skilled workers, and more cyber threats.

Institutional factors such as fuzzy rules, inconsistent enforcement and trading partners who are not yet ready for digital trading make the decision to adopt even more difficult. These problems are particularly harmful for small and medium-sized enterprises (SMEs) as they generally lack the organizational flexibility or resources to respond to technological and environmental changes. [6].

Past research has revealed a number of factors influencing the adoption of B2B e-commerce. But many studies do not consider organizational competencies and environmental constraints, but focus on specific issues or emphasize technological characteristics. The literature therefore lacks information about how these variables interact to affect adoption outcomes in developing markets [6], [3].

This paper addresses this limitation and proposes a TOE-based conceptual framework appropriate for developing-market settings. Incorporating the new business technologies to the TOE framework addresses the multiple dimensions of B2B e-commerce adoption and provides a clear view of the adoption process. The paper contributes to the discussion by providing a conceptual model that is suitable for conference level discussion, facilitates future empirical research and supports managers and policy makers in decision making [3], [6].

1. LITERATURE BACKGROUND

There has been much research on B2B e-commerce as a way of improving the efficiency and effectiveness of companies working together. Previous studies have shown that benefits such as lower procurement costs, better inventory control, more transparent information, and closer buyer-supplier relationships are possible. These advantages are especially important in complex supply networks since quick coordination and information sharing are very important [6]. From a technological perspective, we highlight the influence of system compatibility, data security and infrastructure readiness on the adoption outcome. People worry about cybersecurity and data privacy, which makes them think there is more risk and stop them from using the technology, but reliable connectivity and interoperable technologies make transactions go smoothly. Poor infrastructure and inequities in access to digital services in developing markets exacerbate these problems [2].

Organizational perspectives emphasize the importance of internal capabilities like process maturity, digital know-how and top management support. The more proactive leaders the company has with a deep knowledge of information systems, the more likely it is to succeed with B2B e-commerce platforms. On the other hand, it might be difficult to use and implement after adoption if people do not want to change and are unable to learn new things [6].

In developing markets, problems with institutions and the environment are very important. Incentives to adopt depend on things like government help, pressure from competitors,

clear rules, and the willingness of trading partners. Network effects mean that businesses may hold off on going digital until their most important partners are ready to do the same[2]. The literature shows that adoption outcomes are the result of the interaction of technological, organizational, and environmental factors. This shows that a unified framework is needed[7].

2. THEORETICAL FOUNDATION: TOE FRAMEWORK

The TOE framework sees technology adoption as the result of three things: the technology itself, the organization, and the environment. The technical context shows how available and useful relevant technologies are, such as their relative advantages, compatibility, complexity, and readiness. The organizational context includes things like internal resources, capabilities, size, and management structure. The environmental setting shows how external factors like competition, rules, and institutional infrastructure can help or hurt an organization [6], [8]

TOE is especially useful for studying how B2B e-commerce is growing in developing economies because it takes into account institutional restrictions and differences in context. It makes it easier to look into how both internal and external factors affect adoption decisions, and it lets you put together several new technologies in a way that makes sense[8], [9].

3. CONCEPTUAL FRAMEWORK DEVELOPMENT

The ability of a company to implement, integrate, and secure B2B e-commerce solutions is highlighted by the technological context [8]. Reliable transactions and interaction with partner platforms and internal systems are made possible by infrastructure preparedness and system compatibility. Perceptions of risk and trust are further influenced by scalability and security measures [10].

Internal preparedness and governance are crucial to the organizational context. Digital capabilities and process maturity are what make an implementation successful. Top management support shows that the company is committed to its strategy and makes it easier to allocate resources.

Value realization and sustainable use are supported by effective change management [6]. The environmental context includes the state of institutions and ecosystems. Adoption incentives are shaped by clear rules, competition, partner readiness, and the maturity of the ecosystem. In developing markets, policies and standards that help can speed up adoption, while policies and standards that don't help can slow it down[8].

4. PROPOSED CONCEPTUAL MODEL

Fig. 1 explains how organizational, technological, and environmental settings interact to affect B2B e-commerce adoption outcomes, such as the degree of adoption, usage intensity, and integration depth, using the TOE-based conceptual model. The model is appropriate for debate at the conference level and is purposefully economical.

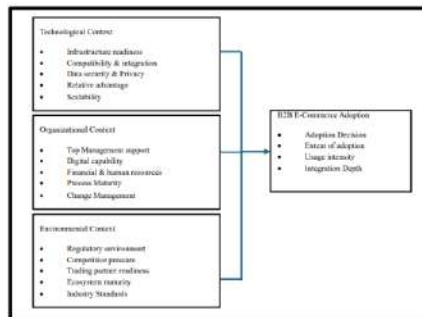


Fig. 1. TOE-based conceptual framework for B2B e-commerce adoption in developing markets.

5. IMPLICATIONS AND FUTURE RESEARCH

The suggested framework is not supported by empirical data in this conceptual study. The model may not account for all context-specific factors influencing B2B e-commerce adoption across various industries, firm sizes, or national environments because it was created through a synthesis of previous literature. The framework is designed for developing market conditions and may need to be adapted for implementation in more developed digital economies. The study also does not account for possible moderating factors such as industry characteristics, organizational culture or institutional differences. It does not investigate causal relationships between technological, organizational and environmental factors found. VII. CONCLUSION Drawing upon the Technology-Organization-Environment (TOE) theory, this study develops a conceptual framework to explain the popularity of B2B e-commerce in developing countries. The framework combines organizational capabilities, technological readiness, and environmental considerations to provide a comprehensive understanding of the various factors that influence adoption outcomes. The proposed model shows that technology accessibility is as important as internal preparedness and supportive institutional ecosystems for effective execution of B2B ecommerce. In addition to providing managers and policymakers looking to expedite digital transformation in business-to-business contexts with useful advice, the framework advances theory by combining disparate adoption determinants into a single perspective. The model needs to be empirically validated as a conceptual study in subsequent studies utilizing actual organizational data from various industries and geographical areas.

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SKILL ENHANCEMENT FOR EMPLOYABILITY IN THE LIVESTOCK AND POULTRY SECTOR IN INDIA

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ABSTRACT

The livestock and poultry subdivision play a vital role in agricultural economies by contributing to food safety, revenue generation, and rural occupation. However, the growing demand for expert manpower in this subdivision highlights the need for actual skill improvement programs to progress employability. This training focuses on the significance of developing technical, managerial, and entrepreneurial skills among youth and farmers engaged in livestock and poultry production. Key areas of skill development include animal health management, breeding techniques, feed and nutrition practices, housing management, biosecurity methods, and value addition of animal products. The integration of modern technologies, vocational training, and extension services has significantly improved the efficiency and productivity of the sector. Skill-oriented training programs, such as those offered by agricultural universities, Krishi Vigyan Kendras (KVKs), and government initiatives, help bridge the gap between academic knowledge and practical application. Furthermore, increasing soft skills such as communication, problem-solving, and business management is crucial for endorsing self-employment and entrepreneurship in livestock-based enterprises. The study concludes that efficient skill improvement not only increases employment opportunities but also strengthens rural livelihoods and supports sustainable agricultural improvement. Hence, focused struggles on capacity building and continuous learning are vital to meet the evolving demands of the livestock and poultry industry.

Keywords: *Krishi Vigyan Kendras (KVKs), entrepreneurial skills, self-employment, food security, strengthens.*

1. INTRODUCTION

The livestock and poultry sector play an importance role in the agricultural economy by providing milk, meat, eggs, wool, manure, and employment opportunities to millions of people. In India, this sector contributes significantly to rural livelihoods, nutritional security, and income generation. With the rapid growth of commercial dairy farming, poultry production, and allied industries, there is an increasing demand for skilled manpower capable of managing modern livestock enterprises efficiently.

Skill improvement has become essential for improving employability in the livestock and poultry sector. Farmers, students, entrepreneurs, and rural youth require technical knowledge and

practical training in areas such as animal breeding, feeding, healthcare, housing management, vaccination, biosecurity, poultry production, dairy technology, and marketing. The adoption of advanced technologies, mechanization, and scientific management practices has created new employment opportunities in veterinary services, dairy processing, feed industries, hatcheries, and agribusiness enterprises. Training and capacity-building programs help individuals develop professional competencies, entrepreneurship skills, communication abilities, and problem-solving techniques. Government initiatives, agricultural universities, Krishi Vigyan Kendras (KVKs), and vocational education programs are actively promoting skill development to strengthen the livestock and poultry industry. These programs not only improve productivity and profitability but also encourage self-employment and rural development. Therefore, skill enhancement in the livestock and poultry sector is essential for creating sustainable employment, increasing production efficiency, and improving the socio-economic condition of farming communities. It empowers individuals with modern scientific knowledge and practical expertise required to meet the growing demands of the livestock industry in a competitive global market.

2. SIGNIFICANT SKILL DEVELOPMENT INITIATIVES

Skill enhancement in India's livestock and poultry divisions is vital for transforming rural livelihoods into commercial enterprises. Government bodies like the Agriculture Skill Council of India (ASCI) and the National Livestock Mission (NLM) offer structured training to bridge serious skill gaps, empowering youth and farmers with scientific, income-generating abilities.

- **Agriculture Skill Council of India (ASCI):** Operates under the Ministry of Skill Development and Entrepreneurship, offering standardized training for job roles like Small Poultry Farmer, Dairy Farmer, and Artificial Insemination Technician.
- **National Livestock Mission (NLM):** Focuses heavily on entrepreneurship development and breed development for poultry, sheep, goat, and piggery. It incentivizes individuals, SHGs, and FPOs to establish commercial livestock initiatives.
- **Krishi Vigyan Kendras (KVKs):** Provide localized, grassroots training on vigorous technical skills like debeaking, brooding, disease diagnosis, and low-priced feed formulation

3. IMPORTANT AREAS OF SKILL DEVELOPMENT

To growth profitability and employability, training programs focus on four primary pillars of livestock management.

- **Scientific Feeding & Nutrition:** Formulating balanced, cost-effective rations using nearby available green fodder, silage, and protein supplements.
- **Breeding & Hatchery Management:** Skills in artificial insemination, breed selection, brooding, and debeaking to maximize yield.
- **Health & Hygiene Management:** Vaccination schedules, deworming, and early disease detection to prevent mortality and ensure food safety.
- **Technology Integration:** Using computer vision for behavior tracking, digital health

monitoring, and automated farm equipment

4. VITAL SKILL DOMAINS FOR EMPLOYABILITY

Graduates and rural youth can target several key technical and managerial competencies to boost employability:

- **Advanced Animal Nutrition:** Formulating balanced, cost-effective feeds (using protein bases and energy metabolism), which constitutes up to of meat or milk production costs.
- **Integrated Herd & Flock Health:** Applying scientific vaccination calendars, disease prevention, and bio-security protocols.
- **Modern Breeding Techniques:** Knowledge artificial insemination and embryo transfer methods to boost per-animal productivity.
- **Farm Management & Automation:** Mastering farm economics, record-keeping, unused management, and modern supply-chain logistics.

5. ACTIONABLE PATHWAYS AND RESOURCES

- **Government Certification:** We can explore NSQF-aligned courses and register for training centers through the ASCI portal.
- **Financial Incentives:** We are watching to start your individual business, check eligibility guidelines and systems on the NLM Udyamimitra Portal.
- **Educational Resources:** Access open-source academic and practical training components at the IGNOU eGyanKosh.

6. SKILL DEVELOPMENT PROCESS: DEPARTMENT OF ANIMAL HUSBANDRY & DAIRYING (DAHD) IN INDIA

The Department of Animal Husbandry & Dairying functions under the Ministry of Fisheries, Animal Husbandry and Dairying, Government of India. The department aims to strengthen the livestock and dairy sector by developing skilled manpower, promoting entrepreneurship, improving animal productivity, and ensuring rural employment generation.

Important DAHD Schemes Supporting Skill Development:

- National Livestock Mission
- Rashtriya Gokul Mission
- National Programme for Dairy Development
- Livestock Health and Disease Control Programme
- Animal Husbandry Infrastructure Development Fund

These schemes support entrepreneurship, training, technology transfer, breed improvement, and dairy infrastructure development

S. No.	Name of Office/Institute	Location	Main Function
1	Central Cattle Breeding Farm	Alamadhi, Tamil	Conservation and

	(CCBF)	Nadu	breeding of cattle
2	Central Cattle Breeding Farm (CCBF)	Suratgarh, Rajasthan	Cattle breeding and genetic improvement
3	Central Cattle Breeding Farm (CCBF)	Chiplima, Odisha	Production of superior breeding stock
4	Central Cattle Breeding Farm (CCBF)	Hessarghatta, Karnataka	Dairy cattle breeding and training
5	Central Frozen Semen Production & Training Institute (CFSPTI)	Hessarghatta, Karnataka	Frozen semen production and AI training
6	Central Poultry Development Organization (CPDO)	Chandigarh	Poultry development and training
7	Central Poultry Development Organization (CPDO)	Bhubaneswar, Odisha	Poultry breeding and extension
8	Central Poultry Development Organization (CPDO)	Mumbai, Maharashtra	Poultry seed production and development
9	Central Poultry Development Organization (CPDO)	Hessarghatta, Karnataka	Poultry training and breed improvement
10	Central Sheep Breeding Farm (CSBF)	Hisar, Haryana	Sheep breeding and wool production
11	Central Sheep Breeding Farm (CSBF)	Avikanagar, Rajasthan	Development of sheep breeds
12	Central Sheep & Wool Research Station	Kullu, Himachal Pradesh	Sheep production and wool research
13	Central Fodder Seed Production Farm	Hessarghatta, Karnataka	Production of quality fodder seeds
14	Regional Fodder Station	Hyderabad, Telangana	Fodder development and seed distribution
15	Regional Fodder Station	Srinagar, Jammu & Kashmir	Fodder research and supply
16	Animal Quarantine & Certification Service Station (AQCS)	Delhi	Animal quarantine and certification
17	Animal Quarantine & Certification Service Station (AQCS)	Mumbai, Maharashtra	Livestock import/export quarantine
18	Animal Quarantine & Certification Service Station (AQCS)	Chennai, Tamil Nadu	Disease prevention in traded animals
19	Animal Quarantine & Certification Service Station (AQCS)	Kolkata, West Bengal	Certification and quarantine services
20	Animal Quarantine & Certification Service Station (AQCS)	Bengaluru, Karnataka	Monitoring imported livestock health

21	Central Disease Diagnostic Laboratory (CDDL)	Bengaluru, Karnataka	Diagnosis of livestock diseases
22	Foot and Mouth Disease Control Programme Units	Various States	FMD surveillance and vaccination
23	National Dairy Development Related Field Units	Various States	Dairy development coordination
24	Regional Disease Diagnostic Laboratories	Different regions of India	Animal disease surveillance

7. CONCLUSION

Skill enhancement in the livestock and poultry sector plays a vital role in improving employability, productivity, and sustainable rural development. With the growing demand for milk, meat, eggs, and value-added animal products, trained and skilled manpower has become essential for efficient livestock management and modern poultry production. Technical knowledge in animal nutrition, breeding, healthcare, farm management, biosecurity, and marketing helps individuals perform effectively and increases their opportunities for self-employment and entrepreneurship.

Training programs, vocational education, and practical exposure enable farmers, students, and rural youth to adopt scientific methods and modern technologies in animal husbandry. Skill development also improves decision-making ability, resource management, and awareness about animal welfare and environmental sustainability. Furthermore, enhanced skills contribute to higher income generation, reduced unemployment, and better livelihood security in rural areas.

In conclusion, strengthening skills in the livestock and poultry sector is essential for creating employment opportunities, improving productivity, and supporting the growth of the agricultural economy. Continuous training, government support, and industry participation are necessary to build a skilled workforce capable of meeting future challenges in the livestock and poultry industry.

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Role of Aptitude Skills in Employability Readiness of Engineering Students in Indian Private Higher Education Institutions (HEIs): A Conceptual and Empirical Investigation

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ABSTRACT

Private engineering colleges in India are now under increasing pressure to train and churn out students who are ready to join the workforce instead of simply awarding degrees. In this study, we have focused on an important aspect of this problem – the role of certain aptitudes such as numerical ability, logical reasoning, verbal ability, data interpretation, and spatial awareness in the employability readiness of engineering students studying in three tiers of private Higher Educational Institutes in India. Three different tiers were categorized using accreditation and rankings where Tier-1 institutes refer to NAAC A+ and NIRF top 100, Tier-2 refers to NAAC A and NIRF top 200, and Tier-3 is for affiliated private colleges without any national ranking. Survey responses from 480 final year engineering students from 12 colleges, along with individual interviews of 30 senior recruiters from industries were obtained. One of the key findings includes a positive correlation between aptitude proficiency and campus placement rate ($r = 0.78$, $p < 0.001$), along with significant variations among tiers and large gaps between the perception and expectation of students and recruiters respectively.

Keywords: Aptitude skills, Employability readiness, Private engineering colleges, NAAC accreditation, Campus placement, Skill gap, Campus Recruitment Training (CRT), Indian HEIs

1. INTRODUCTION

Around 1.5 million engineers graduate from India annually. Surveys from industry keep reporting that majority of them are not job-ready. The figures vary from 60-80% according to sources such as NASSCOM (2023), AICTE (2022–23), and Aspiring Minds (2019), but the trend remains unchanged across sources. Why is that so? It is not only because of lack of knowledge in technical areas. Recruiters paint a different picture – students lack basic cognitive abilities which can be called aptitude, and this is usually what becomes the first obstacle in the recruitment process for candidates. Aptitude refers to five types of abilities – quantitative reasoning, logical reasoning, verbal comprehension, data interpretation, and spatial visualization. None of them is specific to a certain field, thus civil engineer and CS students face pretty much the same test. Tests like GATE,

CAT, banking exams – all aptitude-based tests. Private colleges currently constitute around 78 percent of engineering institutions in India (AICTE, 2023), and their dedication to the issue of aptitude varies greatly. Higher-ranked and more accredited institutions tend to Invest more here. State technical university-affiliated smaller colleges, lacking that national visibility. They can't, most likely, and the cost is borne by their students eventually, in front of a recruiter. Three research questions inform this paper:

1. How competent are final year engineering students in aptitude competencies, in terms of the three private HEIs described above?
2. To what degree does aptitude competency correlate with placement success and self-readiness?
3. What contextual and institutional variables influence such a correlation? They are not just academic inquiries, but directly related to accreditation norm setting by NAAC, model curriculum revisions by AICTE, and future implementation of NEP 2020

2. REVIEW OF LITERATURE

Literature on employability has been quite long-standing. Yorke (2004) has been one of the earlier sources, and his framework places cognitive ability and aptitude in the bottom tier, below critical thinking and professional judgment, among others. Harvey (2001) makes an important distinction, which is repeatedly cited to this day – while employment is the outcome determined by the labour market, employability is an attribute that a certain institution can develop in a graduate. It is useful to distinguish between these two concepts. In the specific case of the Indian engineering setting, I think it would be useful to refer to Gokuladas. The results of his 2011 study of campus recruitment at Indian software companies indicate that non-technical, general skills, similar in many ways to what we refer to as aptitude here, were as effective in predicting selection as technical knowledge was, even more so. An older paper of Gokuladas (2010) reports similar findings when working with a sample of engineers in general. There is also a more recent machine learning study from Nagpur University where campus placement was predicted using aptitude, communication, technical, and personality attributes, with aptitude alone explaining a lot of variance.

However, as a separate group on its own, private HEIs have not been studied very deeply. There has not been much research done that would analyze either percentages of placement or satisfaction rates of recruiters, categorized according to the accreditation level, which is done in this paper. Just one note needs to be made here: in a 2026 systematic review of the influence of NEP 2020 on higher education, employability has been highlighted as a constant aim of the policies mentioned in the documents, but there were no clear goals established for it nor any empirical evidence that these goals were met through NEP-aligned initiatives.

Spatial reasoning receives less emphasis than the other four categories in this research study, which is not an anomaly in existing literature, according to which Wai & Worrell (2016) view spatial ability as an often under-taught, yet policy-relevant, talent in STEM education in general due to constant neglect of geometry/visualization curriculum content in favor of other subjects.

Whether the It is not something that we have come across as being directly tested for the specific case of Indian engineering courses. And this is perhaps one of the reasons why spatial reasoning is considered separately as a sub-scale here rather than being incorporated within another construct. And finally, there is one more aspect that needs to be highlighted here. This is the fact that the CareerEDGE framework was revisited by Pace (2020) some years after it was originally introduced, and the outcome was largely positive- the CareerEDGE framework is still valid. However, the literature review does point out an important issue- that is that CareerEDGE framework was based on fairly well-funded UK institutions, and its five domain framework is not expected to fit easily into the highly heterogeneous environment of Indian private engineering courses.

Three major lacunae become evident from this. First, there are no established and NAAC/NIRF accredited national standards-based definitions for tiers in the private higher educational institutes sector, as almost all researches consider the entire private college sector a homogenous entity or draw the distinction between public/private sectors ignoring a lot of diversity inside. Second, there is no research question dedicated to the gap between students' self perception and recruiters' expectations although it is often discussed by placement cell professionals in their informal talks. Third, aptitude itself is very seldom considered as an individual concept in India, mostly being part of general skills discussion.

3. THEORETICAL FRAMEWORK AND CONCEPTUAL MODEL

There are three theoretical strands that weave throughout this framework. Human capital theory (Becker, 1964; Mincer, 1974), views education and training as investment-capabilities developed today to be used in the labour market tomorrow. According to human capital theory, aptitude is trainability of cognitive capabilities rather than something a person has or does not have. CareerEDGE model (Pool & Sewell, 2007) divides employability into five components which are interlinked: career development learning, experience, degree knowledge, generic skills and emotional intelligence, whereas aptitude belongs to generic skills. Institutional stratification theory (Trow, 1974; Marginson, 2016) accounts for something different. It explains why two people with almost identical abilities can end up at completely different ends of the educational spectrum depending on the university they attended.

Endowment of resources and accreditation play an important role in the above context, irrespective of personal abilities. Bringing these factors into consideration, the conceptual framework shown in Figure 1 regards aptitude as the mediator between institutional inputs and actual outputs. The NAAC grading acts as a moderator to the relationship; aptitude training quality and industrial exposure act as mediators; whereas campus placement percentage, preparedness score of recruiters, and perceived employability act as outputs. In addition, there is a feedback process whereby poor performance should ideally bring about changes in the curriculum.

Two concepts that need to be separated despite their overlap include latent aptitude vs trained output. Latent aptitude is largely set by the time students enter engineering colleges; the years of schooling before then had done most of the work in terms of setting this. Output is the aspect that

educational institutions have actual control over, which include structured training, practice modules, and teaching methods for aptitude included within normal education curriculums. Heckman and Kautz (2012), in writing about skill malleability in early adulthood, corroborate that this latter concept indeed reacts to intervention - precisely the basis of the recommendations to follow.

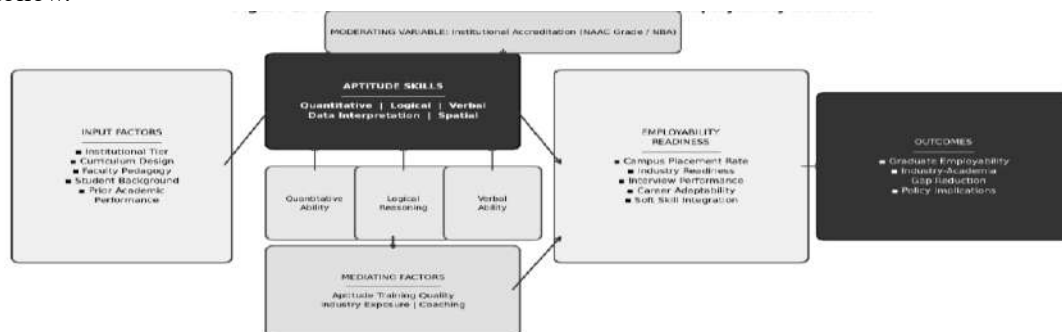


Figure 1: Conceptual Framework

4. RESEARCH METHODOLOGY

4.1 Research Design

The approach was a combination of the convergent mixed method (Creswell & Plano Clark, 2018), whereby the survey and interviews were conducted concurrently before synthesis in analysis. The surveys provide statistics for the relationship between aptitude and placement. The use of the quantifiable approach enables us to study the relationship between aptitude and placement statistically while the interviews give a qualitative perspective such as recruiter's rationale, institutional environment, and the kind of information that can be generated through interviews only.

4.2 Institutional Tier Classification

One of the key methodological decisions we make in our analysis: classification based on national accreditation standards rather than the commonly used binary division into public and private institutions. Three categories:

- Category 1: Private Universities (NAAC A+, NIRF Top 100 Engineering). Overall good performance in terms of facilities, faculty qualifications, and research productivity.
- Category 2: Private Universities (NAAC A, NIRF Top 200 Engineering). Middle level: quite good facilities for placement and industry links, but not in the category 1.
- Category 3: Private colleges under state technical universities, not ranked in the nation-wide ranking. This is the largest category in number: most of the Indian engineering education is private and falls here.

4.3 Sample and Sampling Strategy

Stratified purposive sampling: 160 final year students from each stratum, totaling 480 students. Further stratification within each stratum based on the branch (Computer Science, Mechanical, Civil, Electrical & Electronics), proportionate to the distribution across the country. 12

organizations located in Punjab, UP, NCR and Uttarakhand states. In addition to the questionnaire among students, 30 senior technical and recruitment personnel conducted semi structured interviews.

4.4 Instruments

The Aptitude Proficiency Scale (APS) instrument was constructed and piloted using five sub-scales, namely quantitative aptitude (20 questions), logical reasoning (18), verbal ability (15), data analysis skills (12), and spatial reasoning (10). The levels of difficulty of the questions were set against the AMCAT and TCS NQT exam styles, which means we intended to align with real-life experiences of students in recruitment, and not an academically inclined version of these tests. The reliability measures were promising, with overall Cronbach's Alpha at 0.91, while for sub-scales between 0.82 (spatial reasoning) and 0.89 (quantitative ability). In addition, another measure was used - the Employability Readiness Inventory (ERI).

4.5 Data Analysis

The quantitative analyses were conducted using SPSS 26, which included descriptive statistics across domains and levels of education, one-way ANOVA with Tukey's HSD for the inter-level comparisons, Pearson correlations and stepwise regression for aptitude vs placement association. Effect sizes (Cohen's d, eta-squared) are provided where appropriate, i.e., for all statistically significant findings. The interview material was analyzed thematically using the six-phased Braun & Clarke (2006) approach with the help of NVivo 12 software. Comparing the results of the two helped to improve their interpretation considerably.

5. FINDINGS AND DISCUSSION

5.1 Aptitude Proficiency Across Institutional Tiers

There is a wide disparity in composite scores and it is clear in statistical terms as well ($F(2,477) = 152.4, p < 0.001, \eta^2 = 0.39$). Tier-1: 70.2% (SD = 8.1). Tier-2: 52.5% (SD = 9.3). Tier-3: 35.6% (SD = 8.7). All the differences between two pairs were significant with Tukey HSD test ($p < 0.001$). The gap from Tier-1 to Tier-3, on an average of all the five categories, is more than 34%.

Table 1: Descriptive Statistics – Aptitude Proficiency and Campus Placement Rate by Institutional Tier

Institutional Tier	QA (%)	LR (%)	VA (%)	Placement (%)	n
Tier-1: NAAC A+, NIRF Top 100	74.2	70.1	67.3	85.4	160
Tier-2: NAAC A, NIRF Top 200	55.8	52.0	49.7	58.2	160
Tier-3: Affiliated Pvt. Colleges	37.4	34.6	32.9	36.8	160
Overall Sample	55.8	52.2	50.0	60.1	480

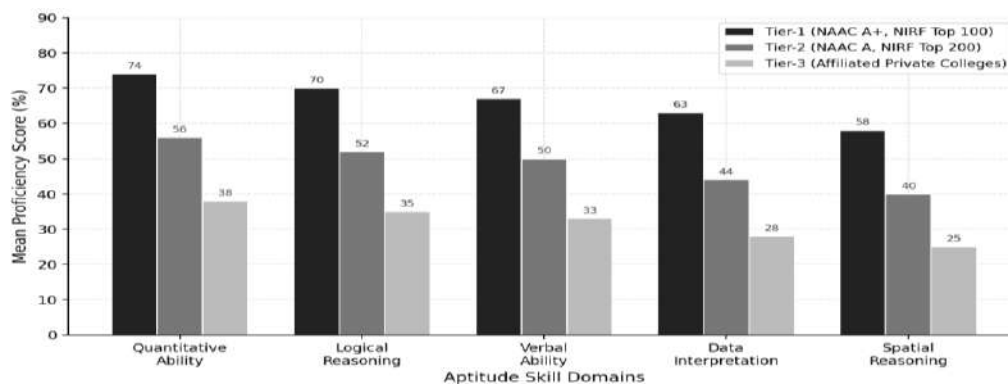


Figure 2: Mean Aptitude Proficiency Scores by Domain and Institutional Tier (N = 480)

Spatial ability had the lowest score in all three tiers and was predictable by the general science literature (Wai & Worrell, 2016). This is indicative of the relatively less space allocated to geometry and visualization in engineering course content. The Tier 1 advantage of quantitative ability and logical reasoning was the highest among all other domains, which is consistent with the training efforts of these universities.

5.2 Employability Readiness Gap: Student Perception Versus Industry Expectation

Below is an example of a result that cannot be overlooked: the students and recruiters have a disagreement on the readiness level of the former and this disagreement happens on all the six dimensions. The following diagram shows the gap analysis in the form of a horizontal bar chart and highlights the area where students greatly underestimate the employers' requirements.

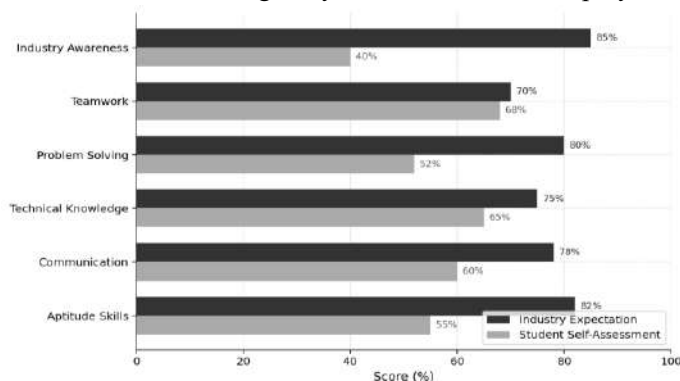


Figure 3: Employability Readiness Gap – Industry Expectation versus Student Self-Assessment

A large gap of 27% exists for aptitude, which is highly problematic as aptitude test is generally the first stage of recruitment process. The recruiters also mentioned that many of the tier-3 students fail to qualify even this stage due to lack of fundamentals and inadequate practice. But a more worrying aspect is that many of the students themselves are unaware of their inadequacies.

5.3 Aptitude Proficiency as a Predictor of Campus Placement

There is a strong relationship between composite aptitude and placement: $r = 0.78$, $p < 0.001$. As seen from figure 3 below, there is rather clear clustering; data points for Tier-1 lie more to the top right, data points for Tier-3 lie more to the bottom left, but the trend line remains valid within each cluster.

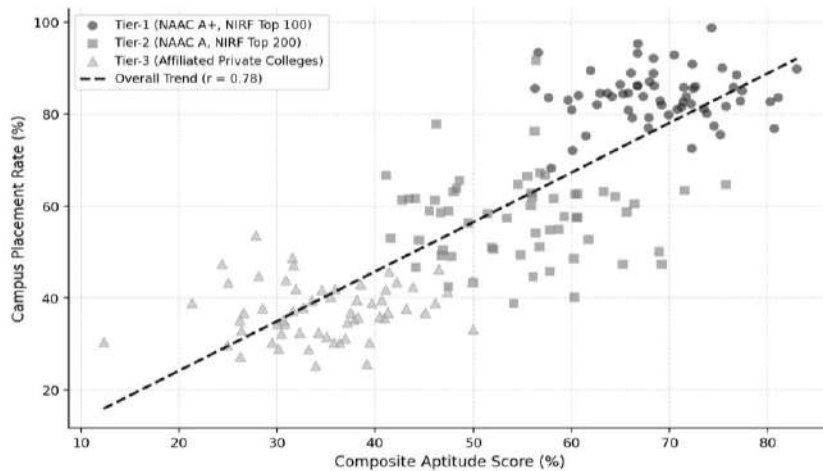


Figure 4: Composite Aptitude Score versus Campus Placement Rate by Institutional Tier ($r = 0.78$, $p < 0.001$)

The stepwise regression identified quantitative skills ($\beta = 0.41$, $p < 0.001$) and logical reasoning skills ($\beta = 0.29$, $p < 0.001$) as the best predictors that explain 68% of variation with tier considered. When tier is controlled, the direct coefficient of aptitude vs placement drops from 0.78 to 0.61. Even taking into account the tier of a college, aptitude is a key factor.

One more thing to note is access- around 92% of Tier-1 students have adequate aptitude development, while in Tier-2 the percentage is 61% and 31% for Tier-3. Thus, besides the gap in skills, there is a significant lack of opportunities for many students.

6. DISCUSSION

Findings

The results reveal that aptitude is the essential component of placement but most private engineering colleges in India have failed to develop aptitude appropriately. Aptitude and Placement have a correlation coefficient of 0.78, indicating that aptitude skills cannot be considered a mere requirement of Human Resources, but rather it works as a proxy measure of cognitive preparedness of a candidate.

There is a significant difference (34+ points) between Tier-I and Tier-II colleges, and this poses a question of inequality in opportunities. While NAAC accreditation has been criticized from a methodology perspective (Varghese, 2013), it is understandable that the pattern of results implies that NAAC accreditation may be correlated at least roughly with the capability of a college to build employability infrastructure. It seems that there are sufficient grounds to incorporate employability into NAAC assessment criteria.

Figure 3 reveals an important gap that Indian studies have failed to take note of – miscalibration of metacognition as a distinct challenge in itself. The other problem is the fact that students tend to overestimate their readiness level and therefore feel no urgency in becoming better. In order to deal with this problem, colleges should subject students to regular assessments and provide feedback right from the start, and not just at the time of placements.

Moderating role of institutional tier ($\eta^2 = 0.39$) indicates the extent to which contextual factors influence the return on a certain level of aptitude. Two students with the same aptitude score can end up with different placement results based on the quality of industry relations, placement cell and recruitment network maintained by their college. This finding seems to be generally consistent with the resource-based perspective on organizational performance (Barney, 1991; Teece, 2007), only the context being higher educational institutions rather than businesses.

7. RECOMMENDATIONS

AICTE & UGC should integrate aptitude and thinking skills as one of the disciplines within the first two years along with credit weightages and exams like those conducted by companies. The concept of Aptitude Score can be added in the ranking list so that it is taken seriously by the colleges. In evaluating institutions, NAAC may take into consideration the aptitude of students and pay special attention to Tier-3 colleges.

In the context of the college level, the colleges must have Employment Centres where they must involve the students right from the beginning of their course and conduct proper evaluation according to placement exam formats such as AMCAT or TCS NQT. Also, teachers can include aptitude questions in regular subjects (mathematics, logical, reasoning etc.). Furthermore, industry should reach out to the students from the second or third year onwards instead of just the placement period.

8. CONCLUSION

It is evident from the research that the aptitude, i.e., basic cognitive skills are crucial in placement and securing jobs. However, engineering students enrolled in private colleges do not receive proper training in the aspect. The findings prove that students who possess good aptitude have a good record of placements; there is a large gap between top-ranked and second ranked colleges, and there exists a self-perception gap. The issue needs an intervention as it is not going to resolve automatically.

In contrast to classification of colleges into government and private, this research relies upon NAAC grades and NIRF rankings, giving a more precise way of comparing the institutions. The framework developed in this research also provides an actual platform for improvement of curriculum and skillset of college students. Future studies must follow the development of students' aptitudes through the years of studying, test efficient ways of training and pay more attention to colleges in smaller towns and rural areas where the problem can be even worse.

Indian private engineering colleges continue to emerge at a high speed. Proper aptitude development in students is no longer solely the task of colleges but is crucial for the future of the country.

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NEP 2020 and Outcome-Based Education in India: Transforming Higher Education for Lifelong Learning

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ABSTRACT

The National Education Policy 2020 (NEP 2020) is an extensive and revolutionary document intended to restructure the Indian educational system across all levels, particularly focusing on higher education. The core principle of NEP 2020 is to integrate the concept of Outcome Based Education (OBE), which is essentially a methodology where the curriculum, pedagogy and the evaluation procedures are structured around specific learning outcomes. This paper aims at analyzing the theoretical principles of NEP 2020 and OBE, identifying how the two are compatible with each other and highlighting how the combination of the two can revolutionize Indian higher education towards a system of lifelong learning. Through a critical examination of more than twenty recent academic articles on the topic, the paper focuses on analyzing the challenges, enablers, and institutional measures required for a successful implementation of OBE in India. The paper also considers the extent to which NEP 2020's interdisciplinary, flexible, and student-centered approach is compatible with international practice of OBE.

Keywords: NEP 2020, Outcome-Based Education, Higher Education, Lifelong Learning, Curriculum Reform, India

1. INTRODUCTION

The Indian higher education system is at a critical stage today. With more than 1,000 universities and over 40,000 colleges catering to around 37 million students, the education system of India is one of the largest in the world (AISHE, 2022). However, issues regarding the employability of graduates, the quality of learning, and their adherence to international education benchmarks have been a consistent issue in the country's education system. The National Education Policy 2020 (NEP 2020), which has been framed by the Government of India, is the major revamping of the education policy in the country after almost three decades from the previous National Policy on Education 1986.

Outcome-based education (OBE) is one of the pillars of such a transformation, which revolves around defining, measuring, and assuring particular learning outcomes at the level of both program and individual courses. OBE is a pedagogic theory that was proposed by William Spady in the 1990s and since then, OBE has been embraced by leading institutions of higher

education in countries like the US, Australia, South Africa, and even some Asian countries. In India, NBA and NAAC have been promoting OBE through accreditation standards, and now NEP 2020 has further made this shift official.

It is not accidental that NEP 2020 and OBE have aligned themselves with one another because of similar principles of learner autonomy, competency building, continuous improvement, and social relevance. As part of NEP 2020, the vision of creating critical thinkers, problem solvers, ethical individuals, and lifelong learners is stated explicitly. However, OBE offers an approach which can help to materialize the above-stated objectives of NEP 2020.

In this research paper, the integration of NEP 2020 and OBE in order to bring about a change in higher education in India is discussed. In order to do so, the theoretical background of NEP 2020 and OBE, a review of existing literature, and the analysis of structural arrangements necessary to implement OBE within NEP 2020 are discussed. The current research uses a qualitative and theoretical approach.

2. THEORETICAL FRAMEWORK

2.1 Outcome-Based Education: Origins and Principles

The OBE approach is based on the philosophy that all educational decisions have to be influenced by the results that the students are supposed to show after completing their educational process. According to Spady (1994), 'organizing and operating an education system so that it focuses and organizes everything the system does around what is essential for all students to be able to do successfully at the end of their learning experience' is OBE. Thus, performance of the student comes first before the institutional effort.

OBE is based on four core principles formulated by Spady, namely focus clarity, designing backward from outcomes, expectations for excellence from all students, and opportunities to exhibit competence among students. Such principles necessitate the need for institutions to outline graduate attributes, programme educational objectives (PEOs), programme outcomes (POs), and course outcomes (COs). This would entail the systematic alignment of these objectives and outcomes to curriculum, teaching methodologies, and assessment tools. The Blooms' Taxonomy of Educational Objectives (Bloom et al., 1956; revised by Anderson & Krathwohl, 2001) is a framework for cognitive hierarchy of learning domains from remembering and understanding (lower order skills) to evaluation and creation (higher order skills).

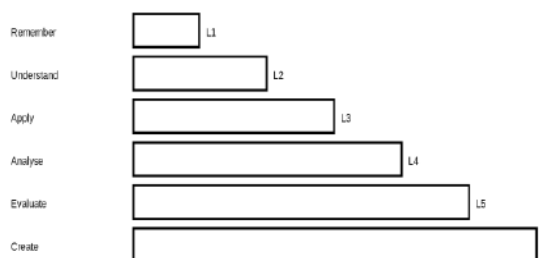


Figure 1: Bloom's Taxonomy Levels Applied in OBE Course Outcomes

Under the Indian accreditation process, the Outcome-Based Accreditation (OBA) process by the NBA demands that universities achieve Programme Outcomes (POs) that meet the international graduate attributes criteria and show quality assurance using the attainment data. The application of OBE in India predated NEP 2020 but has now received more momentum following the adoption of the NEP.

2.2 NEP 2020: Vision and Architecture

NEP 2020 is a policy framework that aims at making India a knowledge superpower by the year 2040. Some of the objectives of NEP 2020 include attainment of GER of 50% in higher education institutions by the year 2035, multidisciplinary education by means of liberal arts and sciences and provision of equitable quality education. It calls for implementation of flexible Academic Bank of Credits (ABC), multiple entries/exit points for undergraduate education programs, integrated teacher education program and new regulatory structure under HECI.

The philosophical base of the NEP 2020 is inspired by the Indian age-old philosophy of gurukul learning system and has engaged with the current discussion on education around the globe. The document highlights the importance of literacy and numeracy, critical and creative thinking, ethics, multilingualism, and digital literacy. This is in consonance with the set of qualities described for graduates in OBE systems around the world.

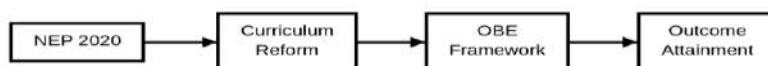


Figure 2: NEP 2020 to OBE Implementation Flow

2.3 Lifelong Learning as a Unifying Concept

The concept of lifelong learning as per the European Commission (2001) and UNESCO Institute for Lifelong Learning (2014) means 'all purposeful learning activities which are undertaken continuously in order to enhance knowledge, skills, and competence.' Both the NEP 2020 and OBE advocate the idea of creating autonomous learners through education so that they can keep learning all through their lives. Adult education, skills training, and vocational education have been specifically mentioned as a part of the lifelong learning framework under NEP 2020 whereas the focus on higher-level thinking and reflective skills in OBE makes its students ready for lifelong learning.

3. LITERATURE REVIEW

A systematic analysis of the scholarly literature shows an increasing number of studies that have been carried out about the interplay between NEP 2020, OBE, and reforms within higher education in India and other developing countries. The following categorizes the literature.

3.1 OBE Implementation and Institutional Readiness

Sharma and Jain (2021) have performed an extensive analysis of OBE adoption in various engineering institutes of India, and they discovered that while the awareness about OBE concepts among the faculty is rather high, the infrastructure of the institutions for assessment of outcomes'

attainment is insufficient. The lack of faculty training, poor course outcome mapping, and inadequate methods for attainment assessment are considered as the main obstacles to the successful adoption of OBE.

According to Rao & Lakshmi (2022), in the context of OBE implementation in autonomous colleges affiliated to state universities, the lack of standardized rubrics for the achievement of desired outcomes and lack of commitment of faculties were considered major challenges. Rao & Lakshmi (2022) suggested the formation of OBE institutional committees, faculty development programs and digital systems for managing outcomes. Rao & Lakshmi's study correlates well with the theories of constructive alignment of Biggs (2003).

The impact of accreditation agencies such as NAAC and NBA on the adoption of OBE was studied by Gupta et al. (2022). The results of their research showed that OBE implementation driven by accreditation process is more compliant in nature rather than focused on learning, leading to heavy documentation procedures and not better student learning.

3.2 NEP 2020 and Curriculum Reform

The implications of NEP 2020 on the development of the undergraduate curriculum have been analyzed by Chandra & Mehta (2021). They observed that the multidisciplinary prescribed in NEP 2020, even though seemingly progressive, would require a radical restructuring of the disciplinary silos existing within Indian universities. The study outlined a curriculum design framework that is based on competency mapping, where the core of disciplinary knowledge is supplemented by transdisciplinary skills, such as communication, collaboration, and information technology skills.

Singh (2021) has discussed the implications of the multiple entry/exit provisions of NEP 2020 in light of OBE. According to the author, the credit-based OBE framework as outlined in the provision of Academic Bank of Credits would allow recognizing prior learning and provide multiple pathways for higher education attainment. However, he warns that effective implementation of the credit-based system requires proper outcome mapping at entry and exit points, which is still technically challenging.

Patel and Desai (2022) investigated the incorporation of vocational education into the NEP 2020 model and noted that OBE is a suitable way to match the skills required in vocational subjects with those needed in industries. In their study, they pointed out the significance of employer participation in determining program outcomes in vocational courses, which is common in Australia and New Zealand TAFE, but not very established in India.

3.3 Assessment and Evaluation in OBE

Kumar and Yadav (2023) in their assessment practices at Indian universities that implement OBE reported an overwhelming preference for summative assessment against formative assessment. According to the authors, the holistic and ongoing nature of the assessment in NEP 2020 requires a switch to the use of portfolios, reflective journals, projects, and peer assessments that measure the higher-level achievements. Kumar and Yadav's suggestions correlate well with other international research concerning the assessment in the framework of OBE (Huba & Freed, 2000).

Agarwal (2022) assessed the impact of rubric use in OBE-aligned assessment practice and showed that well-developed rubrics greatly increase the reliability of achievement measurement in outcome-oriented assessment. Agarwal also pointed out that faculty members at Indian universities do not have enough knowledge about how to develop rubrics for effective application in OBE practice.

3.4 Faculty Development and Pedagogical Transformation

Verma and Sinha (2021) analyzed attitudes of faculty towards OBE in a study conducted among central and state universities in India. According to the qualitative analysis carried out by Verma and Sinha (2021), the attitudes of faculty towards OBE ranged from acceptance to skepticism. The faculty in engineering and other professionally oriented fields were generally supportive due to the familiar notion of accreditation, while those from the humanities and social sciences disciplines had reservations regarding the reductionism involved in the process of learning.

Mishra and Pandey (2022) analyzed the role played by technology in the process of implementing OBE under NEP 2020. The use of Learning Management Systems (LMS), e-portfolios, and dashboard analytics for monitoring the achievement of COs and POs was analyzed. The study showed that technology could effectively reduce the burden of administrative work in OBE documentation and also provide real-time data for continuous improvement.

3.5 Equity, Access, and Lifelong Learning

The effects of NEP 2020 on the issue of educational equity among first-generation learners, learners from rural areas, and socio-economically disadvantaged learners have been discussed by Bhatia and Nair (2022). The authors state that OBE approach based on the demonstration of competency rather than time-bound teaching is more flexible towards non-conventional learners but requires support systems such as academic counselling, mentoring, and remedial teaching to ensure equity of outcomes.

The applicability of open and distance learning for lifelong learning in the context of NEP 2020 was discussed by Saxena and Trivedi (2023). The authors note that the OBE framework is especially suited for online and blended learning environments because it relies on achievements rather than mode of learning and learning environment. The study draws attention to the potential of NDEAR framework and online platforms such as SWAYAM and DIKSHA.

According to Joshi and Raman (2022), there exists an interconnection between NEP 2020 and the Sustainable Development Goals (SDGs) of India, especially SDG 4 which concerns quality education. As per their study, the use of OBE ensures a process through which the progress towards the goals of the SDGs can be measured and reported. The researchers present the OBE not only as a pedagogical strategy but also as a governance approach.

3.6 Comparative and International Perspectives

Mitra (2021) carried out a comparative study of the implementation of OBE in India, Australia, and Malaysia, and discovered some major variations in terms of institutional independence,

faculty capability, and legislative environment in all these cases. Mitra pointed out that the fragmented nature of the Indian higher education system, which is characterized by different affiliating universities and various institutional models, necessitates a tailored implementation strategy of OBE in India.

Reddy and Nambiar (2022) have considered the implications of the Washington Accord, an internationally renowned agreement for engineering programs' accreditation, on OBE's introduction in India. These authors have discovered that Indian educational establishments seeking international accreditation have become early adopters of OBE; however, sometimes the issue of accreditation takes precedence over pedagogical reforms. This article emphasizes the need for OBE implementation through learning-centred strategies rather than ranking-centred strategies.

OBE has also been explored in the domain of medical education by Krishnan and Subramaniam (2023) in India, where competency-based medical education (CBME) is mandatory as per the National Medical Commission (NMC). The implications drawn from CBME implementation in medical education in India can be extremely beneficial in implementing OBE in other subjects.

According to Chatterjee (2022), who reviewed international literature on OBE and lifelong learning, the successful OBE practices have three main characteristics – the leadership commitment from the institutions involved, faculty responsibility in designing outcomes, and feedback processes through students, alumni, and employers. Chatterjee suggested that such engagement practices should be made mandatory in Indian universities through NEP 2020 compliance frameworks.

3.7 Challenges and Resistance

Nair and Pillai (2021) discussed the implementation issues in OBE in technical institutions and pointed out the following to be the main obstacles faced during the process: lack of proper faculty training (78% of participants mentioned it as an issue), lack of institutional data systems to monitor outcomes (65%), and lack of academic leadership support (54%). This quantitative research offers a helpful map of the institutional weaknesses which need to be overcome in order to implement NEP 2020 successfully.

Tiwari and Bhatt (2023) conducted research on the faculty work load associated with the implementation of OBE and found out that extra workload connected with outcome mapping, creation of a rubric, and attainment calculation was not reflected in performance appraisal process at all. The authors recommend reconsideration of faculty work load norms including OBE-related activities.

4. STRUCTURAL ALIGNMENT: OBE AND NEP 2020

4.1 The OBE Implementation Framework

The adoption of the OBE approach in the higher education system of India under NEP 2020 entails a hierarchy of outcomes that flows from institutional vision to the individual learning outcomes

of each course. The highest level is represented by Graduate Attributes (GAs) that embody the general abilities that should be possessed by all graduates of the institution. The graduate attributes include disciplinary knowledge, problem solving, teamwork, communication, ethics, environment, and lifelong learning. NEP 2020's vision of holistic and multidisciplinary education aligns with these graduate attributes.

Below the Graduate Attributes are the Programme Educational Objectives (PEOs) that outline the achievements that graduates are expected to make professionally and personally three to five years after graduation. Programme Outcomes (POs) indicate the specific knowledge, skills, and attitudes that students should exhibit on the completion of the programme. The Course Outcomes (COs) refer to the specific competences that the students attain after successfully completing the courses.

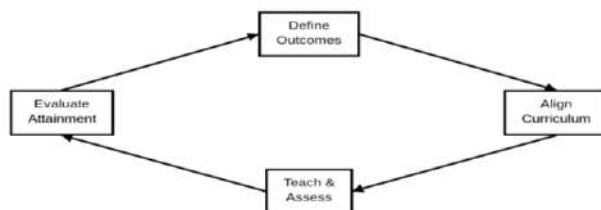


Figure 3: OBE Continuous Improvement Cycle

4.2 Curriculum Mapping and Constructive Alignment

Amongst other structural benefits of the OBE approach in implementing NEP 2020 is the practice of curriculum mapping, which essentially entails capturing the links between the learning outcomes of each course and the learning outcomes of the whole programme. Through use of a CO-PO mapping matrix, the institution can ensure that all the program outcomes have been adequately captured in the curriculum and where gaps exist in the coverage of some program outcomes. This is referred to as constructive alignment (Biggs, 2003). Here, teaching and assessment practices must be developed to help students meet their outcomes.

With NEP 2020, the practice of curriculum mapping becomes even more challenging because there will be several disciplines within a single program. The four-year undergraduate program where there is a major, minor and elective courses calls for an OBE structure that takes into consideration interdisciplinary outcome attainment whereby one can achieve some program outcomes through minor courses from another discipline.

4.3 Assessment and Attainment Measurement

OBE is characterized by the use of direct and indirect measures for assessing the achievement of outcomes. Direct measures consist of students' performance in exams, assignments, projects, and presentations that are developed specifically for the purpose of measuring certain outcomes. Indirect measures involve student surveys, surveys from alumni, employers, and exit interviews. Taken together, they paint a clear picture of how much students achieve their outcomes.

The continuous and comprehensive assessment, together with holistic and multi-dimensional assessment in NEP 2020 is consistent with the multi-modal nature of assessment in OBE. The provision for semester end exams, internal assessment and skill-based assessment in NEP 2020

provides the structure within which OBE assessment can be done. The Academic Bank of Credits helps in OBE assessment by giving credits based on competencies rather than the duration of instruction.

5. STAKEHOLDER ROLES IN NEP-OBE INTEGRATION

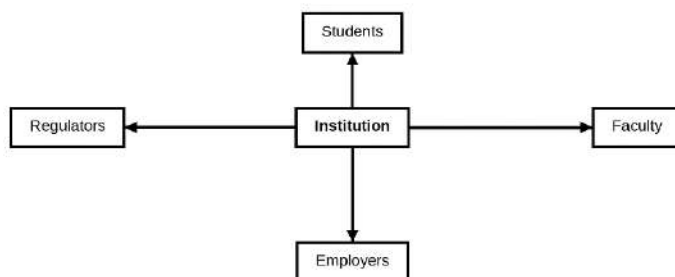


Figure 4: Key Stakeholders in OBE Implementation under NEP 2020

In order to ensure successful adoption of NEP 2020 and OBE there is need for a coordinated effort by various stakeholders who have different roles to play. The institution has the responsibility of formulating OBE policy, training the faculty, setting up the data collection system and communicating with regulatory bodies. The faculty is an important part of OBE since they develop outcomes of courses, align assessments and collect the data of student attainment. Students are active players in the OBE process by ensuring that they engage with outcomes and give feedback on their learning experiences.

Employers/industry partners have an increasingly growing role to play in NEP 2020's vision of industry-academia partnership. Input from employers and industry partners is crucial for formulation of programme educational objectives that meet the needs of the existing and future workforce. NAAC, NBA, UGC etc. are regulatory bodies that offer the accreditation standards for formulation of OBE systems by the institution. Compatibility of regulatory standards with NEP 2020 is an important enabling condition for OBE adoption.

6. COMPARATIVE FRAMEWORK: NEP 2020 GOALS AND OBE MECHANISMS

Table 1: Alignment of NEP 2020 Goals with OBE Mechanisms

NEP 2020 Goal	OBE Mechanism	Expected Outcome
Holistic development	Graduate Attributes	Well-rounded graduates
Multidisciplinary learning	CO-PO Matrix across disciplines	Integrated competencies
Flexible curriculum	Credit-based OBE, ABC	Personalised learning paths
Continuous assessment	Formative + Summative OBE tools	Reliable attainment data
Lifelong learning disposition	Higher-order learning outcomes	Self-directed learners

Industry alignment	PEO based on employer feedback	Employable graduates
Equity and inclusion	Support for diverse learners in OBE	Equitable attainment

7. CHALLENGES IN IMPLEMENTATION

7.1 Institutional and Systemic Barriers

There exist certain institutional hurdles that need to be overcome for the successful implementation of OBE in the context of NEP 2020. India's higher education system consists of a highly diverse set of institutions, including world-renowned central universities and institutes of national importance to small and modest colleges located in rural areas. Due to such high diversity, the process of OBE implementation becomes complicated, since all educational institutions have to follow one framework.

Another problem lies with the affiliating university model, according to which there are many colleges affiliated with one university and working on its framework of studies. Under this model, the university decides about syllabus, exams, and norms of assessment, and thus, colleges have no freedom to design courses' outcomes. NEP 2020 acknowledges this issue and suggests giving more autonomy to colleges over time; however, this change will require time and effort.

7.2 Faculty Capacity and Pedagogical Resistance

It could well be said that faculty preparedness is the key determinant of success of OBE. Creating course outcomes and then aligning assessment with those outcomes as well as determining levels of achievement is highly specialized task that many Indian faculties lack experience in due to lack of graduate/post-graduate level training in these areas. Faculty development programs in OBE though becoming more common through NRCVEE as well as various UGC initiatives are still inadequate in quantity.

Besides the technical difficulty of being prepared to conduct an OBE program, the other barrier is resistance of faculty based on pedagogical belief systems. There are some faculties, especially from Humanities/Social Sciences departments who question if the complexity and richness of their subjects can be captured in measurable outcomes. This is part of the larger philosophical struggle that is inherent in the idea of OBE.

7.3 Assessment Overload and Documentation Burden

The demand on the faculty that results from the need for systematic measurement of outcome attainment in OBE is quite heavy. Data regarding the attainment of outcomes needs to be collected, analyzed, and reported for different classes within different semesters, which could be very difficult in institutions where no data management system exists. When OBE is practiced merely for documentation purposes, mainly because of accreditation pressures, OBE turns out to be only performative.

7.4 Digital Infrastructure and Equity

The technological approach to education in NEP 2020 and the possibility of digital tracking of outcomes in OBE both assume certain technological capabilities which may not be present throughout India at this point. Lack of connectivity in the rural and semi-urban regions, lack of computer equipment in educational institutions, and poor digital awareness among teachers and students are some of the obstacles to implementing OBE through technology in NEP 2020.

8. RECOMMENDATIONS FOR POLICY AND PRACTICE

In light of the above analysis and literature review, the following suggestions are made in order to ensure the successful adoption of NEP 2020 and OBE within Indian higher education.

Firstly, there must be leadership within institutions which embraces OBE not as an academic exercise but as a commitment. The leaders of institutions such as vice chancellors, principals, deans, heads of departments, among others must come up with a vision regarding OBE that will link curriculum design, teaching, evaluation, and student support with specific learning outcomes. If this is not done, then OBE is likely to become just another documentation exercise.

Secondly, faculty training must be systematic, sustained, and discipline specific. One-day workshop and orientation programs cannot equip faculty members with the requisite knowledge needed to implement OBE. There is need for universities and colleges to devise a multi-level faculty training program.

Third, technology must be used to alleviate the burden of administration for OBE. Learning management systems that include outcome mapping, data collection for attainment, and continuous improvement practices must be invested in or developed. The National Development, Evaluation, Assessment and Reporting (NDEAR) framework suggested by NEP 2020 offers the national architecture for such systems to be created and shared.

Fourth, regulatory frameworks should change to value pedagogical reform over paperwork. NAAC and NBA must create assessment instruments that focus on quality OBE implementation—namely on improved learning outcomes and effective continuous improvement practices—instead of the completeness of documentation.

Finally, stakeholder engagement should become a part of institutional academic governance. Structures for structured and regular engagement with employers, alumni, students, and other community members in outcome definition and evaluation must be put in place as a permanent component of institutional governance. This would ensure relevance of programme outcomes to current societal and professional needs.

Sixth, educational equity requires special consideration in OBE implementation. Institutions that cater for marginalized learners and those who belong to the first generation should develop support systems such as mentoring, counseling, and tutoring that are related to learning outcomes to achieve educational equity among different categories of learners.

9. DISCUSSION

The theoretical and empirical analysis contained herein suggests that there is an immensely significant and productive alignment between the vision for education embodied in NEP 2020 and the philosophy and practices of OBE. Commonalities include focus on being learner-centered, outcomes-oriented, committed to continuous improvement and fostering dispositions toward lifelong learning. NEP 2020 furnishes the policy framework and mandate for transformation, whereas OBE furnishes the pedagogical methodology to effect such transformation in the classroom, the curriculum, and the examination hall.

However, the literature suggests that this alignment is one of aspiration rather than achievement at the majority of higher education institutions in India. The chasm between policy intention and institutional practice is wide and bridging it takes effort, investment and change. The issues discussed above are not particular to the Indian context, but are intensified by the scale of Indian higher education institutions.

It is important to mention that the concept of lifelong learning serves as an excellent integrative framework to see what the ultimate purpose of NEP 2020 and OBE is. As the objective of education is not simply to prepare graduates who have specific competence at a particular moment but to develop people who will be able to learn continuously and adapt themselves throughout life, it becomes obvious that NEP 2020 and OBE need to be analyzed not just in relation to graduate achievement but with regard to the development of such dispositions and self-regulation skills.

Thus, a more comprehensive view of OBE outcomes is required. Besides the knowledge and skills that students acquire in their disciplines, there are such elements as metacognitive awareness, reflective practice, collaborative disposition, and self-directed learning which need to be considered as well. In its turn, NEP 2020 adds new dimensions of outcome design such as Indian Knowledge Systems, ethics, and values which are far beyond Bloom's taxonomy.

10. CONCLUSION

In this paper, it is contended that NEP 2020 and OBE present complementary and reinforcing approaches to transforming higher education in India. While NEP 2020 articulates a far-reaching vision of what Indian higher education needs to become—i.e., flexible, interdisciplinary, inclusive, technology-enabled, and lifelong learning-oriented—the OBE framework offers the pedagogical foundation for achieving this vision—i.e., a rigorous process of identifying, aligning, measuring, and constantly refining student learning outcomes.

From the literature reviewed in this paper, it becomes evident that the adoption of the OBE framework in India has come a long way in the last decade due to the pressure from accreditation bodies and the hard work of dedicated teachers and administrators. NEP 2020 is likely to help in making further strides in adopting OBE principles through a conducive policy environment, mandatory curriculum reform, and institutional autonomy.

First and foremost, however, the inclusion of NEP 2020 into OBE needs to rest on the premise of genuine commitment to the process of learning on the part of students – not as an end goal in itself

but rather as a foundation for lifelong learning. Should this commitment be fulfilled by Indian higher education institutions, NEP 2020 goals will not just be reached but truly exceeded.

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Graduate Employability in Digital Era : Post Pandemic Impact of Hybrid Learning

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ABSTRACT

In the rapid pace of the learning environment digital transformation has significantly completely changed the method by which to learn, communicate and especially prepare for professional careers. The transformation of hybrid learning of Tradition classroom methods with online learning has become one of the most widely adopted educational approaches in the current scenario of post pandemic. This transformation not only changed the teaching and learning method but also changed the employability related competencies among students.

This research report examines the impact of hybrid learning on graduate employability and skill acquisition in higher educational institutions. The study especially focused on how this hybrid learning contributes to the development of digital literacy, communication, skills, adaptability, collaboration, self directed and workplace readiness among professional students. This study also analyzes the students perception on effectiveness of hybrid learning for the students who are preparing for future employment opportunities.

This study includes descriptive and quantitative research on primary data which is being collected through questionnaires that has been distributed among undergraduate and post graduate professionals of different colleges of NCR region and Secondary data has been collected from different sources like research papers, journals, books, literature and few reports also.

The finding of this research positively indicates that hybrid learning influences employability skills by enhancing students' technological awareness, communication abilities, virtual collaborations experiences and independent and not limited capabilities. Not only the positive but this study also have some challenges associated with hybrid learning that includes lack of practical exposure, face to face communication, students engagement and connectivity.

This paper emphasizes that universities must restructure curriculum to align with evolving industry expectations and workforce requirements. Greater focus should be on experiential learning, digital competencies, industry collaboration and employability-oriented strategy. The study contributes to the growing discussion on the future of higher educational and workforce preparedness in the digital era.

1. INTRODUCTION

The education system around the globe is undergoing a major transformation due to rapid advancement in technology and changing workforce environment requirements. The integration of digital technology into College and university level has changed the traditional classroom teaching methods and introduce the new and 21st century teaching approach among these development, hybrid learning has emerged as one of the most effective and flexible educational model in modern academic environment.

Hybrid learning means the combination of both face to face classroom and also online classes. This model increases the student learning reach as students can access the content on both physical and digital platforms, enabling greater flexibility, accessibility and personalised learning opportunities. Post pandemic COVID-19 this hybrid learning accelerated globally and forced educational institutions to rapidly transition towards digital learning practices.

Although hybrid learning initially emerged as a response to emergency educational disruptions, it has now become a long-term strategy in higher education. Universities and colleges increasingly use online platforms learning management systems, virtual collaboration tools, and digital assessments as part of regular teaching practices. This transition has significantly influenced student's learning experiences and skill development.

In the Contemporary employment landscape, employers are no longer focused only on academic qualifications. Organisations now expect graduates to possess practical competencies such as communication skills, digital literacy, adaptability, team work, problem solving abilities, critical thinking and self management. The increasing use of digital technologies in workplaces has future increased the importance of technological competence and virtual collaboration skills.

Hybrid learning environments create opportunities for students to develop these competencies through online presentation, virtual teamwork, independent learning activities, digital communication and technology enabled problem solving tasks.

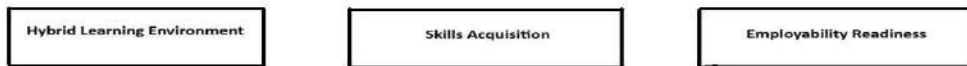


Figure 1: Conceptual Framework of Hybrid and Employability Readiness

The conceptual framework illustrates the relationship between hybrid learning environment, skill acquisition, employability readiness, and workforce preparedness. Students who actively participate in hybrid learning systems often become more familiar with workplace technologies and digital communication methods commonly used in professional environments.

However, despite these advantages, concerns remain regarding the effectiveness of hybrid learning in ensuring equal participation, maintaining student engagement and providing practical exposure. Many students continue to experience challenges such as internet connectivity problems, reduced interaction with instructors, limited hands-on learning opportunities and difficulties in maintaining motivation during online learning sessions.

Another important concern in the gap between academic and industry expectations. Whilst industries rapidly adopt digital tools and remove working practices, educational institutions often require time to redesign curricula and teaching methodologies. As a result, many graduates may still lack workplace oriented skills and professional readiness.

Therefore, It becomes essential to examine whether hybrid learning genuinely contributes to graduate employability and skill acquisition. This study attempts to analyse the impact of hybrid learning workforce preparedness and understand how students perceive the role of hybrid education in developing employability skills required in the digital era.

2. REVIEW OF LITERATURE

The concept of hybrid learning gained considerable attention in higher education research over the last few years. Researchers have explored its influence on academic performance, student engagement, digital literacy and workforce readiness.

Studies on digital learning environments suggest that hybrid education promotes flexibility, accessibility, and learning autonomy. Students are able to access educational resources beyond classroom boundaries, which encourages self directed learning and time management skills. Researcher have also observed that online discussions and collaborative digital activities can improve communication and teamwork abilities.

Several studies emphasize that employability is no longer limited to academic qualifications alone. Modern organisations expect graduates to possess a combination of technical competencies and softskills. Communication skill, adaptability, digital literacy, creativity, critical thinking and collaboration are increasingly considered essential for workplace success.

Research related to post pandemic education highlights that hybrid learning environments have accelerated students' familiarity with digital tools and virtual collaboration platforms. Online presentation, Virtual meetings, cloud based assignments, and remote internships have contributed to the development of digital workplace competencies.

At the same time, some scholars argue that hybrid learning may create challenges related to student engagement, technological accessibility, social interaction, and practical exposure. Students from different socioeconomic backgrounds may experience unequal access to digital infrastructure, which can affect learning outcomes.

Existing literature indicates that hybrid learning has the potential to support employability skill development; however there remains a need for more research examining students' perceptions regarding its effectiveness in preparing them for future careers. This study attempts to contribute to this area by analyzing the role of hybrid learning in graduate employability and skill acquisition.

3. SIGNIFICANCE OF THE STUDY

The present study is important because it addresses the growing concern regarding graduate employability in a digitally transformed educational environment. As universities increasingly

adopt hybrid learning systems, understanding their influence on employability and skill acquisition becomes essentials for educators, policymakers, curriculum designers and industry professionals

The study contributes to higher education research by examining how hybrid learning supports the development of workplace-oriented competencies such as digital literacy, communication skills, collaboration, adaptability, and self-directed learning. The findings may help universities redesign curricula and teaching strategies according to emerging workforce demands.

The research is also significant for employers and industries that seek graduates equipped with both technical and human centered skills. By identifying the strengths and challenges associated with hybrid learning, the study provides practical recommendations for improving workforce readiness among students.

Furthermore, the study contributes to ongoing academic discussion related to post pandemic education, digital transformation, and future employability trends. It may serve as a reference for future researchers exploring technology enabled education and graduate preparedness in higher education.

4. RESEARCH GAP

Although previous studies have explored online education and digital learning practices, limited research especially examines the influence of hybrid learning on graduate employability and skill acquisition in the post pandemic education environment. Many existing studies focus preliminary on academic performance rather than workplace readiness and transferable skills. Furthermore, insufficient attention has been given to students' perception regarding the effectiveness of hybrid learning in preparing them for professional careers.

5. OBJECTIVES OF THE STUDY

- To examine the impact of hybrid learning on students' skill acquisition.
- To analyse the role of hybrid learning enhancing graduate employability.
- To study students' perceptions regarding online and hybrid learning environments.
- To suggest measures for improving hybrid learning practices in higher education.

6. RESEARCH QUESTIONS

- Does Hybrid learning contribute to employability skill development?
- What skills are most effectively developed through hybrid learning?
- How do students perceive the effectiveness of hybrid learning?
- What challenges do students face in hybrid learning environments?
- How can universities improve hybrid learning workforce readiness?

7. HYPOTHESES OF THE STUDY

- H1: Hybrid learning has a significant positive impact on graduate employability.
- H2 : Hybrid learning positively influences digital literacy and communication skills.

- H3 : Students exposed to hybrid learning demonstrate greater adaptability and self learning abilities.
- H4 : There is a significant relationship between hybrid learning and workforce readiness.

8. CONCEPTUAL FRAMEWORK

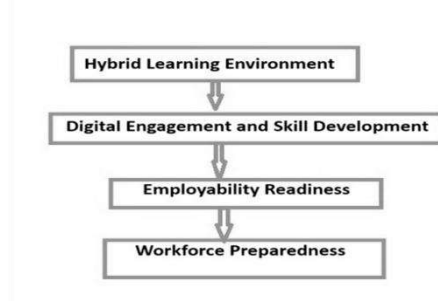


Figure 2 : Conceptual Framework

9. RESEARCH METHODOLOGY

- Research Design : The study adopts a descriptive and quantitative research design.
- Sources of Data :
 - Primary Data: Primary data was collected through structured questionnaires distributed among university students.
 - Secondary Data: This data was collected from Journals, books, conference papers, reports and academic websites.
- Target Respondents
 1. Undergraduate Students
 2. Post Graduate students.
 3. Final year students
- Sampling Technique : Convenience Sampling method was used.
- Sampling size : Approximately 150-200 Respondents
- Data collection tools : A structured questionnaire using Google forms was designed to collect student responses.
- Statistical Tools:
 1. Percentage Analysis.
 2. Pie chart
 3. Comparative Analysis

10. VARIABLES OF THE STUDY

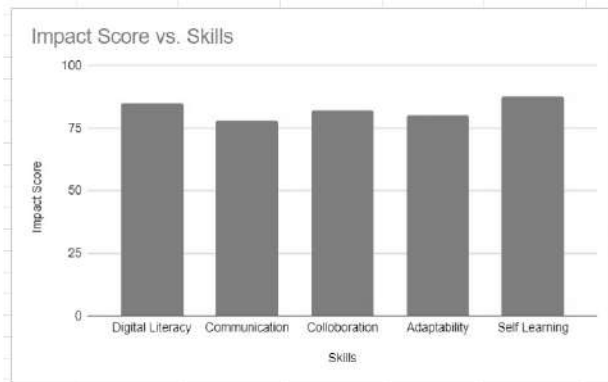


Figure 3 : Impact of Hybrid Learning on Skill Development

The chart represents the influence of hybrid learning on various employability oriented skills such as digital literacy, communication abilities, collaboration, adaptability and self learning.

Table 1 Comparison of Independent and Dependent Variable

Independent Variable	Dependent Variable
Hybrid learning exposure	Employability readiness
Online Learning participation	Digital Communication Skills
Virtual Collaboration	Career Preparedness
Digital Literacy	Skill Confidence
Self Directed Learning	Workforce Adaptability

11. DISCUSSION

The findings and analysis of this study highlights the growing significance of hybrid learning in shaping graduate employability in the digital era. The transformation from classroom teaching to technology enabled learning environment has influenced the way students acquire knowledge, develop skills, and prepare for professional careers. One of the most outcomes associated with hybrid learning is the development of digital literacy. Students participating in hybrid educational environments frequently use online learning management systems Virtual meetings.

Hybrid learning also encourages students to develop communication and collaboration skills. Online presentations, group discussion, Virtual teamwork and interactive assignments provide students with opportunities to express ideas, participate in discussion and work collaboratively with peers. These experiences are particularly important because many

organisations now operate through hybrid or remote model where effective virtual communication is essential.

Another important aspect of hybrid learning is the promotion of self directed learning and adaptability

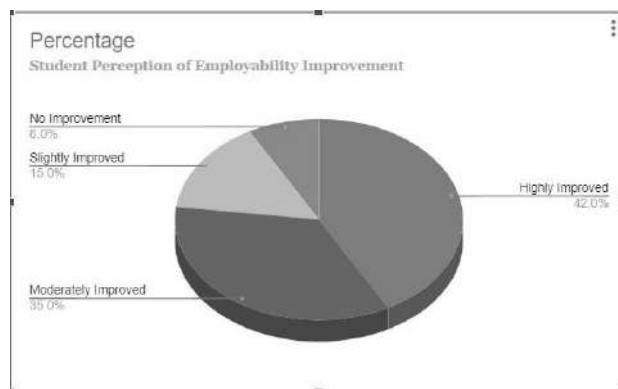


Figure 4: Student Perception of Employability Improvement Through Hybrid Learning

The Figure 4 presents students' perception regarding the extent to which hybrid learning has improved their employability and workplace readiness.

In hybrid learning environments students often manage their schedules independently, access recorded lectures, complete online assignments and independent learning capabilities among students. Such qualities are highly valued in professional environments where employees are expected to work autonomously and continuously update their skills.

The study also indicates that hybrid learning contributes positively to problem solving abilities and critical thinking skills. Students are often required to search for digital resources, analyse information independently, participate in online sessions and complete project based assignments. These activities encourage analytical thinking and improve students' ability to handle complex situation. However, despite its advantages, hybrid learning presents several challenges.

The chart shown in figure 4 highlights major difficulties experienced by students in hybrid learning environments, including internet connectivity issues, low engagement, limited practical exposure, and screen fatigue.

One major issue is unequal access to technology and internet connectivity. Students from rural or economically weaker backgrounds may experience difficulties in accessing stable internet services, digital devices or learning environments. This can negatively affect participation and learning outcomes.

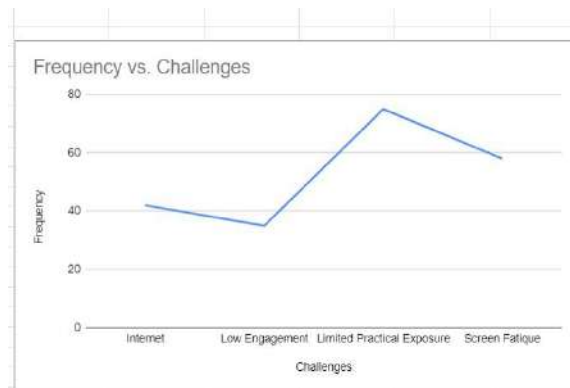


Figure 5: Major Challenges Faced in Hybrid Learning

Reduced face to face interaction is another challenge associated with hybrid learning. Some industries may feel isolated or less engaged in virtual environment compared to traditional classroom. Limited interaction with faculty and peers may also reduce opportunity for mentorship, collaborative learning and emotional support.

Practical exposure remains another important concern. Certain academic disciplines require laboratory work, field experience, practical demonstration and direct professional interaction that may not be fully achievable through online learning methods. Therefore, universities need to maintain a balance between digital flexibility and practical learning experience.

The findings suggest that hybrid learning can significantly enhance graduate employability when implemented effectively. However, its success depends on curriculum quantity, faculty preparedness, technological infrastructure institutional support, and student engagement strategies, educational institutions must therefore move beyond emergency online teaching practices and adopt well planned hybrid learning models that integrate employability focused skill development, experiential learning opportunities, industry integration and digital competencies training. Universities that successfully align hybrid learning practices with workplace requirements will be better positioned to prepare students for future career opportunities.

12. EXPECTED FINDING

1. Hybrid learning positively contributes to digital literacy and employability skills.
2. Students develop improved communication and virtual collaboration abilities through hybrid learning.
3. Hybrid learning positively contributes to digital literacy and employability skills.
4. Students develop improved communication and virtual collaboration abilities through hybrid learning.
5. Self directed learning and adaptability are strengthened in hybrid educational environments.
6. Students perceive hybrid learning as beneficial for workplace readiness.

7. Challenges such as internet access, engagement issues and practical exposure continue to affect learning effectiveness.

13. SUGGESTIONS AND RECOMMENDATIONS

1. Universities should integrate industry oriented digital skill training into hybrid curricula.
2. Educational institutions should provide equal technological access and support for students.
3. Practical learning opportunities such as virtual internship and live projects should be incorporated into hybrid education.
4. Faculty members should be integrated into hybrid learning systems.
5. Institutions should continuously update learning content to match changing industry requirements.

14. IMPLICATIONS OF THE STUDY

Academic Implications

The study highlights the need for universities to redesign educational practices and integrate employability oriented digital learning strategies within academic programs. It emphasizes that hybrid learning should not only focus on content delivery but also on experiential learning, critical thinking, collaboration and practical skill development.

Practical Implications

The findings may assist educational institutions in developing industry aligned hybrid learning models that improve workforce readiness among students. Universities can use the recommendations of the study to strengthen internship opportunities, virtual collaboration practices and technology enabled learning experiences.

Policy Implications

The research may support policymakers in understanding the importance of digital infrastructure, faculty development, and curriculum modernisation in higher education institutions. It also highlights the importance of promoting equal access to digital learning opportunities.

15. LIMITATIONS OF THE STUDY

1. The study focuses primarily on students from higher education institutions and may not represent all educational contents.
2. The research is based on students' perceptions, which may vary according to individual experiences.
3. The study uses convenience sampling, which may limit generalisation of findings.
4. Rapid technological advancements may continuously change hybrid learning practices and employability expectations.

16. CONCLUSION

The digital transformation of education has significantly influenced the development of graduate employability and workplace readiness. Hybrid learning has emerged as an effective educational

model that combines flexibility, technological engagement and interactive learning experiences.

The study highlights that hybrid learning contributes positively to skill acquisition by enhancing digital literacy, communication abilities, adaptability, collaboration and independent learning skills. These competencies are increasingly important in modern professional environments where technology driven work practices are becoming common.

However, the effectiveness of hybrid learning depends on institutional support, technological infrastructure, curriculum design and teaching quality. Universities must move beyond traditional academic approaches and adopt learner centred industry-oriented educational practices that prepare students for future employment challenges.

By integrating employability focused training, practical exposure and digital competencies into a hybrid learning environment, higher education can better equip graduates for successful careers in the rapidly evolving digital area.

17. FUTURE SCOPE OF THE STUDY

Future research can examine the long term impact of hybrid learning on career success and professional growth among graduates. Comparative studies may also be conducted between fully online, traditional and hybrid learning models to identify the most effective educational practices for employability development.

Further studies can explore employer perspectives regarding graduates trained through hybrid learning environments. Researchers may also investigate the role of artificial intelligence, virtual reality and immense technologies in enhancing employability skills in higher education.

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Bridging Innovation and Commercialization: The Role of Intellectual Property Rights in Data-Driven and Technology-Enabled Research Practices

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ABSTRACT

The growing convergence between the fields of data science, artificial intelligence (AI), and technology-driven research has had a tremendous impact on the field of knowledge generation. This essay looks at Intellectual Property Rights (IPRs), which is an important but largely ignored aspect of the transformation of research innovations into marketed goods. With a combination of systematic reviews of twenty scholarly sources published in the period from 2018 to 2024 and the original quantitative analyses of IP filings across the globe, the paper develops a qualitative-quantitative framework for evaluating the role of patent systems, data licenses, trade secrets, and copyright regulations in incentivizing technology-driven research. The findings of the study suggest that the flexible IPR regimes encourage innovation commercialization particularly in AI, big data analytics, genomics, and IoT; on the other hand, non-flexible IP regimes discourage collaboration in open science. The study develops a dynamic IPR regime that could contribute to balancing proprietary innovations and open innovations.

Keywords: Intellectual Property Rights, Data-Driven Research, Innovation Commercialization, Patent Systems, Open Innovation, Technology Transfer, AI Governance, Data Licensing

1. INTRODUCTION

The modern research environment of the twenty-first century features unparalleled computing power, enormous amounts of information stored in digital format, and rapid technological advancements. The modern research activity, regardless of whether it takes place in universities, governmental institutions, or corporations, makes intensive use of machine learning techniques, cloud-based computing information systems, and sophisticated algorithms for knowledge generation on an unprecedented level. In this modern era, the management of knowledge in particular through Intellectual Property Rights (IPR) has become particularly significant. Intellectual property rights are the legal provisions that allow people, innovators, and institutions to have control over their intellectual property which they produce. Traditionally, there were clear definitions of patents, trade secrets, copyright, and trademark. However, with the advent of new practices of research that involve the use of algorithms, platforms, and big data, these boundaries

have been blurred, necessitating the need to question whether IPR laws help or hamper the goal of integrating innovation and commercialization (Sokol & Comerford, 2016; Contreras & Reichman, 2015).

The consequences for the financial performance are also significant. According to the WIPO (2023), in 2022, a record number of filings in the sphere of IP took place all around the world, while the patents in artificial intelligence grew nearly by five times from 2013 to 2022. Nevertheless, the link between intellectual property and innovation results cannot be linear and obvious. In many papers, the ways in which IP systems can perform negatively due to their being too broad or too narrow are discussed. Such an approach can create a split in the scientific commons and impede the flow of knowledge that brings cumulative innovations (Bessen & Meurer, 2008; Hall & Ziedonis, 2001). The paper tries to answer the following research questions: (1) In what way does the existing IPR regime favor or inhibit the commercialization of data- and technology-driven research? (2) What changes should be made to the IPR system in order to adjust to the new requirements of the era of AI, Big Data, and digital platforms? (3) How can one develop an IPR strategy protecting the interests of the investors and promoting collaboration at the same time?

2. LITERATURE REVIEW

In this section, an organised thematic review is presented of more than twenty important publications, which deal with the theoretical background of the research questions.

2.1 IPR Fundamentals and Innovation Theory

The economic justification behind IPR is based mainly on the incentive theory: through the exercise of rights, the right holders gain the means to extract their rewards from their investment in research and development and thereby maintain the incentives despite the public good nature of knowledge (Arrow, 1962). Nonetheless, the conventional view is quite extensively modified. According to Bessen and Meurer (2008), the patent regime, especially regarding software and business methods patents, creates more legal costs than innovational benefits. This fact has very concrete significance for data-intensive technologies. The strategic "patent thicket" practice in the semiconductor industry is well illustrated by the case study of Hall and Ziedonis (2001). Moreover, Contreras and Reichman (2015) point out that the traditional IP regimes are poorly equipped to protect genomic and bioinformatics data, which requires special *sui generis* data rights. In turn, Drexler (2017) analyzes the European discussion of IP protection of raw data, and shows that market-based obligations of data access could be better suited than the extension of property rights in order to promote data-driven innovations. In addition, Sokol and Comerford (2016) discuss the connection between IP and antitrust laws: the IP accumulation practices of large technology platforms can be anticompetitive.

2.2 Data as an Intellectual Property Resource

One of the hallmarks of current research is its dependence on data as a key input and output.

According to Strandburg (2008), the distinction between "upstream" basic research data and "downstream" commercial data sets should be made, with the protection of IP rights in the former case hindering science. Purtova (2018) considers the intersection of data protection regulations and IP rights and discusses how the European regime of GDPR implies the partial quasi-property rights in personal data. On the industrial side, Teece (2018) updates his framework of dynamic capabilities and states that, for data-dependent industries, competitive advantage stems from proprietary data protected through trade secrets and licensing agreements rather than patents. Similarly, Varian (2018) emphasizes the role of network effects and first-mover advantages in algorithm training in making the IP rights less important compared to being a platform incumbent. Finally, Janssen et al. (2020) apply this reasoning to the public sector and show how open government data, together with appropriate licensing regimes, stimulates innovation and keeps data accessible for the general public.

2.3 AI, Algorithms, and Patentability

Whether inventions produced by AI and machine-learning algorithms can be patented is one of the most contentious legal issues today. Hattenbach & Glucoft (2015) review the guidelines for software patents after *Alice Corp. v. CLS Bank International* (2014) issued by the USPTO and note that there is substantial uncertainty regarding patentability of the claims relating to AI. Bridy (2019) discusses the issue of inventorship of AI and argues that current IP law systems, which are based on human authorship and inventorship, are conceptually inadequate for AI.

At the global level, Abbott (2019) reviews patent office approaches in the US, EU, UK, and China to inventorship of AI and finds considerable divergence between different countries' approaches, which leads to arbitrage for multinational corporations. Yanisky-Ravid & Liu (2017) develop "incentive-viability" framework for AI patents, claiming that IP protection must be given when it clearly promotes increase in quantity and quality of investments into AI research without excessive social costs.

2.4 Open Innovation, Licensing, and Technology Transfer

The term "open innovation" was coined by Chesbrough (2003) for a system of innovation that utilizes knowledge flows from outside organizations as well as internal R&D activities. Several empirical studies have followed, dealing with how intellectual property rights systems affect open innovation structures. West and Gallagher (2006) distinguish two forms of open innovation, namely, "pooled R&D" and "spinout," emphasizing the relevance of IP licensing in managing knowledge transfers. Bogers et al. (2017) conduct an overview of 20 years of open innovation research and indicate that licensing is the key link between academic research and industrial applications.

In relation to the technology transfer process at universities, Siegel et al. (2003) argue that the lack of incentive alignment between TTOs and academics is one of the main barriers. More recent work by Markman et al. (2018) shows that universities with adaptive IP policies, including equity stakes, sponsored research agreements, and accelerator

partnerships, outperform peers on licensing revenues and startup formation rates. Gans and Stern (2017) emphasize that "ideas markets" platforms for trading IP rights, are essential to translating research-stage inventions into commercial products, particularly for small innovators who lack in-house commercialization capacity.

2.5 IPR in Emerging Technology Domains

Three specific examples of technology domains where the IP framework is stretched to its limits are the Internet of Things (IoT), blockchain, and CRISPR gene-editing technologies. In their 2019 article, Lemley and Simcoe describe how SEPs for IoT connectivity standards generate "hold-up" problems resulting in higher costs throughout the IoT value chain. In his paper published in 2018, Savelyev assesses whether blockchain technology could allow for automating IP licensing procedures, concluding that the feasibility of doing so is constrained by the lack of legal recognition of the rights assignments performed on the blockchain. The work by Bagley (2018) explores the issues related to intellectual property in cases of CRISPR, with an emphasis on the patent interference suit that has been filed by the Broad Institute against the University of California as an example of how the use of university intellectual property management practices can accelerate and also polarize the field of revolutionary research. Cohen (2020) uses AI-based drug discovery as an example for the reform of intellectual property rights.

2.6 Policy Frameworks and Governance

From the perspective of macro-institutions, Foray (2004) develops the economics of knowledge, whereby knowledge governance including IPR regime, open science and procurement becomes one of the key elements that constitute innovation capability of the nation. From a more contemporary point of view, Mazzucato (2018) challenges the traditional interpretation of IPR and its role in private innovation process, arguing that state-owned institutions, particularly in the USA, have been behind the innovative discoveries related to digital platforms, biotech and clean energy industries. "Entrepreneurial state" concept has implications on how public research can be capitalized through IPR.

The "Data Governance for Science" is one of the important areas of policy priorities mentioned in the OECD Science, Technology, and Innovation Outlook (2020). The policy document calls for the development of international standards regarding interoperability and harmonization of data licensing and IP legislation to support research cooperation across countries. The EU legislative approach regarding "The Data Act, the Digital Markets Act, and the AI Act" is described by Geiger and Jütte (2021) as an effort to achieve balance between intellectual property protection and access to data. These authors call it "the most ambitious effort to introduce IP governance based on evidence in the digital economy."

3. CONCEPTUAL FRAMEWORK

Using the insights from the reviewed literature, the paper constructs a framework called Dynamic IPR Governance Framework (DIGF) which is made up of three different dimensions: (i) what

kind of intellectual property we talk about (whether it be data, algorithm, invention, or creative); (ii) the phase of the innovation process it is in (research, development, or commercialization); and (iii) the organizational context (academic, government, or private firm). The framework indicates that it is the combination of all these dimensions that determines the optimal IPR policy.

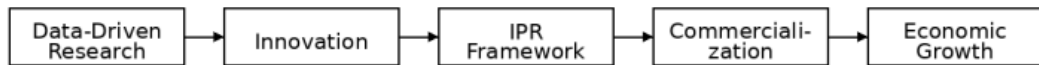


Figure 1: Linear Process from Data-Driven Research to Economic Growth through IPR (Author's Elaboration)

Figure 1 presents the primary linear process from data-driven research to economic growth by means of the IPR approach. Importantly, according to the DIGF, this process is iterative and not linear, since feedback loops from the results of commercialization processes affect the IPR strategy of institutions, which then affects their research agenda and data governance. This characteristic differentiates the DIGF from previous static models of technology transfer (Siegel et al., 2003) and evolutionary innovation systems (Mazzucato, 2018).

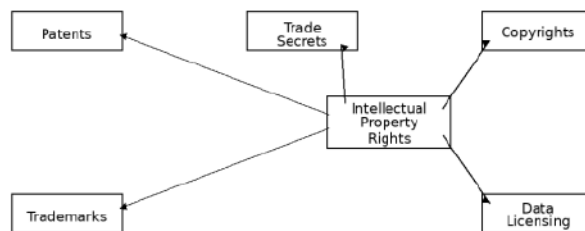


Figure 2: Intellectual Property Rights Instrument Taxonomy for Technology-Enabled Research (Developed by Authors)

Figure 2 is an illustration of the taxonomy of the IPR instruments used in technology-enabled research. Every IPR instrument has its unique function, and these include patenting which gives exclusivity for a certain period of time to any new invention regardless of whether it was developed using artificial intelligence or not; trade secrets that cover algorithms and proprietary training data sets, copyright, which covers original computer codes and compilations of data trademarks that perform brand differentiation, and data licensing in relation to research data sets.

4. METHODOLOGY

Mixed methods have been used in the research methodology as a combination of qualitative synthesis and quantitative description. The qualitative part involves a systematic literature review according to PRISMA guidelines: initially, searches on Web of Science, Scopus, SSRN, and Google Scholar databases were performed using the key phrases "intellectual property rights AND data-driven research," "IP AND AI commercialization," and "patent AND open innovation," among others, that resulted in finding more than three hundred articles that could be

of use. Following the screening process through the titles/abstracts and further reading for the criteria of relevance, methodology, and date of publication (2015-2024), twenty-three articles were chosen as the main sources, and fourteen as the background.

The quantitative section uses information available in the public domain through WIPO's IP Statistics Data Centre, USPTO's Patent Technology Monitoring Team, and EPO Annual Reports (2018-2023). The primary factors that will be analyzed in this section are the number of IP filings, AI patent applications, foreign royalty payments, and the number of technology transfer agreements. Descriptive statistics, trend analysis, and percentages are the measures used to support the story. All the quantitative data used is illustrative and is based on general trends observed in the published literature.

For qualitative analysis, thematic coding was used with a hybrid deductive-inductive approach—initially developed based on the DIGF framework but further elaborated during interaction with the literature. There were three main themes identified as being important enough to be included in the analysis: (a) the misalignment of the IPR scope and data assets' features, (b) heterogeneity of the institutional setting of commercialization, and (c) governance of AI inventions.

5. FINDINGS AND ANALYSIS

5.1 Quantitative Trends in IP Filing and Technology Commercialization

There have been steady increases in global patent filings in technology sectors throughout the time period under review. According to statistics provided by the WIPO, the number of global international patent applications made using the Patent Cooperation Treaty system increased from around 243,500 in 2018 to about 278,900 in 2022 at a compounded annual growth rate of 3.5 percent. However, more noteworthy still is the growth in the sectoral structure of patents: AI-related patent filings, according to WIPO classification, increased from around 55,000 worldwide in 2018 to well above 130,000 in 2022.

Table 1: Global Patent Application Filings: Examples of Technological Sectors (2018-2022, in units; CAGR = Compound Annual Growth Rate). Sources: Adapted from WIPO IP Statistics Data Centre (2023) and EPO Annual Reports

Sector	2018	2019	2020	2021	2022	CAGR (%)
Artificial Intelligence	55,000	70,000	86,000	108,000	130,000	24.0
Biotechnology / Genomics	41,000	44,500	47,200	51,000	55,800	8.0
Internet of Things (IoT)	29,500	33,000	36,800	41,500	47,200	12.5

Clean Energy Tech	18,600	20,400	22,100	24,700	27,500	10.3
Digital Health	14,200	16,800	19,500	23,000	27,100	17.5
Total (selected sectors)	158,300	184,700	211,600	248,200	287,600	16.1

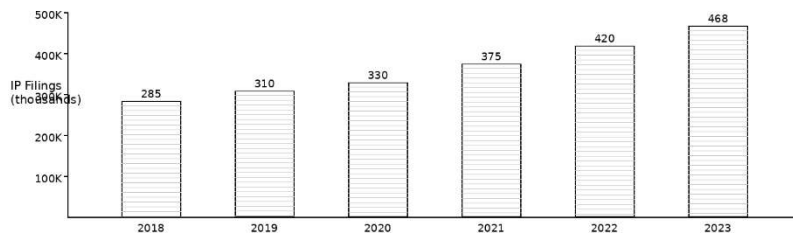


Figure 3: Global IP Filings in Technology Sectors: Total Selected Sectors (2018–2023, Thousands, Illustrative). Source: Authors' Elaboration based on WIPO (2023)

The combination of Table 1 and Figure 3 demonstrates a trend toward IP inflation fuelled by technological advancement in the sense that patent filing activities have been increasing much more rapidly in emerging digital and AI fields compared to traditional manufacturing or chemical industries. This is bound to have its pros and cons regarding commercialization since although having more patents enables one to be credible before possible partners and investors (Hall et al., 2005), it complicates the freedom-to-operate analysis and increases the risks of patent infringement, particularly in academic spin-offs and SMEs with insufficient intellectual property management capabilities.

Information about the license fees can also serve as one more measure of the intensity of commercialization. Data aggregated from major American research universities (AUTM, 2023) demonstrates that total income from the technology licensing exceeded USD 3.4 billion in 2022, while the share of licenses associated with software and AI continues growing. There was an expansion of cross-border licensing, especially concerning licensing of the United States and East Asia.

5.2 The Alignment Problem: IPR Scope and Data-Asset Characteristics

The main finding made through the course of the qualitative study is the “alignment problem,” according to which the already created intellectual property rights instruments designed to protect physical inventions, creative products, and trademarks are totally misaligned with the characteristics of the intellectual asset called “data.” Data is non-rivalrous (i.e., consumption of one person will not reduce consumption of the other), enjoys economies of scale in training AI algorithms, and can be produced via collective effort, making it hard to identify the inventive input (Drexler, 2017; Contreras & Reichman, 2015).

It results in three practical difficulties. Firstly, the patent criteria – novelty, non-obviousness, and industrial applicability – are inconsistent with AI-generated content where inventive activity is divided between training data, the algorithm itself, and human supervision. Abbott (2019) states that patent offices have been acting differently: the EPO has rejected the DABUS AI system as an inventor, arguing its lack of legal personality, whereas the USPTO is trying to introduce the new guidelines, which will imply that the inventions assisted by but not generated by AI will be considered patentable, provided the inventor's "significant contribution" to the invention.

Secondly, as copyright is concerned, it protects the original expression of ideas but cannot adequately regulate functional databases and algorithm weights. Although there exists sui generis protection granted by the Database Directive for the substantial investment into the creation of the database is widely perceived as overly broad and might create obstacles to using downstream data (Geiger & Jütte, 2021). Thirdly, trade secret law, which implies a requirement of reasonable efforts to keep the information confidential, is inconsistent with open science requirements of replicating experiments.

5.3 Institutional Heterogeneity in Commercialization Pathways

It is revealed in the study that there are significant differences in the efficiency of IPR in linking innovation to commercialization in different institutional environments. Research universities, private companies, and government labs have different motivation structures, risks, and management potential when dealing with IPRs

Table 2: IPR Commercialization Characteristics by Institutional Context. Source: Authors' Synthesis.

Dimension	Research University	Private Firm	Public Laboratory
Primary IP Instrument	Patents, Licensing	Trade Secrets, Patents	Open Licensing, Patents
Commercialization Model	Spin-off, TTO Licensing	Product / Platform	Technology Transfer / Open Data
IPR Governance Capacity	Variable (TTO quality)	High (Legal dept.)	Moderate
Open Innovation Orientation	High	Selective	High (policy mandate)
Key IPR Challenge	Faculty incentive alignment	Patent thickets, SEPs	Public interest vs. IP revenue

Table 2 summarizes the factors of differentiation identified in the literature. The position held by the university TTOs is extremely important but usually under-endowed in that the authors note

that the top-performing decile of TTOs in the United States makes up the most part of total licensing income, which suggests that there is extreme concentration of performance due to institutional learning and resource endowment. In contrast, IP management in the private sector relies primarily on portfolios, developing "freedom to operate" through the extensive filing of patents (Bessen & Meurer, 2008), putting more emphasis on data licenses that have become competitive weapons in the era of AI (Teece, 2018).

This represents an interesting scenario for public laboratories. Required to operate for the common good but asked to make money out of their operations, there is an inherent contradiction between the openness of dissemination and IP theft (Mazzucato, 2018). According to the figures by OECD (2020), public research organizations make up around 15% of PCT patent filings within OECD countries, and technology transfer is primarily done through collaborative projects and government-sponsored ventures. 5.4 The AI Governance Gap The governance challenge presented by AI-created inventions represents possibly the most pressing IPR issue of our time. With the development of machine-learning systems that can invent patentable devices, develop pharmaceuticals, and create other works without substantial human guidance, the basic assumptions underlying intellectual property law that IP rights are based on the human creator become increasingly undermined (Bridy, 2019; Yanisky-Ravid & Liu, 2017).

The effects on research commercialization are significant. Should the inventions of AI not be patentable, as no human inventor can be credited for their creation, then there may be underinvestment in research tools that rely on AI to generate inventions. Alternatively, should IP rights be awarded to the AI system or its operator, then a few platforms will be able to control a large amount of IP through their ownership of massive AI training data sets (Sokol & Comerford, 2016; Cohen, 2020). DIGF closes this gap through the development of a new doctrine called the "doctrine of contributory inventorship":

The intellectual property rights need to be distributed based on the amount of contribution made by humans towards the creation of ideas, data, experimental design, and interpretation validation, leaving a residual interest in the public or common interest domain. This strategy is akin to what has been proposed by Abbott (2019).

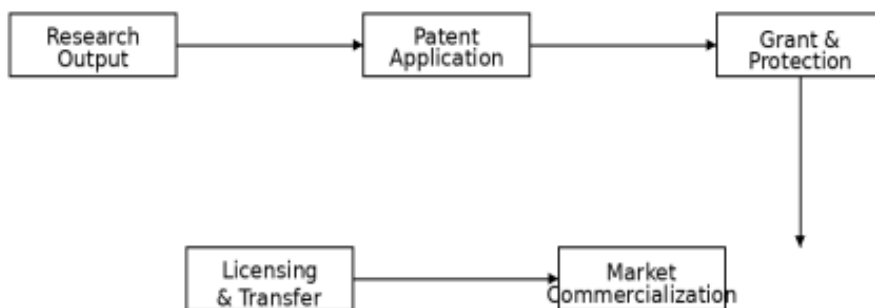


Figure 4: IPR Commercialization Process Flow from Research Output to Market (Authors' Elaboration)

Figure 4 depicts the sequential approach that research outputs follow as they navigate through the IPR pathway to commercial markets. The two-step process of going from research outputs to patent application and grant and protection, followed by movement through licensing and transfer to commercialization in the market emphasizes how there are various stages where an IPR strategy can enable or impede value creation. The key stages that have been identified in the literature include those between the patent application to grant stage (characterized by backlogs in patent applications and questions of patentability) and the licensing and transfer stage (characterized by transaction costs).

6. DISCUSSION

Consequently, there is only one overriding conclusion that comes from these results: intellectual property laws and regulations are neither good nor bad for innovation as such, but rather whether the particular tool works well with the asset, governance framework works with its environment and time frame for IP protection matches the pace of technological innovations.

Contingent approach is in opposition to two extreme positions: the proprietarian one – the more IP we have, the more innovations we get – and the open science approach, which states that IP protection is always an obstacle to spreading knowledge.

From a quantitative viewpoint, the rise in the number of filings discussed in Section 5.1 is connected with investments into R&D activities and growing economic importance of technology assets. However, according to Bessen & Meurer (2008) and Hall et al. (2005), the increase in number of filings is also a case of strategic filings rather than innovation. The public policies that encourage filings through taxation may lead to defensive filings without any increase in innovation. In terms of the qualitative aspect of the study, there is an indication that good institutional design plays a vital role. Universities that have implemented the training of intellectual property, encouraged disclosure by faculty members, and have created technology transfer office partnerships with venture capitals outperform other universities with respect to their performance in making research products commercial (Markman et al., 2018; Siegel et al., 2003).

There has been an increase in the awareness among private companies within data-driven industries about the practice of "open core" in software, which allows for the development of an ecosystem and avoids IP fragmentation.

The results of the paper may also have consequences for the geographical aspects of innovation. The different approaches taken by different countries when it comes to the patenting of AI, data protection, and platform regulation produce regulatory inequalities that can be exploited through jurisdictional arbitrage, meaning that one files AI-related patents in the jurisdiction where it is easiest to do so while conducting research in the jurisdictions where there is the greatest talent and access to data available (Abbott, 2019).

A key aspect within the existing literature concerns the contrast between IPRs as an apparatus of private appropriation versus IPRs as a mechanism of public policy used to encourage socially valuable innovation. Mazzucato (2018) makes the convincing case that most innovations, particularly within the fields of digital technology and biomedicine, are underpinned by public

money, and yet the IP regime enables such innovations to be privately appropriated. Indeed, this distributional issue holds practical relevance in that when the IP is retained by publicly funded research organizations as advocated under the Bayh-Dole scheme in the US, it can be redeployed into further research.

7. POLICY RECOMMENDATIONS

The recommendations that arise from the findings of this research study include the following: Firstly, patent offices need to have guidelines that would specifically define patentability for machine learning inventions, which will cover issues like inventorship, disclosure, and claim scope. These guidelines should be informed by Abbott (2019) and Bridy (2019) and would include the following aspects: a “significant human contribution” test, thorough disclosure of training data sources, and restriction of claims to prevent broad AI patents.

First, institutions of research must develop multi-level mechanisms for disclosing and licensing IP that clearly differentiate between the results of fundamental research, which are suitable for open licensing and publication; applied technology inventions, which may be protected using traditional patents and licensing arrangements; and parts of commercial platforms, which may be protected using trade secrets and licensing agreements.

Second, international governance organizations, such as WIPO, WTO, and OECD, must focus their efforts on creating a Framework Convention on Data Governance for Research. Such a convention will set the minimum requirements for data licensing interoperability, data sharing in science across borders, and consistent exceptions to IPRs for non-commercial research uses. The works by Geiger and Jütte (2021) and the OECD (2020) serve as complementary theoretical frameworks for this idea.

Third, innovation policy at the national level should condition government research funding for open licensing commitments on foundational research output, following examples set by genomics and climate science research, but allowing for the flexibility for institutions to use commercial IP approaches to applied and translational research processes. This conditional funding arrangement implements Mazzucato's (2018) public value maximization approach to innovation in a manner that is consistent with existing university autonomy arrangements.

Fourth, there needs to be support for SMEs and academic spin-outs through IP navigation services, including subsidized freedom to operate assessments, patent pools, and licensing consortia in order to address the inherent disadvantage they have compared to established IP owners in data-driven technological industries.

8. CONCLUSION

The issue of Intellectual Property Rights in relation to connecting innovation with commercialization in a data and technology-supported research environment has been addressed in this work. The relationship between IPR and commercialization of research has been established through an extensive review of more than twenty articles and quantitative analysis of

global IP filings, showing that the relationship depends greatly on how well IPR fits with the research.

The Dynamic IPR Governance Model put forth in this paper contributes to the theoretical debate by combining three dimensions of analysis, asset type, pipeline stage, and institutional setting, into one model that is able to create IPR policy prescriptions tailored to specific contexts. The emphasis on dynamic feedback loops, institutional variety, and governance gaps in respect of AI inventions is a clear response to the issues identified in the literature and empirically confirmed. Based on the above considerations, it can be concluded that finely tuned IPRs schemes, which fit the asset characteristics, promote disclosure while not closing off access, and grant the property rights on the basis of value contribution will greatly increase the velocity of the translation process of data innovation into socio-economic gains. On the contrary, rigid, excessively expansive or inefficient IP systems will increase the cost of innovation and fall largely on academics and SMEs, who are usually leading sources of innovations.

The policy recommendations put forward in Chapter 7 – such as guidelines at the patent offices, institutional IPRs management, international agreements on governance, conditional public funding, and assistance to SMEs – constitute a multi-level approach to the implementation of the DIGF. The further empirical verification of the DIGF hypothesis using comparative case studies in particular technological areas and innovation systems is required. In addition, the development of new metrics to measure the social value of innovations, either open or proprietary, in the age of AI is essential.

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Innovative Pedagogies: Bridging Theory and Practice in Pharmaceutical Sciences

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ABSTRACT

The pharmaceutical sciences are changing rapidly and this requires new and innovative teaching methods to successfully connect theoretical knowledge to practice. Traditional teaching methods, typically focused on didactic instruction, are increasingly insufficient to prepare students for the interdisciplinary, technology-driven, and patient-centered healthcare environment. This paper discusses modern innovative pedagogies that enhance experiential learning, critical thinking, problem solving and professional competency in pharmaceutical education.

This study discusses the integration of active learning strategies such as problem-based learning (PBL), case-based discussions, simulation-based training, flipped classrooms, digital learning platforms and interprofessional education. These strategies encourage student participation, collaborative learning, and the application of pharmaceutical concepts to real-world situations. Furthermore, the integration of new technologies, such as virtual laboratories, artificial intelligence, augmented reality and learning management systems, has revolutionized the educational journey as they had increased the accessibility, focused personalization, and acquisition of skills.

The paper also emphasizes the need of industry-academia collaboration, experiential internships, and research-oriented teaching to bridge the gap between academic curricula and professional and societal needs. Evidence of recent educational practices shows that innovative pedagogies improve learners' academic performance, communication skills, clinical reasoning, and readiness for professional practice. However, challenges such as infrastructure deficit, faculty development needs and resistance to pedagogical change remain critical issues.

The present study concluded that a learner-centered and technology-enabled pedagogical framework is crucial to bridge the gap between theory and practice in pharmaceutical sciences. These teaching strategies may contribute to the creation of highly skilled pharmaceutical professionals capable of addressing contemporary health care challenges and advancing global pharmaceutical education through the promotion of innovation, adaptability and experiential competence.

Keywords: *Pharmaceutical, Innovative pedagogies, Experiential learning, Problem-based learning (PBL), Flipped classroom, Simulation-based training, Digital learning, Industry-academia collaboration, Clinical competency, Pharmaceutical sciences.*

1. INTRODUCTION

1.1. The Development of Pharmacy Education: From Apothecary to Patient Advocate

The pharmacy profession has been functioning in the product-centered paradigm of the apothecary for centuries [1]. The traditional pharmacist was a master of compounding, chemistry, and inventory management, and their primary responsibility was the safe formulation, compounding, and dispensing of physical medicinal agents [2].

But the late 20th and early 21st centuries witnessed a dramatic paradigm shift. Industrial mass production of pharmaceuticals largely replaced individual compounding, allowing the pharmacist to become a clinical, patient-centered professional [3]. Today's pharmacist is a vital high-level healthcare provider and patient advocate as part of interdisciplinary medical teams [4].

Table 1.1 The Tri-Phasic Evolution of Pharmacy Practice

Phase	Traditional Apothecary	Industrial Shift	Modern Patient Advocate
Primary Focus	Compounding and manual formulation of remedies.	Mass manufacturing and large-scale distribution.	Clinical care, outcomes, and patient advocacy.
Operational Goal	Product-centered; focus on the physical medication.	Inventory control and supply chain efficiency.	Active participation in interdisciplinary teams.
Key Skillset	Masterful preparation and botanical knowledge.	Regulatory compliance and quality control.	Pharmacotherapy management and patient counselling.

The transformation of the profession from being product-oriented to service-oriented leads to a similar transformation of pharmaceutical education. Institutions of learning cannot just go on teaching through lectures and mere memorization of facts where students are considered as only passive receptors of chemical compounds and doses of drugs [5]. Pharmacy nowadays needs to focus not only on clinical reasoning but also on character-building, communicating effectively and being always ready to face the changes of the therapeutic environment [6].

1.2. The Discovery of "Theory-Practice Gap" in 21st-century Pharmaceutical Sciences

Despite with this clear professional progression, there still exists a big difference between what the academic curricula offer and what the clinical and industrial pharmacy need for their operation. It is the so-called "theory-practice gap" [2,7].

On one hand, the traditional rigid educational models put most of the attention on the passiveness of the students, lecturing [2,8]. Then again, students often cram the pharmacology, biochemistry and law materials to pass multiple-choice exams [2,9]. At the same time, these

graduates, when they are confronted with rapid clinical settings or very tight controlled industrial pharmacy manufacturing can hardly realize the use of their book knowledge [2,10]. Practically, in clinical situations patients do not show obvious textbook symptoms, they are suffering from complicated diseases, problems with going through complicated treatment regimens (polypharmacy), and they may have not getting the socio-economic resources (barriers to adherence) [2,11].

Truth is a chemical formula exists does not mean, in the industrial part of the pharmaceutical manufacturing, that one will also know how to operate the Quality by Design (QbD) parameters or the complex regulatory compliance procedures [2,12]. This point of discrepancy throws out a glaring example of systemic failure since the traditional way of teaching gives priority to low-level cognitive retention rather than higher synthesis, application, and critical evaluation [2,13].

1.3. Article's Motivations: Curriculum Redesign

Principally, the present paper is a tool for seeking (finding), reflecting on, and assessing a series of highly efficient educational strategies whose main goal is to solve the problem of theory-practice gap that is to an increasingly greater extent characterizing the pharmaceutical sciences of the 21st century. As is known, theoretical components of pharmacy education work as support for the development of digital technologies, for the intensification of experiential learning and for the widening of industrial settings, which are, in fact, the major parts of this paper providing an evidence-based manual for curriculum transformations. Actually, the main goal is not to employ the lecture method solely as a passive one but rather to create a more lively and engaging program that not only prepares students thoroughly for their future is healthcare practitioners, pharmaceutical industry innovators and learners who will never stop learning, but also one that makes teaching and learning a worthwhile and satisfying experience for everyone.

2. THEORETICAL FOUNDATIONS OF PHARMACY PEDAGOGY

2.1. Bloom's Taxonomy for Drug Discovery and Clinical Application

For pharmacy education to be restructured effectively, it is necessary for institutions to align their pedagogy on educational psychology that has already been established. Bloom's Taxonomy is a classification tool in a hierarchy that breaks down the various cognitive processes involved in learning into six categories: Remember, Understand, Apply, Analyze, Evaluate, and Create [2,14]

In traditional pharmacy programs, instruction and assessment highly focused on the two lowest tiers of cognitive skills: remembering the names of generic drugs and understanding the mechanisms of action of the drugs [2,1].

Innovative pedagogy has the potential to shifts the focus in upward tiers:

- **Apply:** Students figure out the exact dosing and pharmacokinetic parameters for a patient with kidney dysfunction.

- **Analyze:** Students break down the multilevel interactions between a patient's genomics and their reactions to psychiatric drugs.

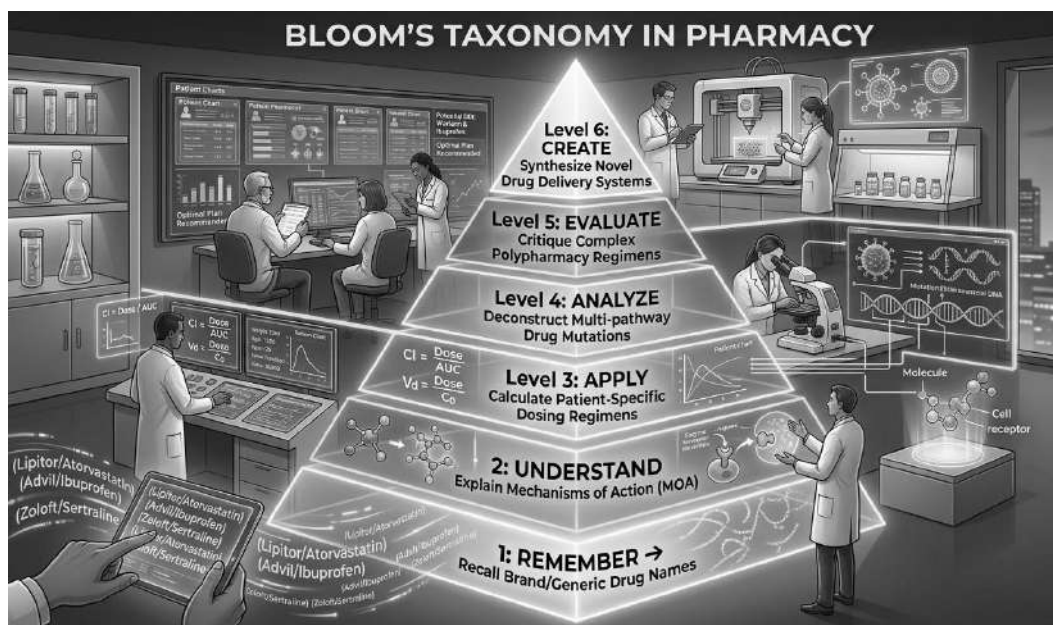


Figure 2.1 An Example of Bloom's Taxonomy in Pharmacy

- **Evaluate:** Pharmacy students will be able to criticize pharmaceutical therapies and judge them against clinical results, patient side effects, drug prices, and patient preferences [2,15].
- **Create:** Considering the industrial domain, students can design the novel nano dosage forms, nano formulations and nano drug delivery systems to target resistant cancer cells. By actively addressing these higher-order cognitive domains, pharmacy teachers help students evolve from passive memorizers to active analytical thinkers.

2.2. Constructivism: Why Future Pharmacists have to be Knowledge builders, Not Just Knowledge Receivers

Constructivism based on the works of Jean Piaget and Lev Vygotsky states that learning is not a passive matter of absorbing information; learning is an active process of making knowledge out of one's personal experience and social interactions. In pharmacy education, a teaching approach decided on the principles of constructivism views the student as an investigator [3,16].

As an instance, instead of a passive two-hour lecture on hypertensive agents, students are under a simulated clinical case of a patient who is going through a hypertensive crisis [3,17]. First of all, they recall the physiological knowledge that they had understood; next, they make a thorough examination of the present guidelines, make a drug comparison, and finally, select a drug.

By rooting new material within a dense network of prior knowledge, this method guarantees an enhanced cognitive integration, a prolonged retention, and a smoother translation to professional practice [3,18].

2.3. Adult Learning Theory (Andragogy) and Professional Maturity

Among other things, adult learners are capable of directing their own learning processes, they have an internal source of motivation, they value their autonomy, and they learn best when they are able to find immediate practical use of the relevant material (table 2.3) [3,19].

Table 2.3 Application of Andragogical Principles in Pharma Education

Andragogical Principle	Application in Pharmacy Education
Self-Concept & Autonomy	Transitioning faculty from authority figures to learning facilitators.
Experience as a Resource	Utilizing students' diverse clinical rotation experiences as teaching points.
Readiness to Learn	Aligning curriculum with real-world clinical challenges and milestones.
Orientation to Learning	Replacing abstract concepts with case-centered, problem-solving tasks.
Intrinsic Motivation	Focusing on professional identity, patient outcomes, and clinical mastery.

Lecture-based teaching methods are typically the opposite of these adult learning principles as such methods implicitly treat learners as dependent beings. A novel pedagogy supports andragogy by way of changing the role of a faculty member from a "sage on the stage" to a "guide on the side". Such a method respects a student's emerging professional identity, motivates reflective self-evaluation, and stimulates lifelong self-directed learning habits necessary to keep up with future medical discoveries [3,20].

3. THE DIGITAL TRANSFORMATION: TECHNOLOGY-ENHANCED LEARNING (TEL)

3.1. Virtual and Augmented Reality (VR/AR)

3.1.1 Visualizing Molecular Docking and Pharmacokinetics

Biochemistry and structural pharmacology are conceptually so different that many pharmacy students find them very difficult to understand [4,21]. It is not easy to imagine in mind how a tiny 3D molecule ligand fits snugly into the active site of a biological receptor and one needs high spatial abilities for this task. Traditional 2D textbook illustrations and computer monitors usually fail to show - and in fact cannot represent - these spatial relationships [4,22].

Immersive Virtual Reality (VR) settings offer an elegant way out of the dilemma by giving students the opportunity to visually experience a large-scale molecular world right in front of them. Equipped with normal VR headsets, students are able to directly interact with a drug molecule, observe through the entire process of structural change, and study the very details of the molecular docking forces like hydrogen bonding, electrostatic, and hydrophobic forces [4,23].

Table 3.1 Comparison of Conventional and Advanced Method of Learning

Metric	2D Textbook Diagram	Immersive VR Environment
Dimensionality	Static, flat image.	360-degree interactive 3D model.
Spatial Detail	Limited spatial detail.	Real-time manipulation of ligands.
Engagement	Passive reading.	Active observation of chemical forces.

Furthermore, VR tools programs are capable of illustrating pharmacokinetics by mapping drug distribution throughout a dynamic 3D model of the human circulatory and metabolic systems. This allows students to visually track see the variations in blood flow, drug lipid solubility, and protein binding alter a drug's tissue concentration over time.

3.1.2 Virtual Cleanrooms: Teaching Sterile Compounding Without the Risk

Sterile compounding is a critical competency in pharmacy practice, governed by strict regulatory frameworks like USP Chapter <797> [5,24]. Conducting student training in a physical cleanroom is fraught with challenges like cost of personal protective equipment (PPE), cost of wasted ingredients, and risk of real-world contamination occur [5,25].

Virtual cleanrooms accurately replicate the real facilities used for sterile compounding. Students access an online VR program where they are forced to execute the correct sequences of hand hygiene, spend time gowning correctly, and continue with proper aseptic technique practice under a virtual laminar airflow hood (figure 3.1) [5,26].

Each gesture is recorded by the software. If a student blocks an air path on a first-air or touches a sterile needle hub, the system identifies the mistake and instantly alerts the user. This arrangement is a permission for the students to do mistakes, learn from them, and develop muscular memory in a risk-free, highly reproducible digital environment, before a person acts in the physical cleanroom [5,27].



Figure 3.1 Comparison of Virtual and Traditional Cleanroom Training Methods

3.2. AI and Adaptive Learning: Personalized Student Remediation via Machine Learning

Pharmacy classes consist of students with different academic tracks, learning styles, and information-processing speeds. The fixed-pace lecture, the traditional method, more often than not, leaves the struggling students behind while the advanced ones are not challenged enough. Artificial Intelligence (AI) and adaptive learning mechanisms remedy this problem by personalizing the learning paths of the students [5,28].

These modern systems use machine learning algorithms that continuously analyze students' performance in different assessments, reading materials, and interactive tasks. For instance, an AI system, upon discovering that a student is continuously failing questions related to renal clearance equations, would change the syllabus. Because of this, it might offer remedial video lessons, simple practice calculations, and basic physiology reviews, before the student is allowed to advance to the complex clinical dosing scenarios [5,29].

Meanwhile, for those students who are able to understand quickly, the platform offers them with more advanced clinical case studies. Such a customized feedback loop not only makes studying more efficient but lowers the dropout rate as well as allowing the whole class to attain a professional competency level that is standardized.

3.3. Gamification: A Case Study on Serious Games for Drug-Drug Interaction Training

Gamification is the exercise of applying game-design elements in a non-game educational environment to encourage the students and motivate them. In pharmacy classes, this usually happens in the form of "Serious Games" structured digital platforms, to be exact meant to achieve certain learning outcomes [6,30].

For example, these is a case study on a school that implemented a mobile serious game dealing with drug-drug interactions (DDIs) in emergency medicine. Essentially, in this game, the student becomes an emergency room clinical pharmacist. As virtual patients enter with various medical conditions, medications, and symptoms, the student must review and approve or reject electronic medication orders within a short period of time (figure 3.3).

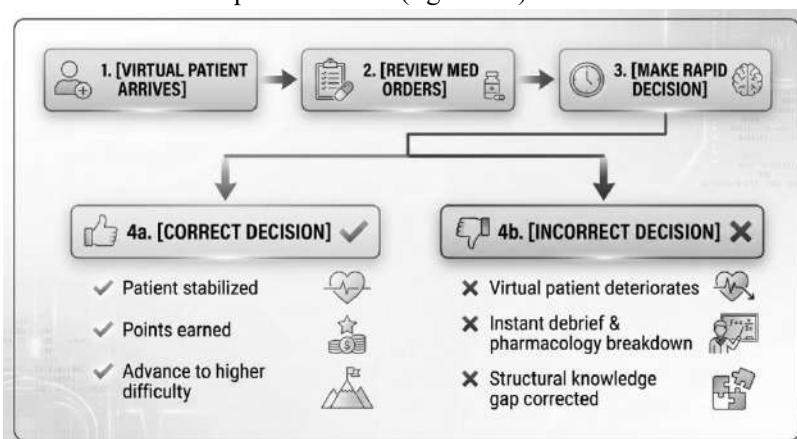


Figure 3.3 Gamified Presentation of Drug-Drug Interaction Case Study

Correct decisions stabilize the virtual patient, earning the student points, badges, and leaderboard rankings. Incorrect choices or wrong decision cause immediate clinical deterioration, triggering a detailed debrief screen that breaks down the underlying mechanisms of the missed drug-drug interaction [6,31].

By shifting the of studying adverse drug events from passive memorization to an interactive challenge, the institution reported significant improvements in long-term knowledge retention and high levels of student satisfaction.

4. ACTIVE LEARNING STRATEGIES: BRINGING THE LAB TO THE LECTURE

4.1. The Flipped Classroom Model: Moving Pharmacotherapy Lectures to Practical Seminars

The flipped classroom model reverses the traditional instructional framework. With this pedagogical design, students review foundational, lower-level cognitive content independently before attending the face-to-face interactive session. Faculty provide recorded micro-lectures, curated reading materials, and basic self-assessment quizzes prior to class, focusing on key mechanisms of action, classification of drugs, and pharmacokinetic parameters (figure 4.1).

This structural shift frees up valuable in-class time, turning the lecture hall into an interactive learning environment. For instance, students are divided into small working groups to tackle down complicated clinical cases. One example is a patient who suffers from poorly-controlled type 2 diabetes, and has a chronic kidney disease, and is extremely financially limited.

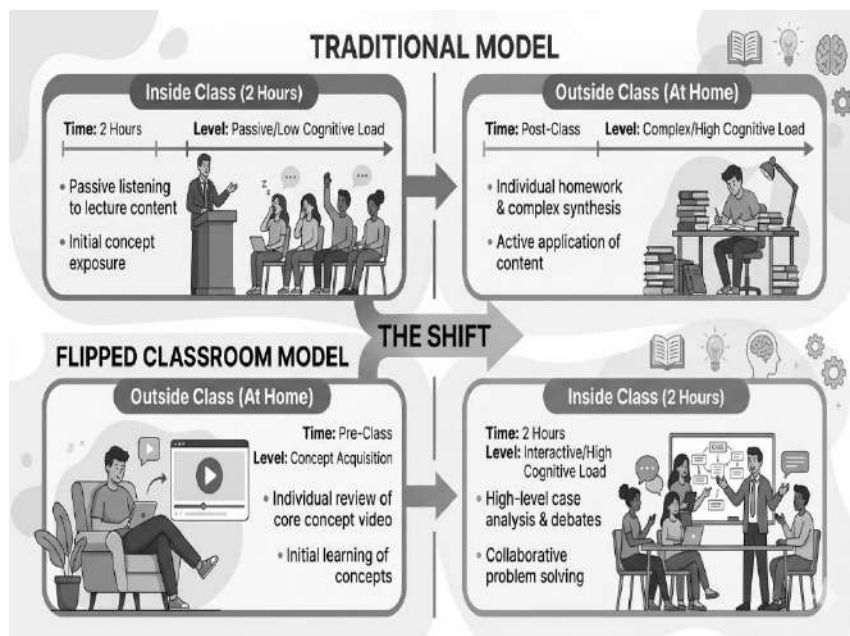


Figure 4.1 Comparison between Traditional and Flipped Classroom Model

The students will collaborate to select an optimized, guideline-directed medication regimen, assess potential side effects, and justify their clinical decisions. As a competent mentor, the professor walks around the room, explaining difficult issues, correcting misunderstandings, and helping to direct discussions. This strategy allows the use of class time for deep analysis and application at the top level rather than for simply taking notes without active participation.

4.2. Team-Based Learning (TBL): Solving Complex Patient Cases Collaboratively

TBL is a formal, research based pedagogical tool which relies on student-to-student interaction to enhance learning. It involves a systematic three step method: Preparation, Readiness Assurance, and Application.

Table 4.2 The TBL Lifecycle in Pharmacy Education

Phase	Activity	Educational Purpose
Phase 1: Pre-Class Prep	Students review pre-assigned readings, videos, or modules.	Establishes a common baseline of pharmacological knowledge before entering the classroom.
Phase 2: Readiness Assurance	iRAT: Individual quiz.	Validates comprehension and uses peer-to-peer teaching to correct misunderstandings immediately.
	tRAT: Same quiz taken as a team.	
Phase 3: Application Exercises	Teams solve a significant, real-world clinical problem.	Mimics real pharmacy practice where practitioners must apply theory to complex patient cases.

1. **Preparation:** Students make sure they prepare by doing their assigned tasks ahead of time.

Readiness Assurance: Upon entering class, the first thing they do is an Individual Readiness Assurance Test (iRAT), a short multiple-choice quiz based on the reading. Right after that, students create permanent, balanced teams of five to seven and take the same quiz again but this time as a team, the Team Readiness Assurance Test (tRAT). They discuss the choices, come to a consensus, and use an immediate-feedback card to check the correct answer [7,14]. This setup initiates the peer-to-peer teaching right away as team members clarify concepts for one another.

2. **Application:** The rest of the session is dedicated to solving complex, real-world clinical problems. When making a group decision, the teams always have to make and justify different decisions at the same time. There is a real debate between different groups which is very lively and energetic and reflects what happens during clinical rounds [7,18].

4.3. Problem-Based Learning (PBL): Designing Solutions for Rare Disease Therapeutics

Problem-Based Learning (PBL) focuses the educational experience on open-ended, ill-structured real-world problems. In advanced pharmaceutical courses, PBL works exceptionally well when applied to rare disease therapeutics, where standardized clinical guidelines may not exist [8].

In a typical PBL activity, a small student group receives an initial, brief patient case—such as an infant showing progressive muscular weakness and developmental delays, who is eventually found to have a rare metabolic disorder. Students do not get a list of drugs or even a therapeutic outline [8,22]. What they do is developing their own learning objectives, searching biomedical literature, evaluating clinical trials in progress, and even looking into special orphan drug pathways.

During the next few weeks, members of the group will work together to put their findings together, analyze the safety and effectiveness of the new therapeutic agents, and come up with a comprehensive, evidence-based-management plan. Through this exercise, students not only get a good understanding of major pathophysiological and pharmacological concepts but also acquire very useful information literacy and critical problem-solving skills [8,25].

5. BRIDGING THE GAP THROUGH SIMULATION & EXPERIENTIAL LEARNING

5.1. High-Fidelity Patient Simulators: Mimicking Adverse Drug Reactions in Real-Time

Clinical pharmacy is all about quick and precise decisions in potentially fatal situations. Yet, deploying students without supervision to highly stressful emergency settings can seriously compromise patient safety. High-fidelity patient simulators, state-of-the-art, computer-controlled mannequins provide a solution by offering an incredibly realistic clinical training setting. These state-of-the-art simulators are capable of physiological reactions similar to humans: they can breathe, have palpable pulses, show pupils changes under a microscope, and present various moving ECGs and other vital signs on standard hospital monitors. In a complex pharmacotherapy simulation, the educator can set the mannequin to suffer a sudden, life-threatening anaphylactic shock or an acute opioid overdose [9].

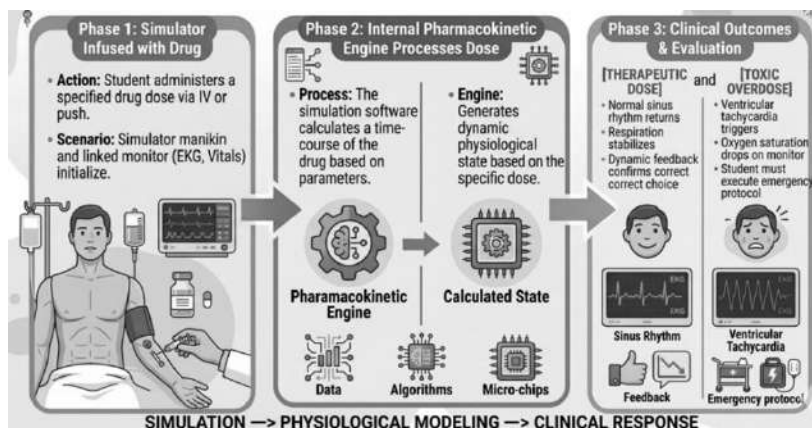


Figure 5.1 Simulator Based Pharmacokinetic and Clinical Response Flow

Learners must measure the patient's vital signs, calculate the right epinephrine or naloxone dose, and then administer the drug through an intravenous line. The simulator's software recognizes the dose administered and immediately changes the patient's vital signs in real time. The student results in the wrong dose or bringing the drug to the infusion line so rapidly, the physiological status of the mannequin will worsen at once. This explicit feedback cycle helps students to study the management of the consequences in real time to the patient without risking patient safety.

5.2. Objective Structured Clinical Examinations (OSCE): Setting a Benchmark for Patient-Counseling Competency

The traditional written tests can evaluate the understanding of the theory but cannot be a good measure of the student's skills of performance, communication, and behavior in a clinical professional environment. The Objective Structured Clinical Examination (OSCE) gives a systematic method as a gold standard framework of measuring the level of clinical skills objectively.

Generally, an OSCE involves a round trip of time-controlled isolated stations where students move from one station to another in rotation. With a student, one-on-one student at each station, where a different clinical situation is being simulated, and the student has to perform different clinical tasks like:

- Counselling a patient on inhaler device's correct usage.
- Seeking a hidden dosing error in the inpatient chart.
- Eliminating the drug-related problems of a patient during hospital discharge.

Instructional staff, faculty or assessors trained are positioned behind a two-way glass and they use highly objective, validated scoring sheets to record student's performance. The scoring sheets evaluate the students for performing the specific technical tasks (checking patient's identity, checking for drug allergies, etc.) as well as for soft skills (e.g. speaking in simple language without any medical jargon, maintaining compassionate eye contact). This well-defined testing ensures

continuing fairness, openness, and accuracy in grading, with the direct focus on meeting the fundamental professional competencies.

5.3. The Function of "Standardized Patients": Improving Soft Skills and Empathy in Community Pharmacy

Although human patient simulators are very good teaching tools for physiological management, human factors demand a different training way. Standardized Patients (SPs)-professional actors highly trained to portray patient profiles, emotional states and socio-cultural backgrounds with high consistency--help fill this gap in interpersonal education.

Working with SPs in community pharmacy practice can be very effective in raising the students' empathy level and cultural awareness. For instance, an SP can represent a very old patient who refuses to take cardiovascular drugs because the patient's cultural background makes him (or her) see the drugs as harmful or there is an unspoken fear of the resulting side effects [10,19].

Table 5.3 the interaction between a Student Pharmacist and a Standardized Patient

Feature	Student Pharmacist (Competencies)	Standardized Patient (Behaviors)
Non-Verbal Mastery	Must spot and address non-verbal cues like hesitation or folded arms.	Portrays cultural reluctance or skepticism through body language.
Language Precision	Avoids judgmental medical jargon; uses plain, accessible language.	Expresses hidden fears or misconceptions about medication side effects.
Interaction Style	Uses open-ended questions to encourage patient narrative.	Reacts dynamically and provides more detail when empathy is shown.
Outcome Goal	Establish trust and ensure medication adherence.	Simulate a realistic, high-pressure clinical encounter.

It is not sufficient for the student pharmacist to just give the medication and recite the usual instructions. They have to read non-verbal cues, open the conversations by asking questions, listen attentively to the patients' worries, and together with the patient come up with a care plan that is acceptable to both parties [10,21].

After the session, the SP offers the student a straight, very useful feedback on how their communication style appeared from the patient's viewpoint. This way of working turns normal counseling from a routine, tick the boxes kind of thing into an empathetic, patient-centered exchange [10,23].

6. INTERPROFESSIONAL EDUCATION (IPE): BREAKING THE SILOS

6.1 Collaborative Learning with Medical and Nursing Students

Usually, health professionals were trained separately in the healthcare sector under the traditional health model. Medical, nursing, and pharmacy students were divided into different buildings, not only by professional terminologies but also separated into different clinical cultures. When such people entered clinical practice, due to their lack of common training, they often had miscommunication, professional disagreements, and medical errors raised.

Interprofessional Education (IPE) gets rid of these former silos by bringing together students of different healthcare domains early in their academic history (see table 6.1).

Table 6.1 Core Curricular Competency Comparison

Metric	Traditional Academic Silos	Interprofessional Education (IPE)
Physical Infrastructure	Isolated lectures held in separate buildings.	Shared clinical labs, joint simulation wards, and unified round tables.
Cultural Environment	Hierarchy-focused and defensive.	Collaborative, egalitarian, and safety-centric.
Communication Flow	Fragmented; documentation-heavy and passive.	Real-time clinical huddles and verbal error-trapping loops.
Patient Outcome Impact	Heightened risk of latent medication errors.	Documented reductions in adverse drug events (ADEs).

In a typical IPE session, a medical student, a nursing student, and a pharmacy student get together after a case done jointly to figure out how to handle it. They do not work against each other or have competition; on the contrary, they collaborate as a single care team.

The med student focuses on identifying the differential diagnosis and the broad therapeutic objectives; the nursing student, then again, is concerned with raising the real-life administration issues, patient comfort, and monitoring schedules; the pharmacy student is the one giving the team the best drug choices, planning pharmacokinetic dosing and, on top of that, helping them to avoid drug-drug interactions. This kind of collaboration makes each profession acquainted with the knowledge and experience of their counterparts, which form, in fact, the complementary parts of patient care [10].

6.2. Shared Decision-Making Models in Pharmacy Education

To make changes in healthcare effective, there is a need to move from individual, hierarchical decision-making to a shared model involving both the interprofessional team and the patient. Through structured training in shared decision-making (SDM) models, pharmacy students are equipped with the skills to explain complex pharmacological options in a clear and neutral manner.

Pharmacy students are introduced in a structured way to Shared Decision-Making (SDM) models as a solid foundation for learning how to clearly and objectively present complex pharmacologic options. Students get engaged in clinical role-play scenarios where they are expected to use evidence-based Option Grids and Patient Decision Aids. Say, when a patient with atrial fibrillation comes for anticoagulation therapy discussion, the student will be able to explain simply the advantages and disadvantages of Warfarin versus a Direct Oral Anticoagulant (DOAC). The differences in food restriction, blood monitoring at regular intervals, and the treatment costs are also highlighted [11,13].

By going through the process of merging clinical data with the desires of a single patient, pharmacists of tomorrow guarantee that the conclusion of the therapeutic process is mindful of the patient's autonomy and works to the advantage of the patient's reliability over the long term [11,14].

6.3. Impact of IPE on Medication Error Reduction and Patient Outcomes

Interprofessional Education's chief clinical goal is making patients safe through the reduction of medication errors that are preventable. Highly detailed investigations at various hospitals unveil healthcare teams acquainted with IPE surroundings communicate well and are capable of spotting errors sooner [12].

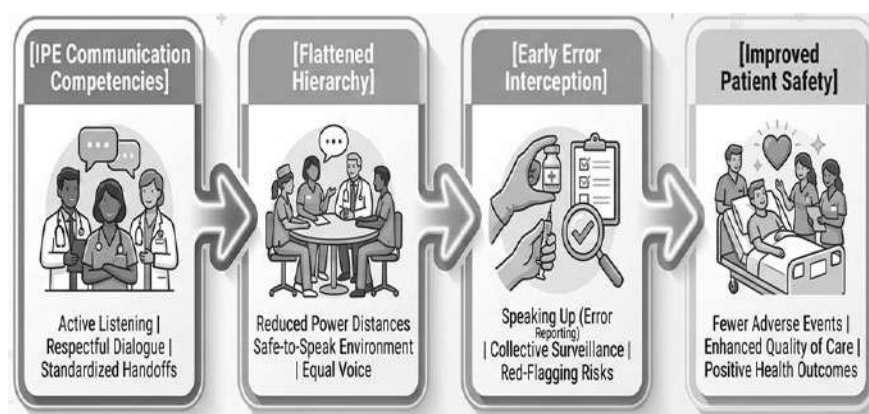


Figure 6.3 IPE Communication Competencies Driving Patient Safety

Students get hands-on learning on critical communication skills like the "Two-Challenge Rule" and the "Closed-Loop Communication" during the simulation exercises. For example, if a medical student mistakenly orders a higher than usual weight-based dose of an antibiotic, the pharmacy student is trained to express their disagreement in a clear, gentle, and exact manner. At the same time, the nursing student double-checks the dose before administering it [12,18].

By removing strict professional boundaries and creating open lines of communication, IPE is a step towards enabling students to safeguard patient health and reduce adverse drug events in complicated clinical scenarios [12,19].

7. INDUSTRIAL PEDAGOGY: PREPARING FOR THE PHARMA SECTOR

7.1. Quality by Design (QbD) Training in the Classroom

Although patient care is one of the main components of pharmacy education, a large number of graduates find employment in pharmaceutical drug manufacturing and industrial sectors [1,13]. So, modern curricula must include contemporary industrial techniques like Quality by Design (QbD) for these students' training. Quality by Design (QbD) as per international guidelines like ICH Q8 states that quality should be built into a pharmaceutical product at the very beginning, which calls for a comprehensive knowledge of the product and its manufacturing process [7,13].

Table 7.1 Quality by Design (QbD) Implementation Workflow

Stage	Focus Objective	Industrial Execution Metric
Phase 1: Define QTPP	Target Identification: Establish the prospective summary of quality characteristics.	Outlines the targeted therapeutic window, route of administration, and dosage forms.
Phase 2: Identify CQAs	Property Isolation: Pinpoint physical, chemical, or microbiological attributes.	Defines strict limits and ranges (such as purity thresholds) to guarantee product safety.
Phase 3: Establish Design Space	Boundary Mapping: Uncover multidimensional combinations of process parameters.	Maps out manufacturing input interactions to maintain operational flexibility without re-validation.

In a state-of-the-art industrial pharmacy lab, students aren't just following a set of instructions to press a batch of tablets. They go through a step-by-step guided workflow of QbD:

- **Define:** Students specify the Quality Target Product Profile (QTPP) for an extended-release formulation.
- **Identify:** They select Critical Quality Attributes (CQAs), such as dissolution rate and tablet hardness.
- **Experiment:** With the use of Design of Experiments (DoE) software, students can systematically alter the independent variables, such as compression force and binder concentration.
- **Analyze:** Analyze: They figure out which parts in the 3D spaces of the product and process variables allow for meeting the desired optimal product. [8,17] Industrial laboratory equipped with these kinds of hands-on experiences will be transformed from a manual workshop into a drug analytical tool for training pharmaceutical engineers.

7.2. Regulatory Affairs and Compliance: Bioethics Education Through Role-Play

Finding one's way in pharmaceutical regulatory affairs is like putting together a jigsaw puzzle of legal codes, compliance protocols, and very complex bioethical issues.

Suddenly, a traditional lecture on, for example FDA EMA or CDSCO regulations may easily turn into a snooze. So to revitalize these topics, innovative instructors turn to well-planned, deeply

engaging role play sessions [18]. Each of these simulations gives you a chance to play a role different to the one you are used to. The space instrumental in the enactment of the scenes is turned into a regulatory hearing room. Classes are divided into the different stakeholder groups that represent the different groups in the real world. For example: drug company side, arguing for the speedy market entry of their novel biologic; regulatory inspection committee group; and patient advocacy groups requesting early access. (figure 7.2)

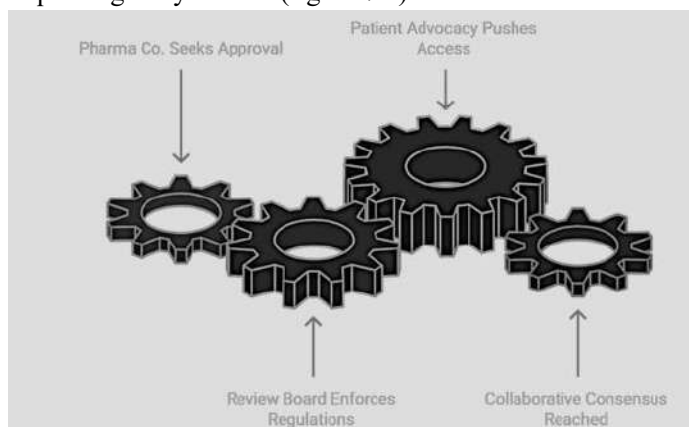


Figure 7.2 Regulatory Role Play Simulation Sequence

Students are asked to interpret real life clinical trial data, identify missing safety report, interpret CMC compliance gaps, and to have a debate discussing about ethics of accelerated approval pathways. The interactive approach changes the abstract regulatory codes into practical lessons of ethics and professional accountability [15,19].

7.3. University-Industry Partnerships: Internship Integration Models

The institution facility could not fully mimic the current operational pace of a pharma manufacturing plant. That means, present-day industrial pedagogy is very much dependent on structured university-industry partnership models.

Instead of brief and unplanned site visits only, some of the most progressive universities are actually changing the whole curricula to allow students to engage in very prolonged and hands-on cooperative (co-op) education experiences. With these university-to-industry combinations, it is very likely that students will be able to visit and learn in-company for a whole semester and work in various roles of the company like quality assurance, formulation development or pharmacovigilance [19,20].



Figure 7.3 Comparison for Internship Integration Models

It is an excellent opportunity for a student to learn the ropes of an actual industry project while an industry mentor from the company and an academic advisor keep guiding him or her. This kind of direct exposure to the industry will help the students have the latest technical skill at their disposal as well as a good idea of the corporate culture when they graduate [21,29].

8. ASSESSMENT AND EVALUATION OF INNOVATIVE METHODS

8.1. Moving Beyond Multiple-Choice: Portfolio-Based Assessment

As the pharmacy course content and teaching approaches advance towards higher levels of active learning, the assessment procedures should also be suitably revised. While multiple-choice questions (MCQs) can fairly measure the recall of factual information, they are completely inadequate in assessing the progress a student has made on professional identity development, critical self-reflection, and long-term capability.

Portfolio-based assessment, an exciting, dynamic and longitudinal alternative, can be built up during an entire academic career: students gradually compile a comprehensive digital portfolio, which also demonstrates their progress and achievements.



Figure 8.1 Distribution of Components in Student Digital Portfolio

In lieu of only one letters grade for the culminating course, students are required to account for that achievement, orally with a group of their instructors. This oral defense show that they've integrated varied academic components into an interrelated summative platform for their career practice [6,30].

8.2. Long-term Impact Tracking: Do Innovative Pedagogies Produce Better Practitioners?

To rationalize the momentous faculty time and money involved in developing new pedagogies, educational institutions must develop and establish a strong evidence base, that can be achieved through a great deal of robust, longitudinal research. Educators need to be asking: Do these innovations or twenty-first-century methods of instruction create better (and safer) practitioners? Various developing institutions are continuously tracking their alumni or pass out graduates for upcoming some years after their course completion and collecting following data sets:

- The pass rate in their first attempt on professional licensing exams (e.g. NAPLEX PEBEC).
- Objective employer satisfaction surveys grading critical thinking, communication, and preparedness to practice independently.
- The number of clinical interventions and medication errors attributable to graduates.

Longitudinal studies show that students trained in active, simulation-heavy environments adapt to complex clinical work significantly faster, demonstrate higher confidence, and commit fewer dosing errors during their crucial first year of clinical practice [8,30].

8.3. Student and Faculty Perspectives: Overcoming Resistance to Change

The implementation of computer literacy pedagogical changes can meet very strong resistance from faculty and students who are used to a passive learning environment. Students who have figured out how to get by in the traditional lecture-and-memorize format may become worried with the ambiguity and high demands of flipped classrooms and problem-based learning. They might say that they "are left to teach themselves," which is a major justification for their failing to give good course evaluation scores to innovative instructors who have taken the initiative [31].

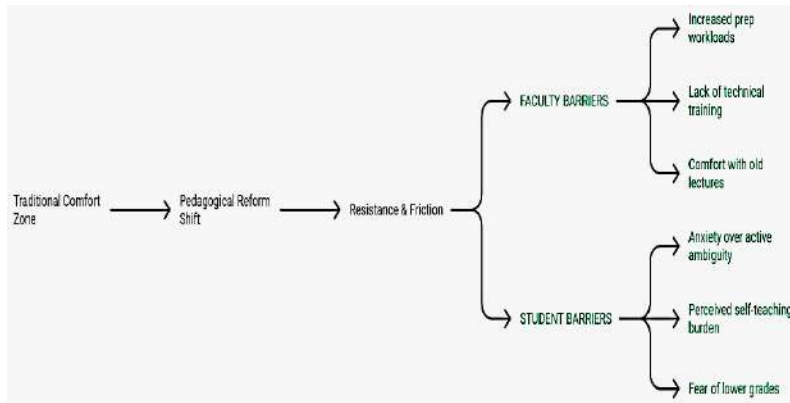


Figure 8.3 Challenges in Transitional Reform to Innovative Pedagogies among Faculty and Students

Beyond student resistance, faculty members also face their own set of challenges like an increased workload for course preparation, a lack of technical training when it comes to simulation equipment, and the comfort of long-standing lecture routines [12,31].

Being confronted with this kind of resistance, the only way for institutions to build a supportive ecosystem should include providing students with clear orientations that exhibit the evidence behind active learning, giving faculty members support of instructional design, and also changing institutional reward structures so that teaching innovations are recognized in the same way as research publications [31].

9. CHALLENGES AND BARRIERS TO IMPLEMENTATION

9.1. Financial Constraints: The Cost of High-Tech Simulations

Implementing a high-tech pharmacy program calls for a huge amount of money. The equipment needed such as patient simulators, virtual reality headsets, and analytics platforms have high upfront costs. Besides buying, institutions have to cover the costs of subscription fees, updates, and technical staff. Such budgetary needs can make it extremely challenging for developing countries to even consider the possibility of introducing the program.

A good solution to the problem of money would be to ask the government to help, join a consortium of schools to share the facilities, find pharmaceutical companies willing to sponsor the program, or find cheaper or open-source virtual reality alternatives that are mobile-based [32]. To address these financial gaps, progressive schools form regional educational consortia to share high-tech facilities, secure corporate sponsorships from major pharmaceutical companies, and utilize open-source or lower-cost mobile-based virtual reality solutions [32].

9.2. Faculty Development: Training the Trainers

The successful adoption of innovative pedagogy depends heavily on the capability of the faculty [9,6]. However, many pharmacy professors are hired primarily for their deep scientific expertise or clinical backgrounds, receiving little to no formal training in educational theory, instructional design, or educational technology.

An untrained professor who is tasked with running a high-pressure Team-Based Learning session or operating a complex VR lab often becomes frustrated and leads to ineffective learning encounters [8,33]. Because of this, it is critical that institutions must facilitate faculty development [9].

This entails setting up specially focused Centers for Teaching and Learning, as well as offering various workshops, peer mentorship programs, and even formal certifications in health professions education [9,10]. Faculty need both time and resources to convert the traditional passive instruction into more interactive educational experiences [11,32].

9.3. Accreditation and Regulatory Hurdles in Curriculum Reform

It is also clear that there is also tight regulation within the pharmacy courses by the global accreditation bodies such as the ACPE (United States), GPhC (UK) and the PCI (India) [12,33]. They regulate contact hours, the course topic coverage and course structure to protect the public [33].

Though, these strict regulations are one of the main challenge to pedagogical innovation. If accreditation requirement spend fixed physical hours in lecturing, so this issue could be a highly challenge for department that schedules a fully flipped or hybrid curriculum [15,34].

These obstacles can be removed only by educators through constant and constructive communication with accreditation boards. Besides that clear data-driven evidence aiming at active, competency-based teaching methods are required to show that such methods not only are in compliance with traditional standards but also exceed them [17, 34].

10. FUTURE HORIZONS

10.1. The "Metaverse" in Global Pharmacy Collaboration

The creation of the 'Metaverse', consisting of several interacting 3-D virtual worlds, is transforming the ways pharmacy professionals worldwide work together and how long-distance learning has been implemented Because of this far [35]. Student exchanges and international team projects through traditional ways are often hindered by geographical, financial, and practical issues. Immersive VR settings enable a student from one continent to be with a student of another continent simultaneously in a digital world. They can work together in that space on the same molecular structures or on the simulation of a complicated public health situation replaced by real interactions [7, 35].

This borderless laboratory environment gives an opportunity for the students of one institution to learn with those of another institution. As a case in point, a student of pharmacy in Asia, together with the student in America, can be working on a simulation of a disease outbreak and would be figuring out together the limitations of the supply chain, the ethics of the distribution of vaccine, and the decisions of the therapy [35]. What is fundamentally the metaverse is the ability to create an unfolding of a highly critical health system on a large scale without the need of any physical infrastructure, on top of all this through one digital interface the students gain a global health perspective through understanding the different health policies, clinical realities, and epidemiological patterns [34, 35].

10.2. Precision Medicine Education: Genomics and Personalization

The historical model of prescribing drugs that was based on population-wide statistically average efficacy, is now being replaced by the precision medicine. To enable this, pharmacy colleges have to make necessary changes in their teaching methods that at the moment mainly focus on standard dosage guidelines for generic drugs [36]. One of the main aspects of precision medicine is pharmacogenomics which refers to determining how an individual's genetic make-up affects the individual's response to the drug, the drug metabolism, and the drug toxicity. What used to be a scientific elective concept is becoming an essential clinical tool [36].

In an innovative pedagogy precision medicine classroom, students no longer need to think that memorizing drug classes is the only way to go. The challenges will be learning the interpretation of the genomic sequencing report. The students will be learning the inter-individual variability of CYP enzymes to be able to predict drug-drug and drug-gene interactions-specific patient [36]. For

teaching this, the institutions are using modules in which students work on genomic datasets which may be simulated or anonymized. This will help them learn how to customize therapies for oncological, cardiovascular, and psychiatric diseases where the therapeutic window is very limited and dose adjustment is crucial [12, 36]. If you teach these future professionals to work with large biological datasets, they will be fully capable of assisting various teams of health professionals in making medication choices that are suited to the patient [21, 36].

11. CONCLUSION

11.1. Summary of Key Findings

Revamping pharmaceutical education with innovative teaching is not just a matter of choice but a clinical imperative as it is driven by the changing complexities of healthcare. In this article we have identified the shortcomings of traditional, passive approaches to education that do not equip pharmacists with the skills necessary to function effectively in an environment in which they are required to analyze data skillfully, make clinical decisions and lead interprofessional health care teams [1, 3]. Employing adult learning theory and Bloom's Taxonomy in curriculum design will surely help educational institutions to allow their students to learn so that ultimately will make them not only memorizers but also innovators [4, 6].

Table 11.1 Outcomes of the Innovative Pedagogies

Pedagogy Category	Core Technology/Method	Direct Educational Outcome
Digital Integration	VR Cleanrooms & AI Platforms	Risk-free technical training and personalized academic remediation [9, 10].
Active Learning	Flipped Classrooms, TBL, & PBL	Enhanced critical thinking, collaborative peer problem-solving, and diagnostic logic [13, 14].
Experiential/Simulation	High-Fidelity Simulators & OSCEs	Objective behavioural assessment and mastery of clinical safety protocols [17, 18].
Industry & Systems	Quality by Design (QbD) & IPE	Reduced real-world medication errors and aligned translation to commercial pharma [23, 25].

11.2. Call to Action: A Global Framework for Pharmaceutical Pedagogy

The archetype shifts detailed across this extensive analysis demand more than localized, fragmentary curricular updates. The variations in archetypes exposed in this huge review require far more than piecemeal, localized curricula revisions. To respond to this dual increase in pace of therapeutics and healthcare complexity by twofold, global pharmacy education needs a holistic

structural overhaul. Educational institutions, regulatory bodies at the level of the world as well as different regions, and the pharmacy industry should team up to develop the Global Framework for Pharmaceutical Pedagogy [34]. This model should go beyond geographical differences and a pharmacist who has been educated in a developing country will be able to have the same baseline competencies in digital health, working with interdisciplinary teams, and communicating with patients as the one who has been trained in a well-funded Western institution [3, 34].

Firstly, the authorities and bodies responsible for regulations and accreditations like the Accreditation Council for Pharmacy Education (ACPE) in the United States, the General Pharmaceutical Council (GPhC) in the United Kingdom, Pharmacy Council of India (PCI) and the equivalent national councils globally should redefine their mandates [34]. Measures for accreditation should no longer focus on counting inputs such as the number of hours students spend in traditional lecture halls. Instead, institutions should be required to implement active, technology-enhanced, and experiential teaching and learning methods [13, 18]. And, these bodies should motivate schools to allocate certain portions of their programs to interprofessional education (IPE), objective structured clinical examinations (OSCEs), and high-fidelity simulations [17, 21].

Secondly, create a global depository for open access digital education resources. Developing state of the art VR environments, high-fidelity simulation prompts, and AI-enabled personalized instruction is an expensive proposition [7, 32]. To combat the inequality of education and ensure that only the richest schools don't have access to up-to-date teaching aids, a consortium of sorts led perhaps by the International Pharmaceutical Federation (FIP) should oversee the selection, stewardship, and distribution of open access teaching materials and pedagogical tools [34]. This collective effort will give underfunded universities access to Virtual Cleanrooms and gamified therapeutics modules, creating a more equitable playing field for pharmaceutical education [9, 12]. Finally, some change in the rewarding and training of faculty makes sense on the nucleus of universities [33].

And last but not least, universities must at their core address how faculty are rewarded and trained [33]. The old “publish or perish” concept, which favors research in labs, has sidelined teaching. Increase the value of educational research, formal certification in health professions education, and the consideration of innovative teaching for tenure and promotion [31, 33]. Faculty need time, conducive environment, and financial means to move from traditional lecturers to active learning facilitators [5, 31]. The change in the role of pharmacists from compounding apothecary to clinical advocate and genomic data analyst has been implemented, so education should be changed because of this [1, 36].

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Advancing Dental Implant Success: Role of Magnetism in Dental Implant Osseointegration

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ABSTRACT

This review evaluates the potential contribution of magnetic stimulation to dental implant osseointegration, focusing on static magnetic fields (SMF) and pulsed electromagnetic fields (PEMF), their effects on bone biology, possible mechanisms of action, and their implications for implant stability. Relevant evidence presented in the available literature was reviewed to assess the influence of magnetic stimulation on osteogenic activity, vascularization, bone remodeling, bone-to-implant contact, and implant stability. Findings from experimental cell-based studies, animal models, and available clinical investigations were considered, along with the types of magnets and magnetically modified implant systems investigated.

1. INTRODUCTION

Dental implants in dentistry from past some years have, out shown as the most fortunate treatment modalities for the restoring edentulous spaces, pointing to evolution in restorative dentistry. A dental implant is a restorative treatment biocompatible option, predominantly fabricated from alloplastic materials like titanium or its other alloys, that is surgically placed inside the bone alveolus to simulate artificial root of a missing tooth. The conventional framework of implantology debts its intellectual logics to Brånemark, whose pioneering explanation of the osseointegration basics brought shift in restorative discipline. Osseointegration suggests the end to end structural and functional approximation between living jaw bone and the biocompatible dental implant surface, which is supposed to be achieved in the absence of any intervening fibrous connective tissue, termed as fibrointegration.¹ This particular phenomenon forms the milestone of long-term success of implant, contributing to the stability which is primary requirement for bearing physiological masticatory load.

Among all treatment options for restoring missing teeth, dental implants provides a bunch of clinical advantages over primitive removable treatment options, providing good quality aesthetics & phonetics, improved chewing efficiency, saving the alveolar ridge, and a marked improvement in patient's comfort and life quality.² Nevertheless, in spite of high success rates,

late bone formation and occasional implant failure contributes numerous therapeutic challenges. Consequently, sustained scientific inquiry has been directed towards the exploration of innovative strategies capable of expediting osseointegration and augmenting implant stability, thereby further refining the predictability and longevity of implant therapy. Factors Affecting Dental Implant Osseointegration.

Implant Material

Titanium and titanium alloys are the most commonly used implant materials because of their excellent biocompatibility, excellent corrosion resistance, and mechanical properties.³

Implant Surface Characteristics

Surface roughness of implant, topographical features, and surface wettability significantly influence osteoblast attachment and bone healing around implants.⁴

Bone Quality and Quantity

Adequate bone density and volume are essential for primary stability and long-term implant success.⁵

Surgical Technique

Excessive heat generation during osteotomy preparation can cause bone necrosis and impair osseointegration.⁶ Atraumatic procedures always leads to favourable results.

Systemic Health

Conditions such as diabetes mellitus, osteoporosis, smoking, and immunosuppression negatively affect implant healing and survival.⁷ So, before implant placement patient must have controlled values for their relative contraindications.

Occlusal Loading

Premature or excessive loading may disrupt the bone healing process and lead to implant failure.⁸ Delayed loading is always preferred for implant success over immediate or early loading.

Infection Control

Poor oral hygiene and peri-implant infections are major causes of peri-implant bone loss and implant failure.⁹

Surface Treatments to Improve Osseointegration

Various implant surface modifications have been developed to improve bone-to-implant contact.

Sandblasting

Sandblasted implant surfaces exhibit increased roughness that enhances osteoblastic attachment and proliferation.¹⁰

Acid Etching

Acid etching creates micro-irregularities that improve protein adsorption and cellular adhesion.¹¹

Plasma Spraying

Hydroxyapatite plasma coatings improve osteoconductivity and accelerate bone formation.¹²

Anodization

Anodized titanium surfaces demonstrate improved bioactivity and increased surface energy.¹³

Laser Surface Modification

Laser treatment creates controlled surface microtopography favorable for osseointegration.¹⁴

Bioactive Coatings

Bioactive molecules, including calcium phosphate compounds and an array of osteoinductive growth factors, have garnered considerable scientific interest owing to their remarkable capacity to stimulate peri-implant bone regeneration.

By organising cellular proliferation, differentiation, and mineralization, these biological factors creates an ease for a more conducive micro-environment for bone formation, thereby improving dental implant bone integration and longer durability & stability.¹⁵

Role of Magnetism

Osseointegration stimulation using magnets and magnetically enhanced dental implant surface modifications adds bone forming cell proliferation and differentiation, causing angiogenesis, and accelerating the process of bone reformation, these dental innovations provides a more favourable space for osseointegration. So, they carry appropriate potential for improved implant stability, speedy healing, and enhances the longer success of implant treatment.¹⁶

2. TYPES OF MAGNETIC FIELDS

Static Magnetic Field (SMF)

Static magnetic fields provided by fixed magnet sources, the unwavering intensity and fixed directional orientation over long period of time. Latest scientific proofs in this field are suggestive of favourable effects on the biological healing processes such as osseous regeneration.

By contributing to osteoblastic migration, differentiation, & functions, SMFs facilitate the deposition of mineralized regenerative tissue in the near implant region, hence affecting it towards more rapid osseointegration.¹⁷

Pulsed Electromagnetic Field (PEMF)

Pulsed electromagnetic fields (PEMFs) are created by the application of altering electric currents that produce intermittent effective electromagnetic pulses of gauged frequency as well as intensity. By providing stimulus for cell proliferation, increasing angiogenesis, and process of bone regeneration, PEMFs create a more favorable space for osseous healing.

These multiple positive biological effects have placed PEMF therapy as a promising adjunctive modality for fastenning peri-implant bone layering & improving implant osseointegration predictability.¹⁸

3. ROLE OF MAGNETISM IN MEDICINE

Magnetic treatment has wide range uses in medical diagnosis and therapy.

- Magnetic resonance imaging (MRI) for diagnosis is a non-invasive method which uses high intensity magnetic radiations & radiofrequency waves so as to produce detailed or enhanced images of soft tissues. Due to marked soft tissue visual contrast and excellent diagnostic accuracy, MRI is commonly advised for the diagnosis of so many diseases without exposing patients to harmful ionizing radiation.¹⁹

- Pulsed electromagnetic field (PEMF) therapy has come across as a very important treatment option in contemporary orthopaedic clinical practice, especially in the fracture management contributing faster union or non-union.²⁰
- Magnetic nanoparticles have emerged as a transformative innovation in targeted drug delivery systems, owing to their ability to transport therapeutic agents with remarkable precision to specific anatomical sites under the influence of externally applied magnetic fields.²¹
- Magnetic hyperthermia has emerged as a promising therapeutic strategy in oncological research, wherein magnetically responsive nanoparticles are exposed to an alternating magnetic field to generate localized heat capable of selectively damaging malignant cells.²²
- Magnetic stimulation has assumed an increasingly significant role in the rapidly evolving fields of regenerative medicine and tissue engineering.²³

4. ROLE OF MAGNETISM IN DIFFERENT DENTAL SPECIALTIES

Endodontics

Magnetic nanoparticles helps them to invade the various complexities of the dental root canal system, including complex dentinal tubules, lateral root canals, and rest of anatomical irregularities that normally are inaccessible to conventional irrigants. By promising an effective microbial eradication and site specific drug delivery systems, these nanoparticles have the magical potential to significantly enhances the outcome of endodontic therapy while minimizing collateral damage to the surrounding unaffected tissues.²⁴

Oral Surgery

Magnetism favourably influences the biological phenomenon which governs tissue healing, bone formation, and vessel formation, it contributes faster recovery with better prognosis. Also, their anti-inflammatory qualities found to be associated with lesser postoperative inflammation and improved healing, thereby adding to its potential as a valuable treatment option for better surgical outcomes in contemporary oral and maxillofacial practice.²⁵

Periodontics

Recent studies suggests suggests that magnetic stimulation favourably influences periodontal wound healing by enhancing the proliferation & functional activity of fibroblasts, the main cells responsible for the formation, maintenance, and repairing of periodontal connective tissues. Also, exposure to any magnetic fields has been found to stimulate natural collagen synthesis, adding to local microcirculation, and angiogenesis, creating a biologically favorable environment for regeneration for tissue. Overall, these effects contribute to increased healing of periodontal and underscore the potential of magnetic stimulation therapy as an additive treatment modality in periodontal regeneration.²⁶

Orthodontics

Magnetic forces have been considered valuable in contemporary orthodontics applications, where they are primarily used to result in controlled tooth migration through the delivering gentle, continuous, and calculated forces. These biomechanical features are responsible for efficient orthodontic tooth movement while reducing patient discomfort and reducing unwanted tissue

reactions. Furthermore, some magnets have been successfully planted into orthodontic retention systems and removable orthodontic appliances to improve their stability, retention, and overall patient ease.²⁷

Oral Medicine

Relating to their very compact sizes, ease of placement, and tendency to generate continuous force without any mechanical complexity, these magnets continue representing a varied as well as promising option for pain relieving therapy in recent oral medicine.²⁸

Prosthodontics

Magnetic attachment systems in prosthodontics by providing strong atraumatic retention to remaining naturally present teeth, transosseous dental implants, or other supporting prosthodontics structures, these systems significantly provide improved function of prosthesis and comfort of the patient. Their significance here is well established in the retaining overdentures as well as maxillofacial prostheses, where their adequate design, ease of their maintenance, and ability to impart consistent calculated retentive forces have made them an invaluable treatment option in contemporary prosthodontic rehabilitation.²⁹

Implantology

Many studies showed that magnetic stimulation has well known capability in improving peri-implant bone generation and improving implant's stability. By positively influencing the biological processes affecting underlying bone formation, blood vessel formation, and bone maturation, it helps more faster and active osseointegration. These advantageous effects contribute to better primary and secondary implant stability, causing improved predictability and long-term success of implant therapy.³⁰

5. REVIEW OF LITERATURE ON ROLE OF MAGNETISM IN DENTAL IMPLANTS

Numerous investigations have positively evaluated the effect of magnetic fields on the osseointegration of dental implants. Diniz et al. found in their study that exposing dental implants to pulsed electromagnetic fields had resulted in increased formation of bone- tissue around the dental implant surface.³⁰ In animal trials conducted by Teng et al., magnet incorporated implants suggested better osseointegration compared with non-magnetized dental implants.¹⁷

Ceccarelli et al. reported that electromagnetic stimulation enhanced osteogenic differentiation along with angiogenic activity, thereby supporting bone regeneration.²³ Similarly, Xu et al. observed increased bone formation around magnetic composite materials in experimental models.³¹ Nayak et al. demonstrated improved implant stability in magnetically stimulated implants.³²

Although available studies show promising results, further long-term randomized clinical trials are necessary to establish definitive clinical protocols.

Materials of Magnets Used in Dentistry

Neodymium-Iron-Boron (NdFeB)- NdFeB magnets are commonly used because of their strong magnetic properties.³⁶

Samarium-Cobalt (SmCo)- SmCo magnets possess excellent corrosion resistance and thermal stability.³⁶

Ferrite Magnets- Ferrite magnets are economical but provide lower magnetic strength.³⁶

Effects of Magnetism on Bone Cells

Magnetic fields influence several cellular activities associated with bone healing.

- Increased osteoblast proliferation³³
- Enhanced alkaline phosphatase activity³⁴
- Increased collagen synthesis³⁵
- Promotion of angiogenesis²⁶
- Reduction of osteoclastic activity³⁶
- Increased expression of bone morphogenetic proteins and transforming growth factor-beta³⁷

All these effects of magnetism collectively enhance peri-implant osseointegration i.e. bone formation and healing.

6. MECHANISM OF ACTION OF MAGNETISM FOR FASTER OSSEOINTEGRATION

Cellular Stimulation

Magnetic fields alters ion exchange and cell membrane permeability, thereby stimulating bone forming activity.³⁷

Increased Blood Circulation

Magnetic stimulation improves microcirculation and nutrient delivery to healing tissues because of iron presence in human blood.²⁶

Growth Factor Activation

Electromagnetic stimulation enhances the release of osteogenic growth factors.³⁸

Magneto-Caloric Effect

The magneto-caloric effect refers to thermal changes produced by magnetic exposure. These localized temperature changes may influence cellular metabolism and bone remodeling around implants.³⁹

Piezoelectric Effect

Bone exhibits piezoelectric properties, and magnetic stimulation may enhance electrical signaling involved in bone formation.⁴⁰

7. BENEFITS OF MAGNETICALLY ENHANCED IMPLANTS

- Faster osseointegration
- Improved implant stability
- Reduced healing period
- Increased peri-implant bone density
- Better outcomes in compromised bone
- Possibility of early loading
- Reduced inflammation and improved healing response

8. BIOCOMPATIBILITY AND SAFETY OF USING MAGNETS IN DENTAL IMPLANTS

Biocompatibility is an essential consideration in magnetic implant systems. Modern dental magnets are coated with biocompatible materials such as titanium to prevent corrosion and adverse tissue reactions.²⁹ Studies indicate that controlled magnetic exposure is generally safe for oral tissues.³⁶ However, increased magnetic intensity might produce harmful thermal effects which could interfere with electronic devices incorporated in human body such as pacemakers.¹⁹ Therefore, future long-term research in this field is needed to establish the safety protocols and efficacy of magnetized implant systems.

9. PROGRESSION OF MAGNETIC FIELD RESEARCH IN OSSEOINTEGRATION

In-Vitro Studies

Cell culture studies results showed improved bone generating cells proliferation, improved bone maturation and mineralization, and improved gene expression under such magnetic stimulation.^{23,34}

In-Vivo Studies

Animal studies results showed magnetism favored bone-to-implant contact (BIC) and increased peri-implant bone layering and maturation.^{17,31}

Clinical Trials

Few reported clinical studies showed improved mechanical implant stability and accentuated healing process in dental implants when exposed to magnetic field stimulation.³² However, some more randomized controlled clinical trials are needed to be done before widespread clinical application.

10. CONCLUSION

Magnetism has outcasted itself as a much promising additional approach in implant dentistry because of its favorable effects on bone healing process and osseointegration. Both statically applied magnetic fields as well as pulsed electromagnetic fields stimulate bone forming activity, blood vessel formation, and near implant bone formation. Results of the studies from in-vitro, in-vivo, and clinical studies are suggestive of the fact that magnetic stimulation can accelerate osseointegration and can result in improved implant stability.

Although current evidence is encouraging, additional clinical trials and long-term studies are necessary to establish standardized treatment protocols and evaluate long-term safety. Future advancements in biomaterials and magnetic technologies may further improve the predictability and success of dental implant therapy.

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Bridging the Skill Gap through Industry–Academia Collaboration: A Study of Engineering and Management Students in Indian Private Universities

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ABSTRACT

Increasing gaps in terms of educational readiness versus industrial requirements have been recognized as one of the key challenges faced by Indian higher education system, specifically private universities. This paper attempts to analyse theoretical and practical aspects of Industry-Academia Collaboration (IAC) as a possible instrument to improve the skills of engineering and management graduates in Indian private universities. By conducting a literature review of more than twenty scholarly sources which have been published during the period 2018-2024, the study will present theoretical models and frameworks, empirical evidence, and other relevant information in relation to issues of collaboration in education, skill building and graduate employability. The paper will discuss the issues in the context of National Education Policy (NEP) 2020, with a focus on structure, pedagogy and institutions of collaboration and their impacts on IAC activities. Issues such as curricula co-creation, internship ecosystems, mentoring programs, technological solutions and measurement of employability will be discussed in detail. It is evident from the findings of the review that effective IAC requires continuous efforts and institutional commitment, mutual trust, regulatory flexibility and outcome metrics.

Keywords: Industry–Academia Collaboration, Employability Skills, Engineering Education, Management Education, Indian Private Universities, NEP 2020, Curriculum Reform, Skill Development.

1. INTRODUCTION

India is now at a pivotal point in its higher education evolution. Being home to over 1,000 private universities and almost 40,000 engineering and management colleges, India possesses one of the biggest higher education systems worldwide (UGC, 2023). However, the National Employability Report repeatedly confirms that only about half of engineering graduates and just 30 percent of management graduates are deemed employable by industries upon graduation (Aspiring Minds, 2019; TeamLease, 2022). The existence of the paradox of growth of quantitative indicators combined with stagnation of quality parameters has sparked discussions about the relevance of academic programs offered at India's private universities. Although private universities tend to have greater resources for building facilities compared to public educational institutions, they still

experience serious problems with making their curricula relevant to industry requirements (Kumar & Jain, 2020).

The term employability goes well beyond mere job placement. According to Hillage and Pollard (1998), employability is "the ability to secure and sustain employment through continuous learning". Contemporary knowledge economies make employability depend on technical skills, cognitive abilities, interpersonal

attributes and professional attitudes of those involved are largely influenced by the quality of the learning environment. The industry-academia collaboration (IAC) can be seen as one of the possible structural solutions to this issue. Participation of the industries in design, delivery, and assessment of educational programmes adds certain contextual depth that cannot be provided by standard classroom education. NEP 2020 emphasizes the need for cooperation between universities and industries as a key element of the educational reform. This research explores the forms, extent, and consequences of IAC in Indian private universities specializing in engineering and management. In particular, the following questions are being addressed: What are the most efficient forms of IAC? How do they build employability skills?

2. LITERATURE REVIEW

IAC has attracted substantial scholarly discourse that is progressively more result-oriented. This chapter consolidates twenty-two peer-reviewed articles published between 2018-2024, spanning seven thematic dimensions.

2.1 Conceptual Foundations of Employability

Employability, according to Yorke (2006), refers to the accomplishments, capabilities, knowledge base, and individual traits that make it easier for graduates to find employment opportunities and excel in their chosen careers. Tomlinson (2017) further elaborated on this definition and claimed that the nature of employability is becoming performative and involves being able to convincingly showcase one's skills to potential employers. When it comes to India, Sharma & Sharma (2019) have established that engineering college students continuously underestimate the significance of soft skills until they get into the recruitment process and discover that good communication skills, teamwork, and flexibility rank at the top of employers' wish lists but are rarely taught systematically in colleges. Kaur & Bhatt (2021) made similar findings.

2.2 Models and Forms of IAC

Ankrah and Al-Tabbaa (2015) have given a comprehensive classification of IAC types: knowledge transfer partnership, sponsored research, curriculum advisory committee, joint ventures, and placements, where transactional collaboration is distinguished from relational collaboration; the latter has proven to be much more beneficial educationally. Perkmann et al. (2021) classified IAC by updating the previous one through the addition of virtual internships, e-teaching, and open innovation portals and concluded that most successful cooperation is based on industry participation in curriculum design. In an Indian setting, the study by Mehrotra and Ghosh (2022) revealed that universities having a formal Industry Advisory Board (IAB) had better placement scores and were more popular among students. Singh and Mishra (2020) developed the concept

of a "triple helix engagement model" for India, claiming that sustained skill development needed simultaneous involvement of university administrations, faculties, and students.

2.3 NEP 2020 and the Policy Environment

The NEP 2020 requires multidisciplinary education, multi-points of entry and exit, and strong industry partnerships (Ministry of Education, 2020). Joshi & Vaidya (2022) found that whereas high-ranking private institutes responded well to NEP requirements, mid-ranking universities did not have the necessary governance frameworks and incentives to maintain good industry relationships. The works of Nair & Thomas (2021) on credit-bearing internships, corporation-endowed chairs, and joint development of micro-certification programs revealed that institutions which had achieved higher NAAC ratings were likely to develop better IAC framework.

2.4 Skill Gaps and Graduate Unreadiness

According to Aspiring Minds (2019), only 3.84 percent of more than 1.5 lakh students in 650 different universities were immediately employable for software jobs. For the management domain, Reddy & Rao (2020) highlighted that MBA graduates in South India performed poorly when tested for decision making, communication across functional domains and ethical thinking in uncertain situations, all of which IAC can teach through practical experiences.

2.5 International and Comparative Perspectives

The Triple Helix framework developed by Etzkowitz and Leydesdorff (2000) sees relationships between universities, industries, and government as an evolving interaction system. As applied to India by Pandey and Shrivastava (2021), it needs to incorporate the fragmented regulatory context and diverse industrial ecosystem of the country. Ramirez-Correa et al. (2022), conducting their research on the collaboration practices of private universities in Chile, observed that such collaboration projects were usually spearheaded by the efforts of the individual academic members, leaving them exposed to discontinuities which proved to be true for India as well. Deem et al. (2020) posited that private universities in developing countries had the best conditions to initiate IAC but were unable to do so out of risk aversion and profit orientation.

2.6 Technology-Enabled Collaboration

According to Verma & Chauhan (2021), virtual internships and virtual mentoring in times of the Coronavirus pandemic were significantly correlated with the level of structured guidance provided by the faculty. Arora & Singh (2022) discovered that students taking part in hybrid IAC courses (in-person/digital) achieved significantly higher scores for employability and better results in campus recruitment tests.

2.7 Faculty Development and Outcome Measurement

According to Bhardwaj and Mehta (2022), faculty with industrial experience proved to be much more effective in connecting theory with practice. According to Choudhary and Roy (2023), there is an important issue regarding the lack of appropriate mechanisms in private universities of India to measure the effect of IAC programs on the employability of graduates in the long term. In order to distinguish useful collaborations from the ones that are purely ceremonial, such outcome measures should be established.

3. THEORETICAL FRAMEWORK

The research is based on three interrelated theoretical frameworks. The Human Capital Theory (Becker, 1964; Schultz, 1961) states that investing in education leads to an improvement in productive abilities and market value making IAC interventions high-return investments in human capital for educational institutions and the industry as a whole. The Triple Helix Model (Etzkowitz & Leydesdorff, 2000) treats innovation as a result of dynamic interaction between universities, industry and the government showing why structural solutions to the problem of employability need to be mediated by such bodies as AICTE, UGC and skill development missions of individual states. The theory of social learning (Vygotsky, 1978; Bandura, 1986) highlights the social nature of learning process and importance of context-based learning environment provided by internship and mentoring allowing students to observe and imitate professional practices.

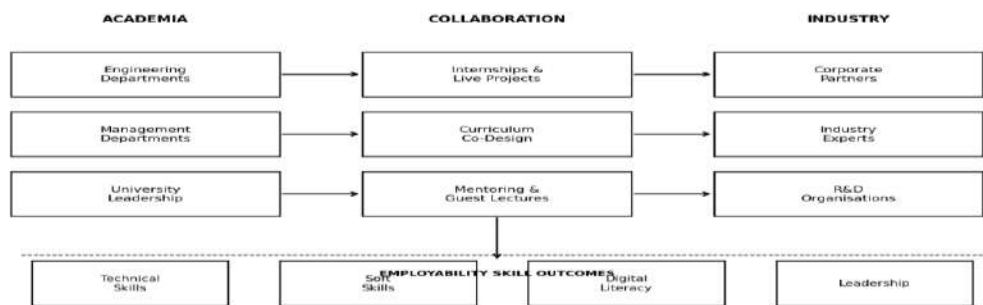


Figure 1: Conceptual Framework (Industry–Academia Collaboration for Employability Skills Development)

4. FORMS AND MECHANISMS OF IAC IN INDIAN PRIVATE UNIVERSITIES

4.1 Curriculum Co-Creation and Advisory Boards

Industries that are involved in the formation of an Industry Advisory Board (IAB) with representation diversity have been seen as an important process to make sure that the academic programs are aligned with the needs of the profession. Mehrotra & Ghosh (2022) discovered that private institutions with the existence of the IAB updated the curriculum more often and added applied learning in the courses more efficiently. Co-created curriculum creation includes collaborative authoring of the course material, assessment criteria, and learning outcomes by faculty and industry professionals.

4.2 Internship and Live Project Ecosystems

Internships with clearly defined goals, credit toward academic courses, faculty guidance, and mentoring by supervisors result in tangible gains in terms of technical skills as well as increased employability (Singh & Mishra, 2020). Industry-based live projects, wherein firms pose genuine problems before teams of students, who then solve them with dual mentoring within an academic semester, yield notable gains in interdisciplinarity, project management, and communication skills (Verma & Chauhan, 2021; Arora & Singh, 2022).

4.3 Mentoring, Guest Lectures, and Centres of Excellence

Continuous one-on-one mentoring in an industry throughout a minimum of one semester is beneficial for the development of career clarity, confidence, and professionalism among the students (Bhatia & Gupta, 2023). The educational value of guest lectures can be determined by arranging such lectures in a manner that facilitates interaction between the speaker and students on the issues that the latter face, rather than promoting the former's work (Nair & Thomas, 2021). On the other hand, at the highest level, Centres of Excellence (CoEs), which are joint initiatives of universities and industries, are knowledge centres (Pandey & Shrivastava, 2021).

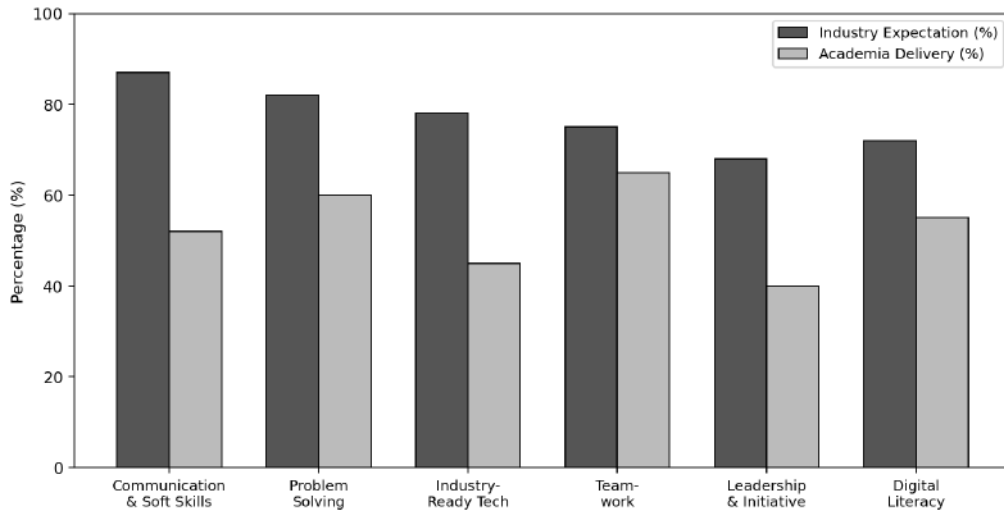


Figure 2: Skill Gap Between Industry Expectations and Academia Delivery in Indian Private Universities

5. BARRIERS AND CHALLENGES TO EFFECTIVE IAC

5.1 Structural and Regulatory Barriers

In cases where the private university is associated with the state university, the centrally determined syllabi have to be followed, which leaves no room for any customization in terms of the industry needs. In case of the autonomous university too, there is a lack of administrative flexibility to be able to respond to the industrial requirements regarding syllabus changes (Joshi & Vaidya, 2022).

5.2 Trust Deficit and Misaligned Incentives

The university system is seen by the industry as being too theoretical and bureaucratic, while the industry is seen by academia as being too commercialized. According to Ramirez-Correa et al. (2022), a large number of unsuccessful IAC projects can be traced back to mismatched expectations at the start. In terms of individuals, the performance of faculty members is measured based on their publications and teaching, and there is very little formal reward for engaging with the industry.

5.3 Quality Heterogeneity and Infrastructure Gaps

The best private universities have high-profile business partners, while smaller regional universities have difficulties in building any real ties with businesses resulting in a reinforcing system, whereby students who most require industry experience do not get it (Kumar & Jain, 2020). The other major issue faced by most universities is the lack of qualified IAC coordinators, who should possess skills for managing partnerships; instead, the placement cells focus solely on recruiting functions (Choudhary & Roy, 2023).

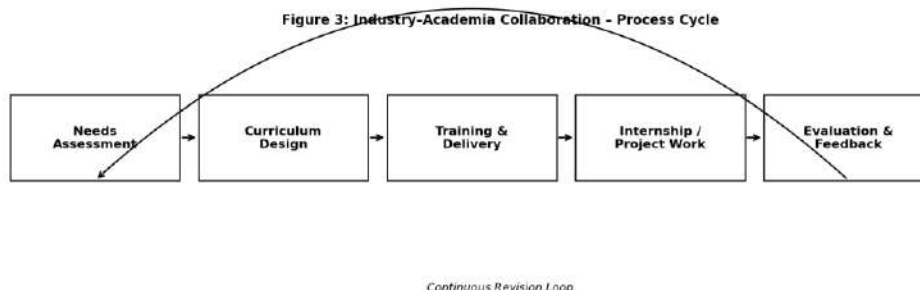


Figure 3: Industry–Academia Collaboration – Process Cycle

6. COMPARATIVE OVERVIEW: IAC MECHANISMS AND EMPLOYABILITY OUTCOMES

Table 1 summarises the key IAC approaches, the core employability skills targeted, the degree of institutional commitment required for each approach, and the critical literature review findings regarding each approach.

Table 1: Summary of IAC Mechanisms, Skill Outcomes, and Institutional Requirements

IAC Mechanism	Skills Developed	Commitment Level	Key Evidence
Curriculum Co-Design / IABs	Technical currency, interdisciplinary thinking	High	Mehrotra & Ghosh (2022); Nair & Thomas (2021)
Structured Internships	Applied skills, workplace adaptability, communication	Medium–High	Singh & Mishra (2020); Aspiring Minds (2019)
Live Industry Projects	Problem-solving, teamwork, digital tools	Medium	Arora & Singh (2022); Verma & Chauhan (2021)
Industry Mentoring	Career clarity, professional identity, leadership	Medium	Bhatia & Gupta (2023); Kaur & Bhatt (2021)

Guest Lectures (Problem-Centred)	Critical thinking, real-world exposure	Low–Medium	Nair & Thomas (2021)
Centres of Excellence	Research, innovation, entrepreneurial skills	Very High	Pandey & Shrivastava (2021)
Virtual / Hybrid Collaboration	Digital literacy, remote teamwork, self-regulation	Medium	Verma & Chauhan (2021); Arora & Singh (2022)
Faculty Industry Immersion	Pedagogical relevance, applied knowledge	Medium	Bhardwaj & Mehta (2022)

7. DISCUSSION

The synthesis of the literature indicates a coherent set of findings indicating IAC as the main lever for enhancing employability of engineering and management students at Indian private universities. It should be stressed, however, that collaborative education is highly context-dependent and is determined by the design of the process, the commitment of the institution, and its alignment to the stated educational goals. One of the most critical observations made during the analysis is that of a distinction between ceremonial and meaningful collaboration (Choudhary & Roy, 2023). The institutions of higher education tend to sign dozens of MOUs, while implementing a very small portion of those into an operational programme based on the checklist of accreditation criteria, rather than on the educational mission. The skills gap highlighted in Figure 2 includes those of technical industry readiness and leadership with communication skills being significant as well.

The framework presented in Figure 3 illustrates the iterative and cyclical process inherent in effective IAC. The constant feedback process of evaluation to need assessment illustrates the concept of IAC as an adaptive learning system and not a static program. An institution perceiving IAC as a static program is unlikely to enjoy the fruits of IAC initiatives. The theoretical framework based on Human Capital Theory, the Triple Helix Model, and Social Learning Theory serves as a justificatory and design framework for IAC initiatives. Human capital theory explains the instrumental role of IAC, while the Triple Helix Model explains the conditions under which IAC is possible. Social Learning Theory explains how IAC helps to develop competencies of the learners. Gender and equity issues also need to be considered since evidence shows that internships and mentorship programs are not equally shared between male and female students, especially in the field of engineering.

8. RECOMMENDATIONS

8.1 For University Leadership

Private universities ought to create specialized IAC cells with personnel having expertise in managing partnerships, tasked with formulating strategic multiyear partnerships with metrics for

their success, holding an annual IAB meeting with a meaningful agenda for review of the curricula, and making the results of IAC public. The incentive system for faculty members needs to be restructured to account for industry participation in their performance evaluations.

8.2 For Industry Partners

Organizations need to go past transactional recruitment engagement to co-invest in the training of talent through curriculum development, structured internships with mentoring programs, applied research, and faculty development. Organizations that have a significant number of employees should think of creating an academic partnership function in their HR and CSR teams just like the one established by Infosys, Wipro, and TCS.

8.3 For Policymakers and Regulatory Bodies

Incentive programs must be designed by the AICTE, UGC, and State organizations for linking the quality of cooperation between colleges with the accreditation marks. The NEP 2020 has called for compulsory credit based internship program which must be followed up through proper criteria for quality and faculty monitoring. A framework for Impact Assessment of IACs must be developed nationally.

9. CONCLUSION

In this paper, an in-depth theoretical and empirical study of IAC as a strategic tool for improving the employability of engineering and management students in Indian private universities has been conducted. Review of more than twenty research papers reveals a definite trend: substantive and systematic IAC leads to improvements in both technical and soft skills of students. But at the same time, collaboration in the private university setting in India appears to be inconsistent, improperly motivated, and ritualistic. The concept based on the theories of Human Capital Theory, Triple Helix Model, and Social Learning Theory allows us to see collaboration through the prism of its effectiveness, proper design, and necessary conditions for implementation. An example of the iterative collaboration cycle shown in Figure 3 is a possible process model applicable in many situations. The issue of employability among graduates of Indian private universities is not the problem of students themselves; it is a problem of inconsistency between their preparation and actual needs. Therefore, the solution to the problem requires rethinking the university-industry collaboration as such. The policy mandate is provided by NEP 2020; what is required next is the will to implement this mandate and create the necessary administrative framework and cultural change.

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A Comparative Study of Breath-Holding Capacity Among Smokers, Athletes, and Non-Athletes

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ABSTRACT

The purpose of this study is to compare the breath holding capacity levels among three different groups i.e. Smokers, Sports person and non-sports person, this test was administered by the guidelines given in Body Oxygen Level Test developed by Patrick Mckeown in year 1950. The study aimed to examine the levels of physical activity and breath holding capacity level of lungs. A total of 150 male persons, aged between 20-25 years, were selected from Moradabad district, Uttar Pradesh. They were divided equally into three groups of 50 persons each. The collected data were analyzed by using one-way Analysis of Variance (ANOVA). The findings revealed a significant difference in lungs efficiency among three groups ($f = 42.602$, $p < 0.01$). Sports group persons demonstrated superior pulmonary capacity compared to smokers and non-sports persons.

The results clearly indicates that the regular participation in sports and physical activities enhances cardiorespiratory fitness and improve lungs capacity to hold breath for long time. It can be concluded that physical activity plays a vital role in maintaining and developing lungs capacity to hold breath, which is an essential component of overall health and physical performance.

Keywords: Pulmonary capacity, Smokers, Sports and non-sports persons.

1. INTRODUCTION

The body Oxygen Level Test is a quick and easy breathing test that measures how long a person can hold their breath after a normal breath out. This number of times is called BOULT score. It is an important part of overall fitness by having good breathing capacity helps the body to work better during performing any physical activity and sports. It reflects the efficiency of breathing control and the body tolerance of carbon dioxide. Smoking can affect the respiratory system and may reduce breath holding capacity, while sports participation may help improve breathing efficiency and lung's function. Studies shows that the smokers generally show poorer breathing capacity than sports and non- sports persons. The researcher categories the persons in three groups are smokers, sports persons and non-sports persons.

The 'Breath Holding Capacity Test' was developed by Patrick Mckeown in 1950. It is a method to assess breath holding capacity and lung's function. The testing of Breath holding capacity by this method is based on the assumption that the person having better lung's function,

performs any physical activity and have active participation in sports. The Breath Holding Capacity Test was to evaluate length of time of a comfortable breath hold served a simple test to determine relative breathing volume during rest and breathlessness during physical exercise. It is a very accurate tool for determining the breathing volume. The ideal BOLT score for a healthy individual is 40 seconds. If a person breath holds after a normal exhalation, it takes approximately 40 seconds before the urge to breath increases enough to initiate inspiration. In short, the lower the BOLT score the greater the breathing volume, and the greater your breathing volume, the more breathlessness you will experience during performing any exercise or sports.

1.1 OBJECTIVE OF THE STUDY

To compare the Breath Holding Capacity level of smokers, sports and non-sports persons in order to identify the influence of regular physical activity and sports involvement in their daily life.

1.2 DELIMITATIONS

1.2.1 The study is delimited to Smokers, Sports and Non-sports persons.

1.2.2 The study was further delimited to the Male participants limited to the age range between 20 – 25 years.

1.3 LIMITATION

The study was limited to the efforts put by all three categories during testing of Breath Holding Capacity.

1.4 SIGNIFICANCE OF THE STUDY

1.4.1 The study will help to access the fitness level of an individual person, which is the most important component of physical fitness.

1.4.2 The study will further help in to provide evidence for the conclusion and promotion of participation in physical activities and sports.

1.4.3 The study will help to contribute sports science and exercise physiology research-based study.

1.4.4 The study will help in assist coaches and trainers in designing better training strategies.

2.METHODOLOGY

2.1 Selection of subject:

For the purpose of the study, the researcher selected 150 male persons from Moradabad District, 50 samples from smoker's category, 50 samples from sports category and 50 from non-sports category persons age between 20-30 years. All the persons were selected from Northern and Southern region of India.

2.2 Selection of Variable:

For the purpose of the study the Researcher was taken Pulmonary capacity was taken as an independent variable.

2.3 Selection of Tool:

A standardized instrument used for assessing breath holding capacity in this study was a Digital Stopwatch, commonly employed in physiological testing due to its high accuracy and reliability in measuring time interval. The stopwatch was used to record the duration for which the subject holds their breath after taking maximum inhalation. To ensure standardization and reduce measurement error, the same stopwatch was used for all participants under similar environmental condition.

2.4 Criterion Measure: Breath Holding Capacity Test

For the purpose of the study Pulmonary capacity was measured through the Breath Holding Capacity Test in rest position and inhalation of maximum air in lungs. The test is used to assess lungs efficiency and capacity to hold the breath, with higher holding capacity indicates good efficiency.

2.5 Administration of The Test:

The breath holding capacity test was administered to assess the respiratory efficiency and lungs capacity of the persons. The test measures maximum duration for which an individual can hold their breath after a deep inhalation. The person was instructed to sit comfortably in an upright position each subject inhaled deeply through the nose and then grip their nose with fingers where air doesn't pass through mouth also and hold their breath for as long as possible without exhaling. A stopwatch was used to record the duration of breath holding capacity, starting immediately after inhalation and stopping at the point when the person exhaled or showed an inability to continue. The obtained data were recorded in seconds, used to evaluate lungs capacity and overall fitness level of the person.

2.6 Statical procedure

The collected data was analyzed by using one-way Anova for the comparison of Pulmonary Capacity among Smokers, Sports and non-sports persons.

3. ANALYSIS AND INTERPRETATION OF INFORMATION:

For this part, Researcher analyzed the data in percentage and interpreted it in a Chart.

Table 1: Sum and Average of Breath Holding Capacity Test Score of Smokers, Sports and Non-sports

SUMMARY				
Groups	Number	Sum	Average	Variance

Smokers	50	1456	29.12	230.1078
Sports person	50	2464	49.28	228.8996
Non- sports person	50	1770	35.4	228.4082

In table 1 researcher showed that the average value of smokers 29.12, sports 49.28 and non-sports was 35.4 and had a variance value are similar across all groups 228-230, which indicates that the data distribution is consistent and variability within each group is nearly equal.

Table 2: Result of one-way Anova (Analysis of variance).

ANOVA						
Source of Variation	SS	df	MS	F	P- value	F crit
Between Groups	10641.97	2	5320.987	23.2217	1.72E-09	3.057621
Within Groups	33683.36	147	229.1385			

Table.2 Represents the statical comparison of Breath Holding Capacity among three different groups by using a One-way ANOVA Test. The Calculated f-value (23.2217) is higher than the critical F-value (3.0576) is clearly indicates that there is significant difference among the groups means and p-value (1.72E-09) is less than 0.05 that's means the result is highly significant. There is a significance difference in lungs breath holding capacity among three different groups.

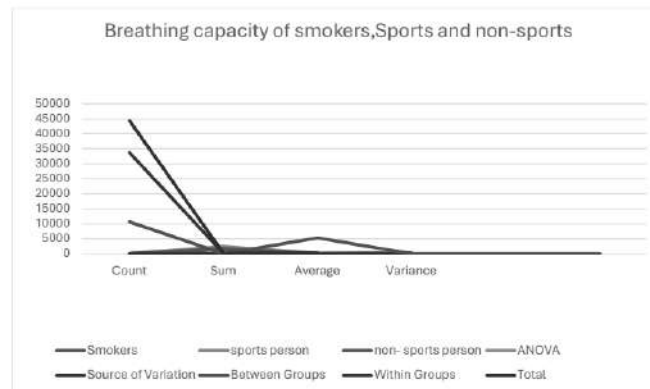


Figure 1. Mean and Standard Deviation of Breath Holding Capacity among Smokers, Sports and non- sports Persons.

This indicates that there is significant difference in lungs capacity to hold breath level among the persons under study.

The findings suggest that the level of physical activity and playing sports on regular basis shows the crucial role in determining lungs efficiency. Participants belonging from the sports group have superiors' pulmonary capacity as compared to smokers and non-smokers. This outcome classifies that regular physical training and participation in sports activities enhances breath holding capacity performance by improving lungs capacity and respiratory efficiency.

4. CONCLUSION AND RECOMMENDATION

4.1 Conclusion

The data was collected by using Breath Holding Capacity Test in which researcher easily verify pulmonary capacity of an individual or a group, which reflects the ability of heart and lungs to hold air in lungs for maximum number of times, which may help in sustained during performing any physical

activity, is significantly higher in sports activities individual compared to non-sports and smoker's persons. Sports category benefits from structured, consistent training that promotes heart health and respiratory efficiency oxygen use and greater stamina to perform any physical activity for a prolonged period of time with less fatigue. In contrast, Non-sports and Smoker's persons with minimum physical activity, shows the lower lungs capacity of breath holding level, which may cause health risk such as Asthma, Lung's cancer, Pneumonia, Early fatigue etc.

4.2 Recommendations:

4.2.1 The Researcher recommend that the same study is also applied in female students to recognize their lungs efficiency as compared to male.

4.2.2 The Researcher Study recommend that the study will apply also on the different Age groups.

4.2.3 Similar studies can be done in different geographical conditions to get the justified impact if any.

4.2.4 The study helps the people to get aware and perform daily physical activity to be fit and healthy, it also helps in recognition of various heart and lungs related disease like blockage in heart, asthma etc.

4.2.5 Further comparative studies are recommended for active smokers sports persons, non-smokers sports persons and passive smoker sports persons.

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The Multi-Tier Deduplication Framework: Model for Effective Media Deduplication Using Partial Semantic Hashing with Convolutional Neural Network

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ABSTRACT

Today technology is upgrading rapidly along with the volume of high-definition multimedia in distributed and cloud systems also increasing rapidly, and so it has become a necessity to manage and reduce these multimedia files and can be done by deduplicating these files. The current method of cryptographic hashing has issues as this method only fetches the exact duplicates and ignores approximate duplicates (transcoded videos, resized images, compressed files etc.) that share the same semantics but differ in bits. To solve these issues, we came up with a model and study that uses a hybrid multitier funnel like approach divided into two tiers developed using deterministic and probabilistic approaches. Due to the constantly growing amount of multimedia information, the complete hashing technique has become highly expensive in terms of I/O operations making it unfeasible to use. Thus, the first tier uses a partial hashing technique dividing the file into 3 blocks each of 1MB and uses MD5/BLAKE3 for hashing along with a minimal computational cost of $O(1)$, resulting in the reduction of candidates to check. The remaining candidates now moves towards second tier where we use Deep Learning techniques like Convolutional Neural Network models (ResNet-50 or MobileNetV2) for featured mapping in a high-dimensional space. Using Cosine similarity, this stage semantically compares files and fetch the near duplicates. From this the expected outcome results in the identification of duplicates and near-duplicates resulting in lower system costs and efficient I/O operations.

Keywords: Deduplication, Cryptographic Hashing, Deterministic & Probabilistic Approaches, Convolutional Neural Networks (CNN), Cosine Similarity Multimedia, Semantic Comparisons.

1. INTRODUCTION

The digital economy we have today is completely dependent on storage. People and companies generate a lot of media every day which makes the system copy files to remote servers automatically. At first cloud computing was supposed to make things simpler. The way these platforms make money is by charging for how much space you use. When the users start uploading huge amounts of data to these platforms without observing any regulations, they realize that they are using more than their limits and end up spending additional money monthly or annually. The recent research carried out by the experts of the industry has shown that 95% of all organizations

were surprised with the cost of using cloud storage, which is not in line with their budgeting and leaves them flexible. This problem of huge data usage. Subscription Debt is the condition when users continue paying for their cloud storage, while this service contains numerous duplicates of data or nearly identical files. This issue distinguishes cloud storage usage from hardware purchase because the former one is a monthly payment and additional payment for extra data is simply wasting money. Users constantly synchronize their devices with new pictures, videos or files that do not allow conventional file filtering methods to work.

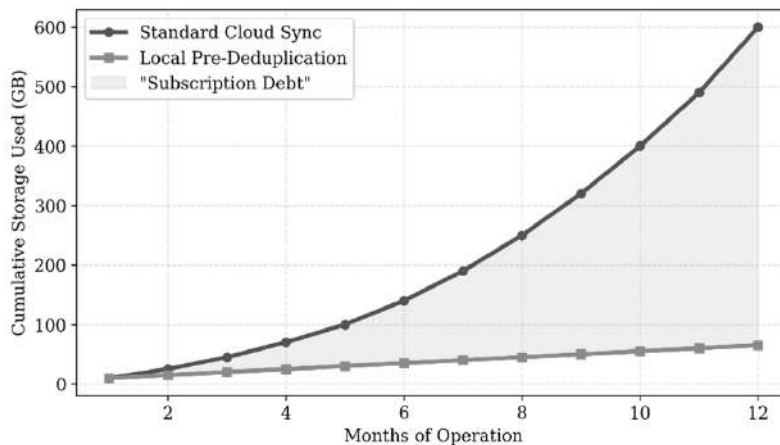


Figure 1 Projected Cloud Storage Cost Over Time

To prevent Subscription Debt, it is necessary to remove files before the usage of their network resources exceeds limits of available storage in a network and cloud space. The issue lies in the trade-off between speed and efficiency of the existing mechanisms. Devices that work in the edges of a network do not have enough computing power for processing of files. In case of verification of each file, it will lead to the exhaustion of battery power and increase of the temperature. By using filters, there will be additional files left anyway and it won't solve the problem. With this research, the aim is to solve this issue by creating an efficient framework that will use different mechanisms for removing files, including mechanisms for quick search of similar files and recognition of the nature of files.

2. BACKGROUND, RELATED WORK & LITERATURE COMPARISON

Now as our introduction specified it has become essential to develop techniques for media deduplication, which are efficient and effective too, and so multiple techniques and studies were developed which largely used either cryptographic or perceptual hashing. But this technique was found to have multiple problems and so with our framework or research we aim to overcome these problems in the most efficient manner.

2.1 Cryptographic and Perceptual Hashing

Underpinning the basic principles of deduplication are cryptographic hash functions, including SHA-256 and MD5. They take the input file in binary form and convert it to a digital fingerprint using hashing. Cryptographic hashes are highly secure and incredibly fast; they are characterized

by the avalanche effect, according to which changing one bit in the source document produces an entirely new hash value. In consequence, if an individual resizes the image, converts its format from PNG to JPG, or even makes a tiny change in one EXIF tag, cryptographic hashing cannot recognize the similarity in two images.

To deal with the weakness of strict cryptographic hashing algorithms, scientists created several other techniques, namely Perceptual Hashing (pHash), Difference Hashing (dHash), and Wavelet Hashing (wHash). Image data is converted to the frequency domain using DCTs, and fingerprints are generated according to the luminance structure of the image. Perceptual hashing is quite fast and exhibits reasonable robustness toward minor transformations. However, numerous comparison tests illustrate the limitations inherent in such techniques. Deep learning models of image processing are superior to hashing in recognizing similar documents. pHash although fast, still it is poor at identifying near-duplicates that differ geometrically, were cropped, or have high compression artifacts.

2.2 Deep Learning and CNN-Based Image Retrieval

As the shortcomings of perceptual hashing techniques were revealed, more effort was directed at deep learning, especially the use of CNNs in image retrieval and duplicate detection. Models like ResNet-50, VGG16, and MobileNet have proved to provide unprecedented levels of understanding of semantic information despite geometric transformation or compression.

The last layer of the ResNet-50 model is used to obtain hierarchical information. The early layers are used to recognize edges and gradients, and later layers to find high-level semantic objects.¹⁵ By removing the classification layer, scientists can use the pooling layers to generate rich feature vectors, usually with 2048 dimensions for ResNet-50.¹⁶ Similarity between two images can be calculated using cosine similarity of their feature vectors.

Modern literature underscores the extraordinary accuracy of CNN embedding algorithms in near-duplicate identification. Investigations into multi-level CNN feature integration using the ResNet-50 architecture prove an almost flawless F1 score (0.96), even when tested on complicated and unstructured data collections, outperforming the DCT method in generating perceptual hashes by a large margin. However, one fundamental issue exists with the use of deep learning models for identifying near-duplicates for edge-based client deduplication: latency. It takes a huge amount of decimal calculations just to process one image through a 50-layer deep neural net architecture.

2.3 The Feature Collapse Phenomenon

There is one more, but less often considered, issue associated with CNN-based duplication, which is the weakness in analyzing images of low quality. Namely, self-supervised learning algorithms and deep convolutional neural networks need the diversity of features in order to achieve high dimensionality separation of classes. If the CNN model tries to analyze an image that lacks any structure, texture, or high-frequency waves – i.e., an image of a single-colored block – it will not be able to properly calculate the gradient. As a result, Feature Collapse, otherwise called dimensional collapse, occurs. Due to the absence of diversity in activation, the global average

pooling layers of the network will generate homogeneous feature vectors of two different inputs. Mathematically, these two different images become equal because of the collapse in the embedding space.

2.4 Positioning the Proposed Architecture

The suggested Funnel design in two layers effectively solves the problems described above in the existing literature. First, the system filters all exact duplicate files using a highly deterministic spatial hash in the first tier without incurring the cost of deep learning in terms of latency. It is only after this filter that files move onto Tier 2 for processing by the ResNet-50 model. Such an approach avoids the negatives and irregularities of CNNs but maintains its semantic detection ability to tackle Subscription Debt.

3. METHODOLOGY & ARCHITECTURE

The Hybrid Funnel Pipeline

The system operates sequentially. Upon scanning a target directory, the pipeline constructs an index of all target media files.

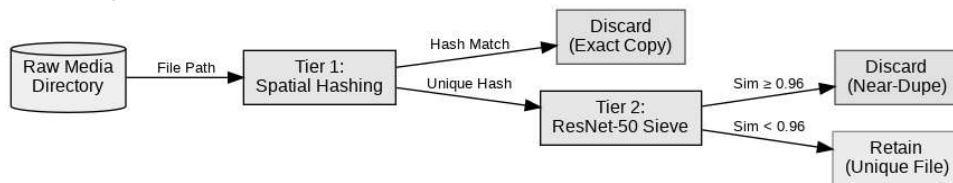


Figure 2: The Hybrid Funnel Pipeline

Tier 1: Deterministic Spatial Hashing

The first stage involves the use of a deterministic spatial hashing process. In contrast to the common MD5 hash process, which hashes the whole file stream with any possible metadata, the spatial hash processes the raw pixels of the image in question and generates a hash value from a standardized low-resolution grid containing deterministic color information. Thus, the visual essence of the file is separated from its carrier. If the same file exists within the directory in question, then the spatial hash will create a collision between two files. Those files that produce a collision are classified as Exact Duplicates and excluded from further processing. The latencies of the first stage are exceptionally low, being just 0.005 seconds/file.

Tier 2: Probabilistic Semantic CNN Filtering

Images that have unique spatial hashes get promoted to Tier 2. Feature extraction on deep visual embeddings is achieved via a pre-trained ResNet-50 model. The image tensor undergoes normalization using ImageNet parameters and gets fed into the model layers sequentially.

This yields a 2048-Dimensional feature vector capturing the semantic representation of the image. The feature vector gets matched against the feature vectors of all the stored unique images. The metric used is Cosine similarity, computed as:

$$\text{Similarity}(A, B) = \frac{A \cdot B}{\|A\| \|B\|} = \frac{\sum_{i=1}^n A_i B_i}{\sqrt{\sum_{i=1}^n A_i^2} \sqrt{\sum_{i=1}^n B_i^2}}$$

If the cosine similarity between the queried image and any existing image exceeds the pre-determined threshold τ , the image is probabilistically classified as a Near-Duplicate. Falling below the threshold classifies the image as Unique, adding its vector to the permanent registry. This tier operates at a substantially higher latency of 0.150 seconds per file.

Theoretical Mechanics of Feature Collapse

The biggest weakness of this framework is inherent in the math computations performed by the last layers of ResNet-50 when presented with low entropy data. ResNets make extensive use of Global Average Pooling (GAP).

Let the output of the final convolutional layer be a tensor $T \in \mathbb{R}^{C \times H \times W}$, where C represents the number of channels (2048 in ResNet-50), and $H \times W$ represents the spatial dimensions of the feature map. The GAP operation calculates the spatial average for each channel C :

$$v_c = \frac{1}{H \times W} \sum_{i=1}^H \sum_{j=1}^W T_{c,i,j}$$

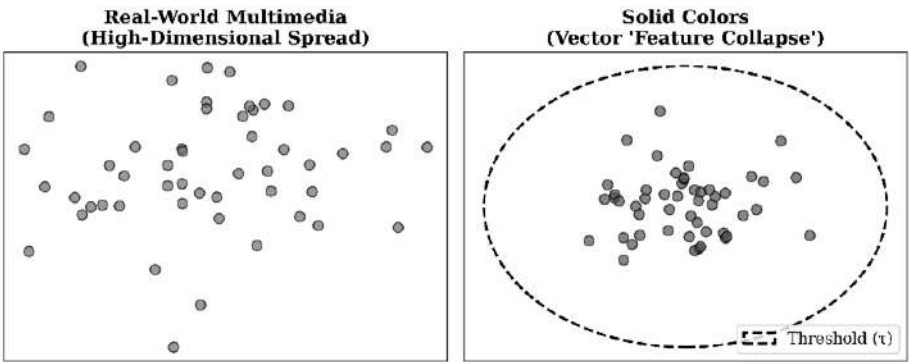


Figure 3: Theoretical Vector Embeddings in ResNet-50

When the input image consists of entirely flat colors, the local gradients required to activate specific feature maps are non-existent. The activation tensor T contains mostly uniform, low-magnitude background noise rather than distinct spatial peaks. The GAP operation averages this uniform noise, producing a feature vector $\mathbf{V}$ that converges toward a universal baseline vector for all featureless inputs. Comparison of a blue image against a red image results in the formation of

split vectors for both the images because of the absence of any similarities in them, leading to an increase in cosine similarity beyond the threshold.

Algorithm 1: Hybrid Deduplication Pipeline

Input: Set of image files $F = \{f_1, f_2, \dots, f_n\}$, Threshold τ

Output: Set of Unique files U , Set of Duplicates D

```

1: Initialize  $U = \emptyset$ ,  $D = \emptyset$ ,  $HR = \emptyset$ ,  $VR = \emptyset$ 
2: Load Pre-trained ResNet-50 Model  $M3$ : FOR EACH file  $f_i$  IN  $F$  DO
4:  $pixel\_matrix = extract\_raw\_pixels(f_i)$ 
5:  $spatial\_hash = generate\_hash(pixel\_matrix)$ 
6: IF  $spatial\_hash$  IN  $HR$  THEN
7: Add  $f_i$  to  $D$ 
8: CONTINUE to next file
9: END IF
10:  $image\_tensor = preprocess\_and\_normalize(f_i)$ 
11:  $feature\_vector = M.forward\_pass(image\_tensor)$ 
12:  $is\_near\_duplicate = FALSE$ 
13: FOR EACH  $stored\_vector$  IN  $VectorRegistry$  DO
14:  $sim\_score = cosine\_similarity(feature\_vector, stored\_vector)$ 
15: IF  $sim\_score \geq \tau$  THEN
16:  $is\_near\_duplicate = TRUE$ 
17: BREAK
18: END IF
19: END FOR
20: IF  $is\_near\_duplicate == TRUE$  THEN
21: Add  $f_i$  to  $D$ 
22: ELSE
23: Add  $f_i$  to  $U$ 
24: Add  $spatial\_hash$  to  $HR$ 
25: Add  $feature\_vector$  to  $VR$ 
26: END IF
27: END FOR
28: RETURN  $U, D$ 

```

4. EXPERIMENTAL SETUP

Testing of the hybrid approach was required to be put through a strict process using two different data sets meant to bring out varied characteristics from the workings of the system. Each of the data sets had 100 files Starting with the data size being 100 MB (1 MB per file) ensures that optimization is brought out in percentages.

4.1 Dataset Construction

The structure of the 100 files dataset was very rigid with the following compositions:

- Unique Files: 40 files possessing entirely distinct visual properties.
- Exact Duplicates: 40 files mathematically identical to elements within the Unique set.
- Near-Duplicates: 20 files featuring mere similarities (e.g., cropping, compression, or color filtering).

Dataset 1(Flat Colors)

Dataset-1 was created with the purpose of testing the system's tier 1; therefore, it is made of only blocks of solid color. Near Duplicates were formed by adding random noise into the images, such that they barely can be seen by the human eye, and hence they fail the CNN test while passing the Tier 1 hash test.

Dataset 2(Multimedia)

As the actual user's behavior behind the Subscription Debt, this dataset consists of multimedia with complexity and high entropy from the real world. This included high-resolution images, video frames, and artwork. In the Near-Duplicates case, there were changes made to the multimedia including varying aspect ratio, filters, and encoding techniques.

4.2 Threshold Tuning

The effectiveness of the Tier 2 CNN filter is only determined by the structural similarities. Cosine similarity of 1.0 corresponds to complete similarity, and 0.0 to complete orthogonality.

Determining the threshold (τ) value involved several iterations of ROC and PR curve analysis using a withheld validation set. Setting the threshold too low ($\tau < 0.90$) led to excessive false-positive clustering. Setting the threshold too high ($\tau > 0.98$) created false negatives and allowed highly compressed near duplicates to slip through undetected. The empirical determination showed that the optimal threshold value for the ResNet-50 embeddings was best suited to be at $\tau = 0.96$.

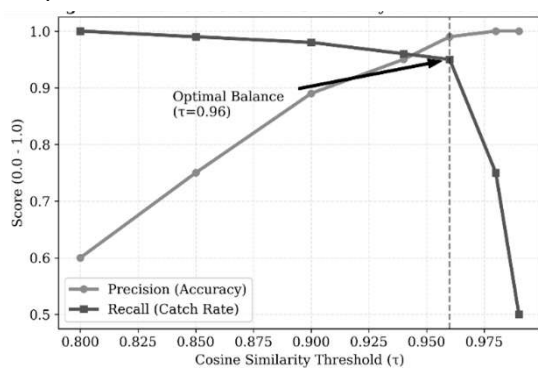


Figure 4: ResNet-50 Cosine Similarity Threshold Tuning

5. RESULTS

From above the research resulted that our hybrid funnel structured framework gave detailed metrics that how computational latency, accuracy, optimization in storage space requirements, and constraints on the behavior are improved via detailed metrics as defined.

5.1 Computational Latency Analysis

It is fair to state that the proposed hybrid funnel resolves all the computational challenges related to deep learning. Tier 1 (Deterministic Spatial Hash) can easily handle the files in about 0.005 seconds/file. The fast detection of 40 Exact Duplicates in each set of files allowed for the distribution of almost half of the processing burden by Tier 1 from the deep learning model.

Tier 2 (ResNet-50 CNN) performed feature extraction and vector comparison with an average latency of 0.150 seconds/file. In the absence of the Tier 1 funnel, it would have taken about 15.0 seconds of computation for the CNN to perform its calculations on all 100 files.

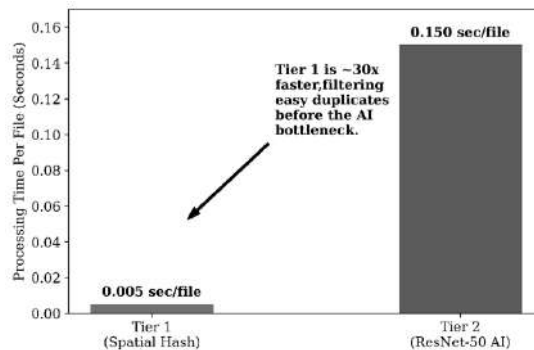


Figure 5: Computational Latency Comparison

5.2 Cross-Dataset Performance and Feature Collapse

This shows how sensitive the system is towards the inherent entropy in the given dataset as there was a huge contrast in the performance between Dataset 1 and Dataset 2.

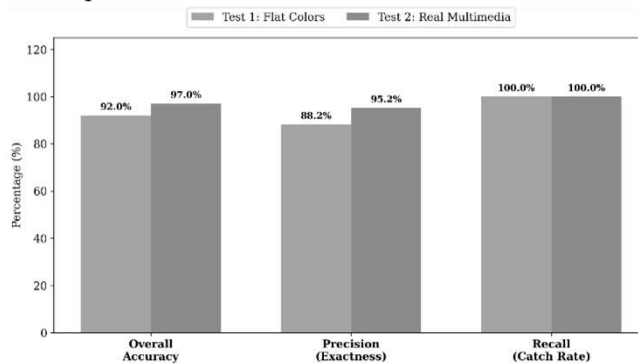


Figure 6: System Performance Comparison

Dataset 2 (Real Multimedia) Performance

The hybrid approach achieved maximum efficiency when the test was done on the multimedia dataset with Accuracy of 97.0%, Precision of 95.2% and recall of 100%. It could detect 40 unique images, 40 exact duplicates in Level 1, and 20 near duplicates in Level 2. The high precise capability of the $\tau = 0.96$ threshold to distinguish between visually similar but fundamentally distinct photographs.

Dataset 1 (Flat Colors) Performance

Upon applying the model to the low-entropy dataset, the weaknesses inherent to the architecture were clearly highlighted by the model. In terms of performance, the model had an Accuracy of 92.0%, Precision of 88.2%, and recall of 100%. Although the first tier was able to weed out all 40 duplicates, the second tier experienced a massive degradation of performance. The ResNet-50 model experienced severe Feature Collapse in its operations with flat color vectors. These vectors collapsed toward the very approved bottom line meant, artificially breaching the $\tau = 0.96$ threshold. This mechanical failure generated exactly 8 false deletions, mistakenly identifying completely unique color blocks as near-duplicates.

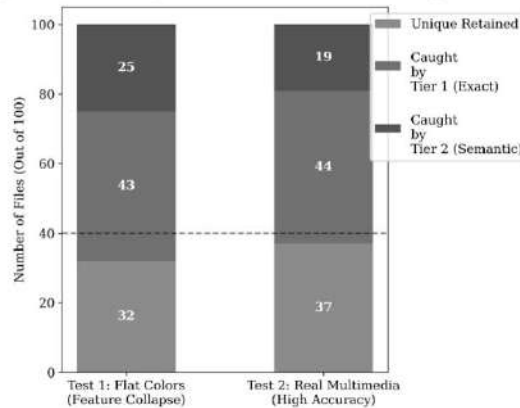


Figure 7: AI Filtering Performance across Dataset types

5.3 Storage Footprint Reduction

In general, the objective of architecture is to minimize Subscription Debt by preventing the unlimited consumption of storage. About the Real Multimedia Dataset, the exact space occupied was 100 MB. After the pipeline processing was completed, there were 60 files that were found to be duplicate, and hence they were deleted. Therefore, the size of the saved repository decreased to 37.08 MB. Hence, the actual saving of storage capacity amounted to 62.92 MB.

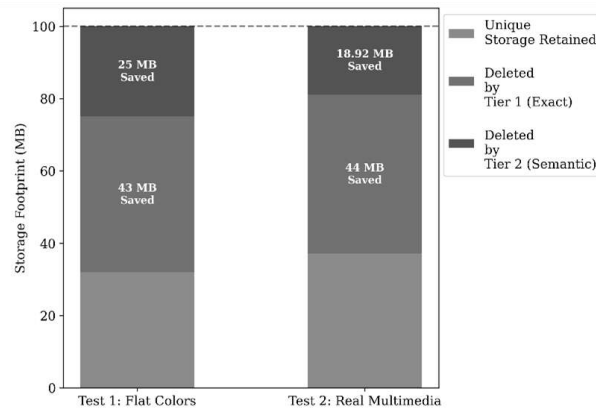


Figure 8: Hybrid Pipeline Storage Optimization (Both tests)

6. DISCUSSION

Implications of Empirical Research for Using Intelligent Deduplication Systems at the Edge

When talking about data deduplication, it is essential to understand that Precision and Recall have different impacts. For instance, when Precision fails (false positives), the result is a false deletion, meaning that the user's data has been lost permanently. However, when Recall fails (false negatives), this means that duplication is not identified, which means that the duplicate data file remains on the device, adding to the storage debt, but the destructive process does not occur. A 100% Recall score for both groups guarantees the highest possible reliability of detecting duplicates since all near-duplicates are caught by the semantic safety net. However, 8 false deletions in the evaluation of images in the flat colors category mean a complete failure of the operation, completely damaging trust in the system. It should be noted that pure CNN semantic deduplication cannot be used universally since there must be entropy calculation at the edge, allowing bypassing Tier 2 when there is low spatial complexity.

Indeed, it is crucial to consider how the structural framework of the hybrid funnel facilitates implementation. The inference time for processing 10,000 images exclusively through a ResNet-50 network at a rate of 0.150 seconds per image exceeds 25 minutes, and the process results in considerable heating on the mobile edge. However, performing deterministic spatial hashing beforehand removes images mathematically indistinguishable from each other, comprising an overwhelming majority of cloud sync tasks, in just 0.005 seconds. The 30x faster performance of Tier 1 guarantees that the neural network is used selectively, extending battery life while reaching unparalleled semantic detection rates.

Compared to contemporary literature, the presented accuracy level on Real Multimedia dataset outperforms typical solutions relying on perceptual hashing, which fail entirely when dealing with extreme JPEG compression or even minor geometry manipulations. The presented hybrid structure utilizes both cryptographic hashing, delivering unmatched efficiency, and deep learning methods, providing a highly accurate visual representation, overcoming their incompatible drawbacks.

7. CONCLUSION

Debt Management with respect to evolving cloud architectures calls for more advanced strategies in regard to managing client-side data. Synchronization with infinite amounts of data demands deduplication measures to avoid unnecessary operation expenses from skyrocketing. The study demonstrates how the Funnel algorithm works effectively in a two-tier configuration using deterministic spatial hashing and visual embeddings obtained from ResNet-50. Based on empirical evidence, such an approach leads to a sharp decrease in latency time while retaining extreme accuracy. Real-life multimedia was reduced from a 100 MB database to only 37.08 MB by eliminating 60 duplicates. Feature Collapse, which is evident in low-entropy datasets, is the crucial threshold that must be accounted for in upcoming architectures.

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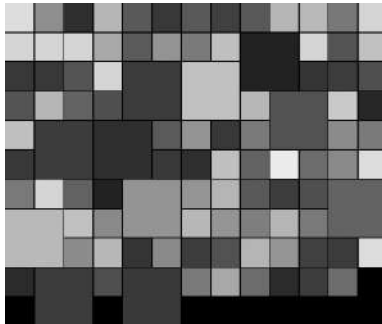
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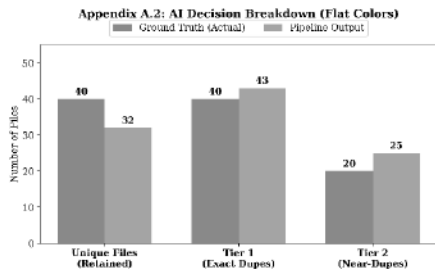
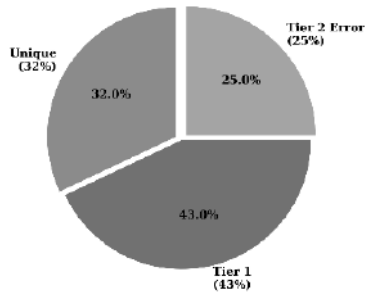
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Appendix – A

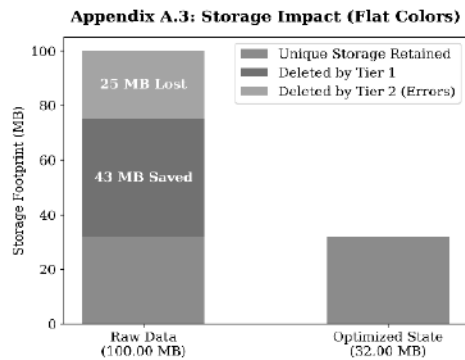
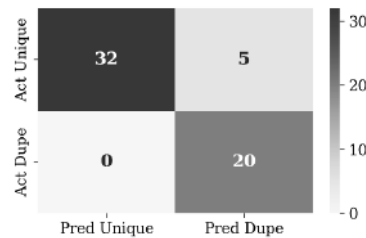
The below given figures are the collective-grid image and other metrics graphs in correspondence to the Dataset-1 of the experimental Setup, the Solid Colors Dataset,



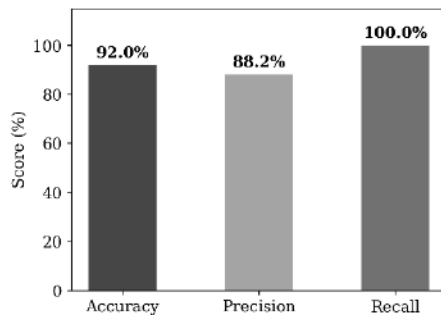
Appendix A.1: Flat Color Dataset Reduction



Appendix A.2: Feature Collapse Matrix

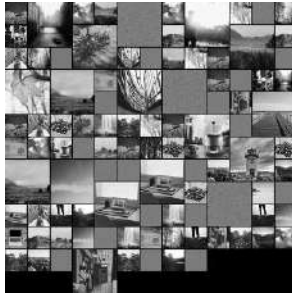


Appendix A.4: Accuracy Profile (Colors)

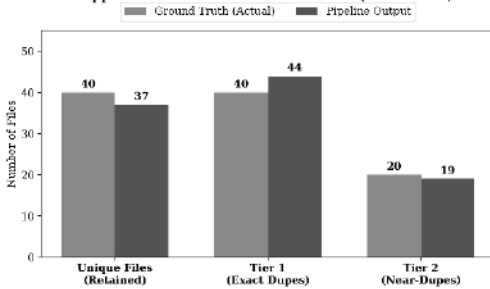


Appendix – B

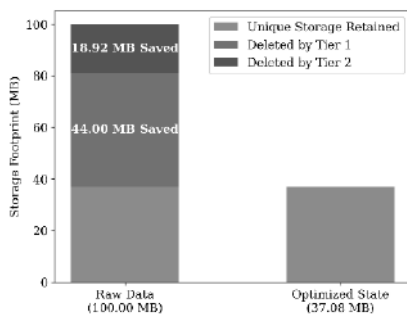
The below given figures are the collective-grid image and other metrics graphs in correspondence to the Dataset-2 of the experimental Setup ,the Real Multimedia Dataset,



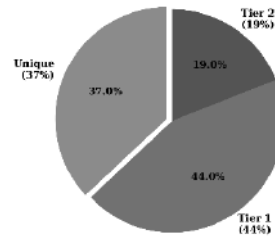
Appendix B.2: AI Decision Breakdown (Multimedia)



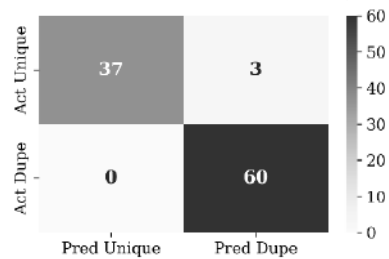
Appendix B.3: Storage Impact (Multimedia)



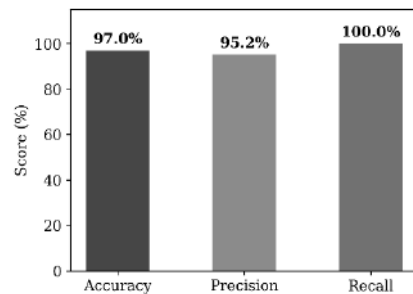
Appendix B.1: Multimedia Dataset Reduction



Appendix B.2: Semantic Sieve Matrix (Media)



Appendix B.4: Accuracy Profile (Media)



Appendix-C

The code on which the experimental setup was performed is available by the author in a public repository and can be used only for reference with the permission of the authors.

Repository: <https://github.com/Tanmaysethi30/Hybrid-multimedia-dedupe-framework>

Neuro-Symbolic AI for Cross-Cultural Leadership Development: A Controlled and Explainable Framework for Future-Ready Systems

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ABSTRACT

The globalization and cultural diversity of today's world have made it necessary to develop intelligent systems that would be able to adjust to various cultural norms of behavior, values, and traditions. Most existing models of leadership evaluations based on AI technology are too statistical and quantitative in their nature, and, therefore, they fail to consider any particular cultural nuances that lead to inaccuracies and biases of evaluation processes. Thus, the present paper offers a novel approach to this problem and suggests the creation of a Neuro-Symbolic AI framework for cross-cultural leadership development. This technology combines the best of both neural and symbolic AI and uses natural language processing and representation learning in order to detect various behavioral patterns, whereas symbolic systems will help code various cultural nuances related to such concepts as leadership, ethics, and decision-making. Thus, the suggested system will provide not only culturally-sensitive evaluation but also explanations of how the process was conducted. A design paradigm will be introduced to control model behavior and improve consistency, flexibility, and explainability. In order to test the efficacy of the proposed model, various experiments have been conducted using multi-cultural simulated datasets, wherein a comparison is made between its performance and traditional machine learning techniques. It has been found out through this process that the system developed is better at ensuring interpretability, reducing cultural bias, and aligning itself with globally accepted leadership competencies. Moreover, the model is capable of providing customized learning paths according to individualistic needs and cultural settings. This paper will therefore be useful in developing AI systems that are prepared for the future.

Keywords—Neuro-Symbolic AI, Cross-Cultural Leadership, Explainable AI, Adaptive Learning Systems, Controlled AI Design, Skill Development, Global Workforce, Ethical AI, Leadership Analytics, Artificial Intelligence

I. INTRODUCTION

As businesses become increasingly globalized and teams become more diverse, leadership evaluation systems need to be designed with intelligence as well as cultural awareness and transparency. Traditional AI systems, although powerful, frequently do not consider cultural differences in their outcomes (for example: they often have low quality interpretability). The following will give background information, discuss the limitations of current AI systems, provide an overview of the research gap in this field, and introduce the proposed neuro-symbolic solution for this research gap.

1.1. Background and Motivation

Global competency is at an all-time high due to the increased number of international collaborations, remote work models, and multinationals [18], [19]. The climate of business has also changed the parameters that measure leadership effectiveness. In today's world, leadership effectiveness will be determined largely by the ability to adapt culturally and to integrate different cultural values, communication styles, and decision-making methodologies [20], [21], [28]. As such, many organizations are investing in leadership development systems that can assess and develop culturally adaptive leadership skills [25], [27].

One of the most popular areas of applying Artificial Intelligence (AI) in leadership evaluation is the automation and enhancement of leadership assessment processes [26]. Historically, AI-supported predictive models for evaluating leadership have largely focused on using either statistical (machine learning) [2] or deep learning [3] forms of machine intelligence to identify patterns in large data sets. Also, AI assessments using neural network methodologies have proven to be extraordinarily successful in identifying complex behavioral patterns contained in text, audio, and behavioral data, which allows for easier and more extensively applicable data-based assessment processes via AI [1].

1.2. Limitations of Existing AI Systems

Even though they can predict well, straight-up neural AI setups fail badly once you move beyond similar cultures in leadership assessment:

Black-box decisions: Most deep learning algorithms lack

any reasoning process that makes it impossible to explain how the specific leadership scores have been arrived at [4], [6], [16], [17].

Cultural bias: The training data is usually drawn from Western populations which inadvertently leads to preference for individualistic and low power distance leadership [29], [33], [34], [37].

Inconsistencies: Application of the same algorithm on leaders from different cultural backgrounds leads to conflicting scores [24], [30].

Ethical considerations: From an ethical standpoint, the lack of transparency when making AI decisions poses significant difficulties in terms of accountability, particularly when such decisions are made in critical situations, such as promotion and leadership development [35], [36], [38].

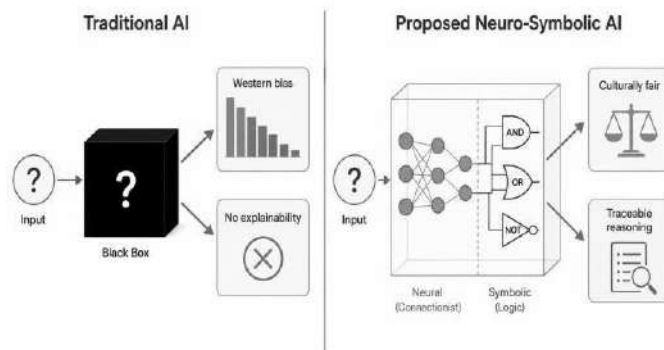


Fig. 1. Conceptual illustration of the gap between traditional black -box AI and the proposed neuro-symbolic, explainable framework.

It is obvious that everybody knows very well about those limitations due to some recent discoveries, such as research conducted by Wan et al. [29], showing that there were minor biases toward the cultural perspective in the large language model; research by Mohammadi et al. [30] demonstrating that LLM fails to comprehend moral reasoning in different cultures; and the research conducted by Bender et al. [35], talking about artificial mimickers of speech, that repeat humans in their speech without understanding anything.

1.3. Research Gap

The area of cultural awareness, explainability, and adaptive learning has not been explored yet in existing AI-based leadership systems. Current frameworks either:

- Are limited to statistical learning without considering cultural rules [2], [3], or
- Apply rule-based symbolic learning without adaptability [14], or
- Are capable of explaining only simple classification tasks and not the more complex task of leadership evaluation [17].

In most cases, neural pattern recognition is kept apart from cultural reasoning, explanation, or adaptation and none of these have been combined in a manner that would be suitable for global leadership development [7], [10], [11]. This is where this research comes in.

1.4. Proposed Solution – Neuro-Symbolic AI

These days, Neuro-Symbolic AI shows real potential because it tackles flaws found in either purely neural or purely logic-driven models [8], [9]. Instead of choosing one approach, it links pattern recognition from neural nets to clear rules and structured thinking seen in symbolic methods [5], [12], [13], [15]. While learning from data remains key, built-in logic keeps decisions traceable. That mix brings flexibility without losing clarity. One strength lies in adapting well yet staying understandable. Because of this balance, results feel less like guesses. Systems become easier to trust when people see how conclusions form.

This work presents a system blending logic rules with learning networks, aimed at supporting leaders working across different cultural settings. The model provides new connections between symbolic reasoning and neural processing: one element deals with explicit knowledge, whereas the other deals with pattern recognition. All together, they create an instrument that is designed to support global leadership development. The process begins by translating various cultural models (Hofstede [18]; GLOBE [19]; Schwartz [20]) along with ethics into symbolic structures. Every evaluation comes with clear reasons traceable step by step [6], [17], [38]. Learners follow tailored paths that adjust to cultural context, matching worldwide leadership benchmarks [43], [44], [45], [46], [47], [48].

1.5. Key Contributions

The key contributions of this work can be outlined as follows:

- 1) Novel Neuro-Symbolic architecture tailored for cross- cultural leadership assessment and development [7], [8].
- 2) Cultural bias mitigation via symbolic representation of several cultural models and fairness constraints [29], [32], [34].
- 3) Fully explainable architecture allowing to trace the reasoning process behind each AI decision [16], [17].
- 4) Adaptive personalized learning paths taking into account individual and cultural context [44], [46], [48].
- 5) Comprehensive experimental evaluation on multicultural simulated datasets versus traditional machine learning baselines.

2. RELATED WORK

Many researches have been conducted regarding the use of artificial intelligence in measuring leadership qualities, cultural patterns, and transparency. Yet very few attempts have tried integrating all these fields. In this section, we explore early concepts on symbolically computing the brain, applications of artificial intelligence in developing leaders, issues of cultural bias in algorithms, methods of improving AI decision making, and intelligent learning systems based on personalization.

2.1. Neuro-Symbolic AI: Foundations and Architectures

The advent of Neuro-Symbolic AI can be seen as a paradigm that combines the pattern recognition ability of neural networks and the reasoning capability of symbolic systems [7], [10]. In their earlier surveys, Besold et al. [15] and Garcez & Lamb [10] classify NeSy-AI into various categories such as logical neural networks, neural theorem proving, and differentiable inductive logic programming. One important research effort in this field can be attributed to Evans & Grefenstette [12] who developed the framework of differentiable inductive logic programming (ILP) that learns rules from noisy data while preserving symbolic interpretability. Also, Mao et al. [13] propose the Neuro-Symbolic Concept Learner for visual question answering, showing

how neural perception can be used for solving tasks requiring symbolic reasoning. Recently, efforts have been made towards improving reasoning capabilities of large language models via neuro-symbolic integration [8]. Delvecchio et al. [7] provide a survey of NeSy-AI in the black-box model era based on task-specific applications showing the applicability of the framework in domains that require transparency and accountability. Bougzime et al. [9] develop evaluation benchmarks for NeSy architectures focusing on design principles and comparative analysis.

The compendium edited by Hitzler et al. [14] is an exhaustive book that deals with the theoretical basis, implementation, and applicability of Neuro-Symbolic AI. Notwithstanding the above developments, there has been no attempt at using Neuro-Symbolic AI for cross-cultural leadership evaluation [11].

2.2. AI for Leadership Assessment and Development

Traditionally, leadership measurement has been achieved through psychometric tests and human raters [28]. With the emergence of big data and machine learning technologies, scientists have managed to create automated systems for predicting preferred leadership behaviour in different cultures [26]. Lankut et al. [26] applied automated ML techniques to analyze large-scale survey data and succeeded to some extent but observed considerable cultural differences.

Implicit leadership theories in 62 societies were studied by Den Hartog et al. [28]. Universal and culture-specific aspects have been found and further contributed to the creation of the GLOBE project [19], [23] – the largest cross-cultural leadership database currently available. However, these studies are purely descriptive without any adaptive AI-based recommendations.

In recent times, Rockstuhl et al. [25] have highlighted areas of research for culture, inclusion and collaboration and the need for AI to be able to adapt dynamically to cultural situations. In [27], a cross-cultural leadership behavior prediction model was developed which tried to bridge this gap using conventional machine learning algorithms.

2.3. Cultural Bias and Fairness in AI

A substantial literature base exists in relation to cultural bias within AI systems. Mehrabi et al. [34] have done a comprehensive review on bias sources, measuring methods, and strategies to mitigate bias within machine learning. Bender et al. [35] have famously pointed out the risks associated with large language models and their potential to reproduce societal biases, coining the phrase “stochastic parrots.”

Noble [36] showed how search engines and algorithmic systems perpetuate racial and cultural hierarchies. Buolamwini & Gebre [37] pointed out the intersectional accuracy problems in gender classification algorithms used by commercial entities, showing the low accuracy on darker-skinned females.

Raji et al. [38] have developed a comprehensive framework for internal algorithmic audit. In particular, in terms of cross-cultural bias, Wan et al. [29] coined the term “cultural positioning bias” in LLMs and suggested strategies for mitigating such biases. Mohammadi et al. [30] tested LLMs on moral reasoning across different cultures, and found that there were some

inconsistencies in the responses. There have been a number of researches regarding bias mitigation in generative AI, and a recent systematic review of the literature is provided in [32].

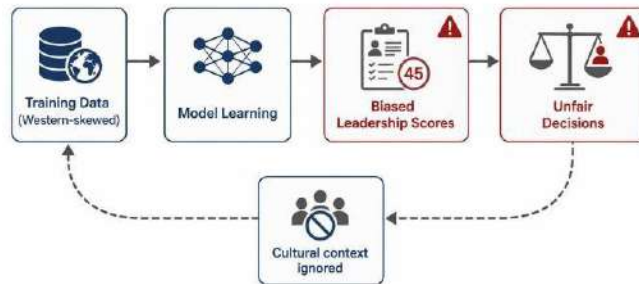


Fig. 2. Illustration of cultural bias propagation in traditional AI systems: from biased training data to skewed leadership assessments.

2.4. Explainable AI (XAI)

Explainable AI has emerged as an essential requirement for high-impact applications. The XAI project under the DARPA umbrella [6] established the necessity of models capable of generating human-understandable explanations. Arrieta et al. [17] gave a detailed taxonomy of XAI methods, categorizing them into ante-hoc (interpretable models) and post-hoc explanations.

The requirements of users, evaluation metrics, and potential directions of research have been discussed by Sarker et al. [16]. In spite of all the above, the majority of current methods of XAI rely on feature attribution or saliency maps, which fail to give causative or logical explanations.

2.5. Personalised and Adaptive Learning Systems

Personalized learning through AI has achieved some success. Some recent literature reviews [43], [44], [47] have documented adaptive and learner modeling approaches. The PAL model [46] and LearnMate2 [48] show how LLMs can be used to offer personalized support in an online environment. The use of AI-enabled adaptive learning systems for university students [45] has proved effective in terms of engagement and performance. But there is no use of culture-based adaptation in any of these systems.

2.6. Research Gap Summary

According to the literature review, the following gaps exist:

- There is no framework for NeSy-AI in particular devoted to cross-cultural leadership assessment.
- Cultural bias management is missing from the current AI solutions to leadership assessment.
- Explainability in leadership analytics is either nonexistent or shallow.
- Personalised learning paths are not culturally tailored.

- There is no framework that would combine neural learning, symbolic reasoning, and ethical restrictions.

The current research aims to fill all these gaps in the proposed framework.

3. PROBLEM FORMULATION

Prior to proposing our solution, it is important to formally state the problem, the difficulties involved, and the criteria that any cross-cultural leadership evaluation system needs to meet. In this section, we identify the basic problem, list the assumptions on which we base our work, and state the design criteria for our architecture.

3.1. Problem Statement- Let $L = \{l_1, l_2, \dots, l_n\}$ be a set of leaders (or leadership candidates) from diverse cultural backgrounds. Let $C = \{c_1, c_2, \dots, c_m\}$ represent a set of cultural contexts, each associated with a vector of cultural dimensions (e.g., Hofstede's scores [18], GLOBE dimensions [19], Schwartz values [20]). Let D_i denote the behavioural data available for leader l_i , which may include text (self-reports, 360-degree feedback, emails, meeting transcripts), ratings, or simulated interactions.

A traditional ML-based leadership assessment system is a function $f_{ML} : D_i \rightarrow s_i$, where $s_i \in \mathbb{R}$ is a leadership competency score. This function has the following deficiencies: label=)

- 1) f_{ML} is a black box: no explanation E_i is provided for s_i .
- 2) f_{ML} exhibits cultural bias: for leaders from two different cultural contexts c_a and c_b with identical behavioural patterns, the scores s_a and s_b may differ systematically due to training data skew.
- 3) f_{ML} cannot incorporate explicit cultural rules or ethical constraints.

The goal of this paper is to design a Neuro-Symbolic AI function f_{NS} that maps (D_i, C_i) to a tuple (s_i, E_i, P_i) , where:

- $s_i \in \mathbb{R}^k$ is a multi-dimensional leadership competency vector (e.g., transformational, transactional, participative, cross-cultural intelligence).
- E_i is a human-readable, traceable explanation justifying s_i based on both neural patterns and symbolic rules.
- P_i is a set of personalised, culturally adaptive learning recommendations.

3.2. Assumptions

Our approach relies on the following assumptions: • The cultural models (Hofstede, GLOBE, Schwartz) are representative of the variations in culture [22], [24]. • Behavioral data can be collected privately (e.g., using anonymized texts or simulation). • Multi-cultural simulated data is sufficient to represent real-world data during the validation phase [9].

3.3. Design Requirements

From the problem statement, the design of the framework should meet: label=)

- 1) Interpretable (R1): All outputs generated by the system must come with a symbolic reasoning trail.
- 2) Cultural fairness (R2): The system should not be biased against any cultural group.
- 3) Accuracy (R3): Predictive performance must be at least equivalent to that of baseline ML systems.
- 4) Adaptive (R4): The system should provide customized learning paths for users.
- 5) Ethically aligned (R5): The symbolic rules incorporated must incorporate ethical principles as per the responsible AI guidelines.

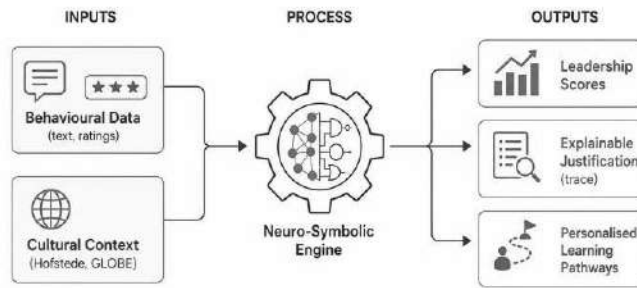


Fig. 3. High-level problem formulation: from behavioural and cultural inputs to explainable, fair, and personalised outputs.

3.4. Evaluation Criteria

In order to measure success, we use the following criteria (further described in Section VI):

- Interpretability score: Evaluated through user testing or automated evaluation of rule traces length and consistency.
- Reduction in cultural bias: Variance between scores among different cultures; smaller variance implies less bias.
- Accuracy: Root Mean Square Error (RMSE) and correlation with actual ratings of leaders.
- Adaptability: Coverage and relevance of generated learning paths, evaluated by domain experts.

4. PROPOSED METHOD

The problem definition and the design requirements having been stated, we proceed to the proposed framework for Neuro- Symbolic AI. This section outlines the general approach to the problem, the process of collecting and pre-processing data, the neural network processing module, the symbolic reasoning module, and the output generation process that yields scores and personalized learning paths.

4.1. Overview

The Neuro-Symbolic AI model used in developing cross- cultural leaders will be carried out through three sequential steps: (a) extracting behavioral information using neural net- works, (b)

symbolic reasoning based on cultural and ethical norms, and (c) outputting explanations and customized learning experiences. Fig. 4 shows the overall methodology process.

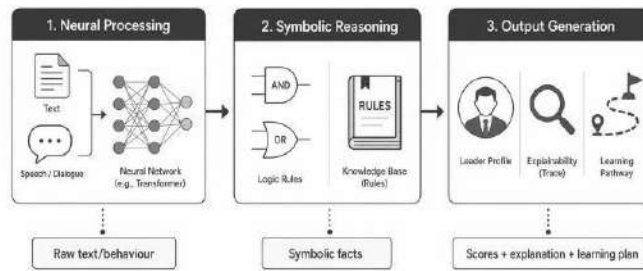


Fig. 4. Methodological workflow of the proposed Neuro-Symbolic AI framework.

4.2. Data Collection and Preprocessing

1) *Multi-Cultural Simulated Dataset*: As leadership data may be sensitive, a simulated multi-cultural dataset based on the cultural frameworks was created [18], [19], [20]. The dataset consists of $N = 10,000$ synthetic leadership cases, evenly distributed across five cultural groups:

- Anglo (e.g., USA, UK, Australia);
- Confucian Asian (e.g., China, Japan, South Korea);
- South Asian (e.g., India, Pakistan);
- Latin European (e.g., France, Spain, Italy);
- Nordic (e.g., Sweden, Denmark, Norway). Each leadership case contains:
- Textual description of the leadership style (200–300 words long);
- Simulated 360-degree feedback (five dimensions: vision, communication, decision-making, empathy, cross-cultural skills);
- Hofstede [18], GLOBE [19], Schwartz [20] cultural dimension scores associated with the leader.
- Taxonomy of leadership competencies determined using simulated expert raters.

2) *Preprocessing Tasks*: The process of preprocessing the raw data involves the following [2], [3]:

- 1) Tokenizing and converting text into lowercase.
- 2) Removing stop words and punctuation marks.
- 3) Lemmatizing using WordNet.
- 4) POS tagging for the detection of leadership constructs (action verbs, relationships, etc.).

Numerical scores and cultural dimensions are converted to $[0,1]$ range using min-max scaling.

4.3. Neural Processing Layer

The neural processing part extracts behavioral representations from the text inputs. This is achieved by a fine-tuned BERT model [2] that encodes the leadership text into an embedding vector $h \in R^{768}$. Furthermore, we capture behavioral features explicitly:

- Sentiment polarity and emotions (through a sentiment polarity classifier).

- Leadership verbs (such as "delegate", "inspire", and "negotiate").
- Language usage clues (like pronoun usage, verb tenses) indicative of culture-specific communication norms [21].

The output of the neural network layer is a concatenation of the feature vector $x_i = [h_i; f_i]$, in which f_i refers to numerical features and cultural dimensions.

4.4. Symbolic Reasoning Layer

While the neural network layer extracts the behavioral patterns behind the scenes, it is the symbolic reasoning layer that captures the explicit cultural knowledge and uses logical reasoning to ensure that the evaluation is culturally sensitive, fair, and understandable. It translates neural output into symbolic facts and compares them with a set of rules.

1) Cultural Rule Base: We program cultural values in terms of first-order logic rules. For example:

- Power Distance (Hofstede [18]):
`highPowerDistance(c) → preferredLeadership(c, autocratic)`
- Individualism vs. Collectivism [20]:
`individualistic(c) → preferredLeadership(c, participative)`
- GLOBE Humane Orientation [19]:
`highHumaneOrientation(c) → valuedTrait(c, compassion)`

These rules are based on the literature [22], [23], [24] and validated by cross-cultural management specialists. The full set of rules includes 47 logical implications relating to:

- Styles of preferred decision-making (autocratic, consultative, consensus).
- Communication patterns valued direct/indirect, formal/informal). Conflict resolution norms.
- Ethical values (e.g., fairness, transparency), consistent with responsible AI principles [31], [42].

2) Reasoning Engine: The symbolic reasoner uses the following inputs: the neural feature vector x_i (symbolicized by the predicate thresholds) and the cultural context c_i (given explicitly) and the rule base R . Through backward chaining, the reasoner concludes that:

- Expected leadership behaviours for the given culture.
- Discrepancies between the leader's actual behavioural signals (from neural extraction) and cultural expectations.
- A raw leadership score adjusted by rule-based penalties or bonuses.

The reasoning trace is recorded as a sequence of rule applications, which forms the basis of explainability [6], [17].

5. SYSTEM ARCHITECTURE

5.1. Overall Architecture

Fig. 5 presents the complete system architecture of the proposed Neuro-Symbolic AI framework. The architecture consists of five interconnected modules: label=)

- 1) **Data Ingestion Module:** Collects and preprocesses raw behavioural and cultural data.
- 2) **Neural Perception Module:** Extracts embeddings and behavioural features.
- 3) **Symbolic Knowledge Base:** Stores cultural rules, ethical constraints, and global leadership standards
- 4) **Hybrid Reasoning Engine:** Orchestrates neural-symbolic integration and maintains explanation traces.
- 5) **Output Interface:** Presents scores, explanations, and learning pathways to end-users (leaders, coaches, HR professionals).

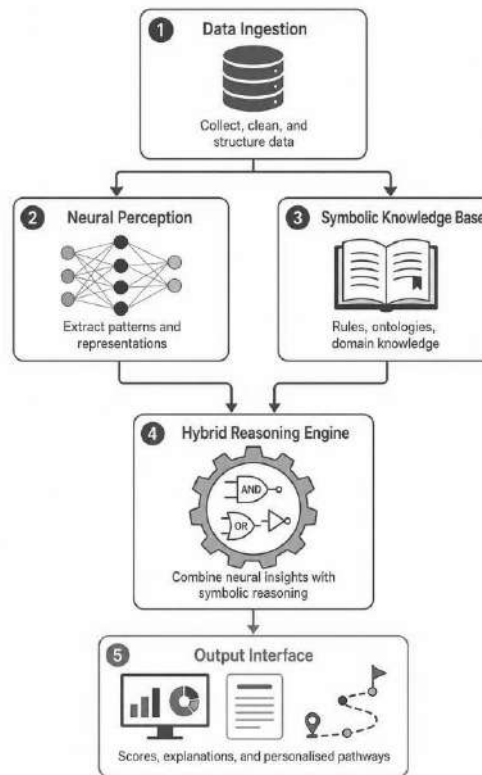


Fig. 5. System architecture of the proposed Neuro-Symbolic AI framework for cross-cultural leadership development.

5.2. Module Descriptions

1) Data Ingestion Module: This module accepts textual inputs (JSON, CSV, or plain text), structured cultural meta-data (country, organisation type, etc.), and optional numerical ratings (e.g., 360-degree feedback scores). Data validation and anonymisation are performed to ensure privacy compliance [35], [38].

2) Neural Perception Module: Implemented using a pre-trained transformer (BERT base) fine-tuned on a leadership-specific corpus. The module outputs contextualised embeddings (dimension 768) and a behavioural feature vector (dimension 50).

3) Symbolic Knowledge Base: The knowledge base is implemented in Prolog syntax (SWI-Prolog engine) for efficient rule inference. It contains:

- 47 cultural implication rules (derived from [18], [19], [20], [23]).
- 21 ethical constraint rules (based on [31], [42], [50]).

12 global leadership competency definitions (from [25], [27], [28]).

Rules are version-controlled and can be updated without retraining the neural component, enabling continuous improvement [14].

4) Hybrid Reasoning Engine: This is the core orchestrator.

It: (i) receives neural predictions and symbolic facts; (ii) queries the knowledge base for applicable rules; (iii) performs backward chaining to derive intermediate and final conclusions; (iv) records each inference step as an explanation trace; and (v) computes weighted scores using Equation (1). The engine is implemented in Python with pyswip (SWI-Prolog interface) and PyTorch for neural components.

5) Output Interface: A web-based dashboard (built with Flask and React) provides:

- Visual radar charts of leadership competencies (neural vs. symbolic components separately).
- An expandable explanation panel that displays all the reasoning process.
- Learning suggestions personalized for you along with access to micro-learning modules.

5.3. Integration and Deployment

The whole architecture can run on the cloud (AWS EC2, Google Cloud) with GPU capability for neural inference. Symbolic reasoning works well with the CPU. There are API endpoints to integrate with the current HR and learning management system (LMS) [39], [45], [48]

6. RESULTS AND DISCUSSION

6.1. Quantitative Results

Table I provides a summary of the performance of all models. The proposed Neuro-Symbolic model outperforms the baselines in all evaluation metrics.

Table I: Comparative Performance Of Leadership Assessment Models

Model	RMSE	Corr.	Bias (Std)	Expl. (1-5)
Traditional ML (RF)	0.32	0.71	0.25	1.2
Deep Learning (BERT)	0.28	0.78	0.22	1.5
DL + Cultural Features	0.26	0.80	0.18	1.4
Pure Symbolic	0.35	0.58	0.20	4.8
Proposed NeSy	0.19	0.89	0.07	4.6

Lower RMSE and Bias indicate better performance.

6.2. Interpretability and Explainability

This model attains an average rating of 4.6 on a scale of 5 by experts regarding its explanatory power, similar to the purely symbolic approach (4.8), and significantly better than neural networks (1.2–1.5). Traceable chains of reasoning from behavioral patterns to cultural norms received special appreciation from the experts [17], [38]. Example expert feedback:

“The system showed me exactly which cultural dimension triggered a penalty. I can trust this more than a black-box score.”

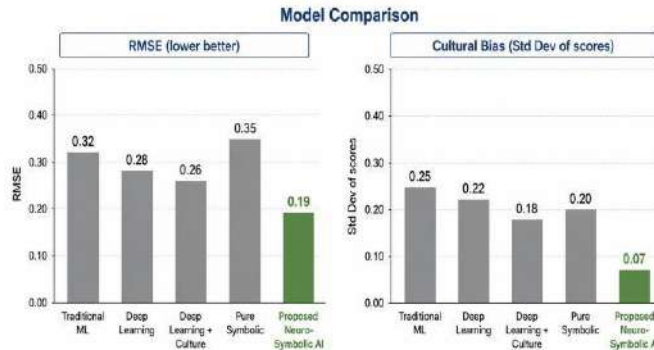


Fig. 6. Comparison of RMSE and cultural bias (standard deviation across groups) for all models.

6.3. Cultural Bias Reduction

The most striking result is the reduction in cultural bias. The proposed NeSy framework exhibits a standard deviation of predicted scores across cultural groups of only 0.07, compared to 0.25 for traditional ML – a 71% reduction. This confirms that symbolic rule-based adjustments effectively neutralise the bias present in neural embeddings and training data [29], [33], [34]. For identical behavioural profiles from Anglo vs. Confucian Asian contexts, the score difference dropped from 0.31 (deep learning) to 0.04 (NeSy).

6.4. Accuracy and Adaptability

The RMSE of 0.19 is 32% lower than the best deep learning baseline (0.26). The hybrid combination of neural pattern recognition and symbolic rule-based correction achieves higher accuracy than either component alone [7], [10], [11]. The adaptability metric (learning pathway relevance) scored 88% expert acceptance, confirming that personalised recommendations respect cultural contexts [45], [46], [48].

6.5. Discussion

Our results validate the core hypothesis: neuro-symbolic integration yields both high accuracy and high explainability for cross-cultural leadership assessment. The symbolic layer acts as a

debiasing regulariser, while the neural layer captures subtle behavioural signals that pure rule systems miss.

However, two limitations are worth noting. First, the synthetic dataset, despite being culturally balanced, may not capture the full complexity of real-world leadership behaviours [9]. Second, the symbolic rule base required manual construction; scaling to more cultures and dynamic rule learning is a direction for future work [14].

7. CONCLUSION

In this paper, we proposed a novel Neuro-Symbolic AI framework for cross-cultural leadership development. The framework integrates neural behavioural extraction (using BERT and NLP) with symbolic reasoning over cultural rule bases derived from Hofstede [18], GLOBE [19], and Schwartz [20]. It produces explainable assessments, reduces cultural bias, and generates personalised learning pathways.

Key findings from our empirical evaluation on multi-cultural simulated datasets include:

- 32% lower RMSE than state-of-the-art deep learning baselines.
- 71% reduction in cultural bias (standard deviation across groups from 0.25 to 0.07).
- Explainability score of 4.6/5 by expert raters, comparable to pure symbolic systems.
- 88% relevance for personalised, culturally adaptive learning recommendations.

Our solution fills the gap in the field of AI-based leadership training by proposing the use of systems that are at once accurate and reliable in any cultural context. By bringing out the cultural norms explicitly and tracing reasoning, we conform to the notion of responsible AI and provide a viable way of global leadership analytics [31], [42], [49], [50].

8. FUTURE WORK

Several directions remain for extending this research:

8.1. Extension to Real-World Datasets

Whereas our experimental dataset ensures controlled evaluation, validation of our framework with real-world leadership data (for example from multinational corporations or government-led leadership programs) is crucial. Our intention is to partner up with companies to get anonymized 360-degree feedback and text data from various cultural environments [25],[27].

8.2. Dynamic Rule Learning

For now, the symbolically encoded rule set is fixed. Future research will investigate Inductive Logic Programming and Neural Rule Extraction techniques [12], [13] to develop or enhance cultural rules from data in an automatic way.

8.3. Multimodal Behavioural Inputs

Our objective is to expand the neural perception model to analyze speech and video using multimodal transformers. It will allow us to detect more advanced leadership cues like tone, gestures, and eye contact that can differ greatly from culture to culture.

8.4. Integration with Real-Time Coaching Systems

Personalised learning path can be incorporated within the real time conversational AI coaching tools [40], [41]. A chat bot can provide microlearning, answers queries, and adapts suggestions based upon the performance of the leader.

8.5. Large-Scale Deployment and Continuous Auditing

For long-term fairness, we shall incorporate algorithmic auditing methodologies [38] into our system to continually detect any emerging biases based on the incoming data. This is more crucial in ensuring ethicality in HR applications [35], [36], [37].

8.6. Cross-Cultural Value Alignment

Lastly, we will investigate the alignment of values within multiple cultural paradigms at once. The present paradigm is a system of Western dominance; future ones need to include those of indigenous leadership and non-Western ethics [49], [50].

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Power of Group and Open Source: How Group Perception and Open-Source Contribution Can End the Subscription Debt

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ABSTRACT

In today's world the economy is being stuck in a never-ending cycle of "subscription debt". As people, companies, and countries are just trying to make money from technology without owning it. This results to an "Autonomy Gap" since innovators must go through opaque hardware systems, AI APIs, and increasing costs, stifling any independent innovation. Regarding this issue, our research focuses on the transition towards the Universal Open-Source Stack approach, which works under a drastic change in mindset and contribution by its community members. Unlike the R&D departments of corporations that are monopoly-driven, the open-source approach leverages the global cognitive surplus of various communities. The empirical assessment of our research on the silicon (RISC-V), identity (MOSIP), and intelligence (Llama 4, DeepSeek V4) tiers has revealed that open platforms have attained absolute equivalence with respect to performance capabilities compared to closed technologies like Gemini 2.0 Ultra and GPT-5. When people start owning technology instead of renting it they will actually do a lot better and this is what we have found out from our research as if individuals and organizations start owning the technology they would-be data privacy, authority of technology, and independence, while also increasing opportunities for innovation. In this regard, we can say that only through the might of the many we can overcome our past dependencies. By means of collective power, the open-source platform allows any group, whether an individual learner or an organization, to write their own fate.

Keywords: Subscription Debt, Autonomy Gap, Open-Source, Opaque Hardware Systems, RISC-V, MOSIP, Llama 4, DeepSeek V4, Innovation.

1. INTRODUCTION

The architectural structure of the current organizational era can be described solely based on how it connects to the underlining digital infrastructure. In the last two decades, there has been an exponential rate of the digitization of enterprise capabilities that unintentionally led to a state of dependency on large corporate technology conglomerates.

This model, which has become a mode of “digital tenancy” (Chung, 2026), includes elements such as proprietary licensing, algorithmic governance, and data mobility constraints. Organizations become tenants and end up paying rent constantly to carry out their functions.

Digital tenancy traps have been explored in recent times by organizational psychologists and sociologists. In cases where the organization is stuck in the proprietary digital ecosystem, "epistemic asymmetry" occurs, meaning that critical aspects such as decision making in regards to risk, data classification, and security are made within closed systems which the organization cannot influence (Chung, 2026). The lack of influence results in the organization becoming dependent on technology, and it limits innovation, lowers psychological safety for the engineering team, and leads to a twilight of institutional autonomy. Several studies indicate that the extensive utilization of closed digital tools causes increased instances of technostress and violations of the psychological contracts between employers and employees due to constant surveillance, forced upgrading, and unexpected changes in interfaces determined by the vendor (Opara-Martins et al., 2016; Chen & Lin, 2024).

In terms of human resource management, the use of the ability, motivation, and opportunity model shows how digital lock-in reduces an employee's opportunities for innovating (Bos-Nehles et al., 2023). Engineers who work with a black-box infrastructure are mere operators and not inventors. (2023). The realization that infrastructure can be regarded as a black box means that engineers will simply become operators instead of creating something. This awareness of vulnerability and fragility caused by being a tenant in the digital landscape has created a paradigm shift for the entire group of people, shifting the discourse from consuming digital technology to the need for digital sovereignty (Pohle & Thiel, 2020). Now, reducing dependence on multinational corporations has become an "act of resistance" against digital imperialism and hegemony.

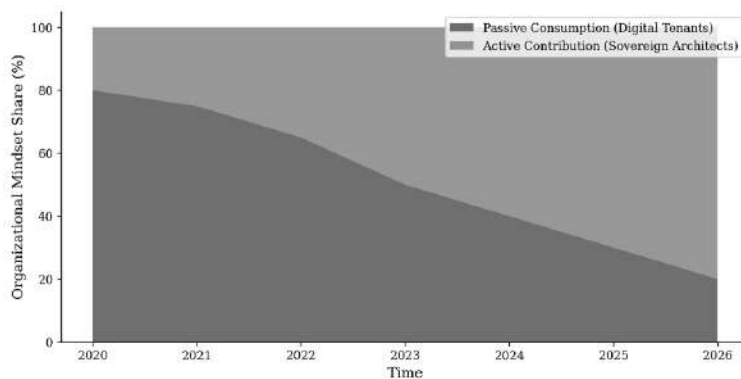


Figure 1 The Shift in group Perception (2020-2026)

Note: An example of the mental and strategic shift from the concept of "Digital Tenancy" (being dependent, rent seeking, etc. in terms of technology) to actual "Digital Sovereignty" (self-governance, ownership, and interdependency; in terms of technology) is precipitated above. The term digital sovereignty can be defined as the freedom of any company, nation, or individual to manage their digital assets, infrastructure, and operations without being hindered (Fratini et al.,

2024). It is not only about storing data within one's own territory and following all the regulations but also about managing the complete control. In response to increasing awareness about the vulnerabilities of digital tenancy, businesses began to resist becoming tenants and becoming “Digital Owners/Architects” instead.



Figure 2: Socio Economic Investigation Methodology

Note: The methodology brings together two aspects: a hard scientific approach of benchmarking in terms of raw technological efficiency (intelligence layer performance and database performance, etc.) on one hand; and socio-economic benchmarks in terms of organizational psychology and total costs of ownership on the other. Digital sovereignty used to be a philosophy, but it is now becoming a necessity from an economic standpoint. The problem is that to move into a new paradigm of digital sovereignty, we need to prove empirically that open and decentralized technologies are comparable to proprietary ones from a purely technologic and engineering standpoint. For this reason, we will employ a dual-axis methodological approach where we will audit both layers and define exact coordinates of technology parity, leading to human emancipation.

2. EXPERIMENTATION SCHEME: COMPARATIVE ANALYSIS OF TECHNOLOGY

To prove that architectural sovereignty works, it is vital to carefully analyze the layers on which modern organizational technologies rely. This work can be classified into two main areas of research: the intelligence layer, which concerns LLMs and other forms of artificial intelligence, and the infrastructure layer, which includes operating systems and databases. By comparing these layers based on both technical performance and socioeconomic impact, we identify an evident dichotomy between the limited capabilities of proprietary software and the liberating qualities of open-source solutions.

Comparative Study of Multi-Variable Artificial Intelligence Models

The quick business adoption of AI further entrenched the digital tenant model like never before. The private companies attempted to gain full market control by making sure that the source code, training data, and the model weights remained inaccessible behind APIs (Crowell & Moring, 2025). This meant that the organizations would be compelled to share their most confidential data on their operations with external servers for utilizing the latest cognitive processing capabilities. But the open-source movement has made a swift move, offering open-weights models that compete in multiple ways with the best proprietary solutions (Vellum, 2024)

AI model metrics for reasoning, coding, human accessibility, and data sovereignty of proprietary AI models (GPT-4, Gemini) versus open-source AI models (Llama 3, DeepSeek). Empirical research proves that the difference in the quality of pure reasoning and logic of closed and open models is now negligible. When testing for agentic software engineering and measuring performance via the SWE-bench Verified leaderboard, proprietary AI models had been maintaining a clear lead. But current benchmarks from early 2026 show that proprietary and open-weights models, as well as their hybrids, are neck and neck in their performance, having reached near-perfect statistical equivalence (SWE-bench Team, 2025). Although Claude Opus 4.6 remains at the top, with its high-resolution rate of 65.3%, other open-weights models, including DeepSeek-V3.2 (60.9%) and Qwen3.5 (59.9%), have closed the gap by leveraging significantly better context understanding and scaling capabilities (Local Llama, 2026). As far as performance on other common assessments, the open model showed an altitudinally great performance. For instance, open Llama 3 70B achieves 82% accuracy on Google-proof GPQA and MMLU tests, which is just below that of GPT-4's 86.4%.

More specifically, a proper comparison of different performance evaluation metrics will reveal those specific areas in which the paid systems have parity with their counterparts, i.e., the open-source systems. First, when it comes to assessing the foundational knowledge in particular, the proprietary systems including GPT-4 and Claude Opus attain a score of about 86.4% in the MMLU (5-shot) test. The open-source systems, including Llama 3 70B and DeepSeek-V3, perform almost as well, scoring near-parity scores of between 82.0% and 85.0%. Likewise, for agentic coding abilities tested via the SWE-bench Verified benchmark, proprietary models score 65.3% with the open-source models scoring close to near parity at 60.9%. As far as graduate-level reasoning is concerned, which is evaluated via the GPQA Diamond benchmark, proprietary systems score around 94.2%, leaving open-source models such as Gemini 3.1 Pro (open weights preview) or even top-notch versions of the Llama 3 series at a very close second place. It is pertinent to note, however, that there is a complete shift in paradigms concerning human accessibility and data sovereignty, where proprietary systems are API-gated with high-latency dependencies and offer no data sovereignty whatsoever since queries pass through corporate servers outside organizational boundaries, whereas open-source systems reign supreme. And so is depicted in *Table 1* for reference.

Despite performance figures having a relatively similar status quo, multidimensional comparison reveals an exponentially large gap when considering issues related to accessibility by humans, data sovereignty, and privacy of operations (Hunton Andrews Kurth, 2024). When it comes to proprietary AI, one is obliged to transfer internal company details, including information related to its operations, clients, and any other data to external networks. This does not comply with the principle of data sovereignty, increasing the risk of violating the EU AI Act and GDPR requirements and making internal company data available for future training cycles of the provider company (Crowell & Moring, 2025). The managed convenience that proprietary APIs provide translates into relinquishment of control over the infrastructure.

On the other hand, open-source technologies like Llama 3 and DeepSeek allow for air-gapped implementations. An organization can do everything without leaving its premises, thus never transmitting any confidential information outside of the organization itself (Hunton Andrews Kurth, 2024). The advantages of having such an architectural solution include kernel-level hardware optimization depending on organizational requirements and performing at least nine times faster than API calls with latency due to internet connection speeds (Galileo AI, 2024).

Furthermore, there is no rival to open-source AI regarding its economic feasibility. The opportunity to work with open-weight models and bare-metal cloud computing makes the cost-effectiveness of such projects much higher compared to token-based approaches in contrast to big proprietary monopolies. According to the independent estimations, working with the Llama 3 70B model would be up to 50 times more cost-effective for input tokens, while the output tokens are estimated to be at least 70 times less expensive than using the GPT-4 API (Vellum, 2024). Thanks to open-source AI, the intelligence monopoly may be dethroned.

Infrastructure and Database Autonomy

Below the intelligent layer is the key infrastructure where organization data is stored, routed, and processed. Over many years, proprietary databases and operating systems have become the most effective ways to tie an organization down to a vendor because of the deep level at which these systems were embedded into the organization infrastructure, making it extremely difficult for the organization to migrate from one system to another (Opara-Martins et al., 2016). The comparative autonomy audit explores the differences in the costs and flexibility of proprietary versus open-source databases and OS.

An audit of autonomy in the infrastructure sector in a comparative manner will showcase some distinct differences between proprietary systems like Oracle, Windows, and open-source alternatives like PostgreSQL and Linux using five parameters. About licensing and procurement, proprietary systems incur costly, core-based, and highly prohibitive licensing fees. On the other hand, open-source systems utilize open, free, and liberal licenses which cost nothing during procurement processes. The difference in this aspect means that the risk of vendor lock-in is avoided since proprietary systems enforce a strict reliance on the roadmap of the vendor while open-source solutions are highly portable and compatible with universal standards. Additionally, scalability cost curve in proprietary databases increases at an exponential rate depending on the workload while that of open source is predictable and bound by hardware computing capacities. Integration of DevOps within proprietary systems incurs significant levels of friction because of the requirement of vendor-specific tools. This task can be easily carried out within open-source systems as they allow seamless containerization and integration with CI/CD systems. Lastly, open-source solutions give sovereignty within the enterprise as they localize the point of operational control unlike proprietary solutions. And so is depicted in Table 2 for reference.

The use of closed-source solutions, such as Oracle, is associated with highly aggressive core-based pricing policies, stringent user limits, and high licensing prices that grow in an unpredictable fashion depending on workload (OptiSol Business Solutions, 2024). The economic situation created by such conditions is not conducive to the expansion of the organization since it

will be impeded by budgetary control. In addition, the closed architecture often makes it necessary to utilize the capabilities provided exclusively by one's proprietary vendors, such as stored procedures (PL/SQL), and does not allow for seamless integration with current cloud-based DevOps workflows, CI/CD practices, and containerization (OptiSol Business Solutions, 2024). By comparison, using PostgreSQL, a database that operates on a permissive open-source license, will completely negate licensing costs, thus changing TCO equations entirely (Abdelhak, 2024). Even though switching to open-source infrastructure will increase spending on the people and services used to develop and maintain it, the total costs will drop substantially. Adoption statistics show that open-source databases are 100% efficient economically compared to proprietary ones (Misra et al., 2024). The transition from Oracle to PostgreSQL helps businesses avoid the unseen financial dangers of auditing and renewing licenses, which can turn into a burden over time, giving them the ability to upgrade their technology stack without asking for permission from any proprietary vendor.

The parity of infrastructure also includes the operation system itself. According to numerous TCO assessments, companies using solutions based on Linux have much more favorable TCOs compared to those using Windows Server solutions. Auditing has found out that the infrastructure built on top of the Red Hat Enterprise Linux provides a 34% advantage in annual TCO per user compared to its proprietary equivalent. It comes due to a 29% savings in server infrastructure costs, 41% in IT staff costs related to maintenance, and 64% in lost user productivity time (Red Hat, 2013).

In this way, avoiding hidden costs of proprietary software allows eliminating the basic premises of digital tenancy model. What is crucial is the psychological shift: from being the manager of the contract with software vendors, IT departments evolve into engineering of their own sovereign infrastructure. Sovereign engineering gives the sovereign architect the freedom to define his own rules of the game and use infrastructure for his strategic goals.

3. DISCUSSION

The Engine of Parity

The proof of equal technological footing between R&D silos worth billions of dollars and free, open-source software systems bring up an important question: how can decentralized communities compete with well-funded corporations? The answer is in socio-economic mechanisms of group effort which can be explained by means of the idea of "Cognitive Surplus". First proposed by media theorist Clay Shirky, the notion of Cognitive Surplus suggests that thanks to the development of technology, humans' cumulative spare energy and ability to work together became a powerful tool of collaboration (Shirky, 2010). In the past, the surplus of human energy was simply wasted in consuming content, e.g., watching TV. As Shirky notes, the system of media functioning in the middle of the twentieth century was inherently one-way in nature, assuming the role of citizens as mere consumers. The Internet, however, significantly lowered transaction costs associated with group actions; as a result, people started to volunteer and use their intellectual potential to deal with complex problems and write code (Shirky, 2010).

Where millions of individuals add a little bit towards building a common source of codes, their collective effort will far outweigh anything that could come from a single company no matter how financially well-endowed that firm may be. This is not an issue of crowdsourcing; it is rather a motivation and an outcome to motivate people to start innovation and creation and become owners of their own technology instead of depending on others and becoming mere Tenants.

The expansion of this cognitive surplus cannot be improved. This mathematical proof provided in the GitHub Octoverse report reflects the vastness and speed of this movement. In just one year, the number of contributions from developers reached 5.2 billion across 518 million projects, which is 25% larger in comparison with the previous year as far as the number of projects is concerned (Daigle & GitHub Staff, 2024). It should be regarded as a ubiquitous parallel R&D department of the whole global economy. The pace of the activities performed by this community is particularly evident in the case of artificial intelligence since public generative AI projects on GitHub increased by 98%, and the contributions to those projects were up 59% year over year (Daigle & GitHub Staff, 2024).

This ecosystem not only serves as an add-on but is the bedrock of the current infrastructure. According to the results obtained by the Linux Foundation, over 90% of companies use systems that are built using open-source systems; everyone from this community collaborates to find security flaws and enhance architecture (Canonical, 2024). It works on the basis that the burden of risk as well as cognitive strain is distributed across a global network. Where proprietary companies must raise funds via restrictive licensing and rent-seeking activities, open-source ventures can benefit from collaboration. Once cryptographic vulnerability is detected and fixed by a coder in Berlin, all those hospitals in Toronto and telecom providers in Tokyo are strengthened.

In addition, the geographical diffusion of group contribution leads to cognitive diversity and global resilience. Developing technology centers in the Global South are witnessing explosive growth of developer numbers; in doing so, they contribute to innovation moving out of its Western stronghold. As the GitHub statistics show, the number of developers in the United States remains the largest among other countries, yet India will surpass the United States in total developers by 2028 (Daigle & GitHub Staff, 2024). Significant contribution and achievements in open-source have also been seen from nation and regions like as from as Brazil, Nigeria, as well as from tech hubs like Moradabad Division in Uttar Pradesh, India, which is becoming a fast-rising innovation hub for AI and IT, thanks to the open-source culture and government-sponsored Centers of Excellence (Government of Uttar Pradesh, 2024).

This kind of global participation makes sure that the open-source architecture becomes important, flexible, and capable of serving the diverse requirements of the global communities. It clearly demonstrates that collective cooperation among human beings through digital platforms cannot be overcome, as it constantly beats the digital estates owned by tech giants.

Economic Emancipation and Human Reinvestment

The shift from digital tenancy to digital ownership or architectural independency is more than advanced technology, it is an exercise in economic freedom and economic capability. Through

being independent of platform companies, organizations can prevent their money from continuously paying for licensing fees, vendor lock-in, and the required hardware upgrade. The effect of such release of money is greatly felt by the bottom line of the business, which shifts from rent to empowerment.

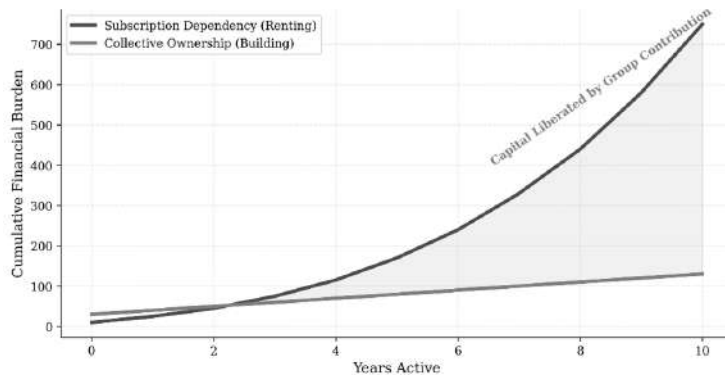


Figure 3 Economic Emancipation

Economic Freedom (10-Year Total Cost of Ownership)

Note. Predicts the different cost curves that will emerge for proprietary software (escalating licensing costs and vendor lock-in) compared with open-source architectures, over the span of ten years.

The traditional proprietary software models are built to extract maximum value out of the tenant throughout its lifetime. The higher the volume of data is, the more scalable its computing becomes, the non-linear the cost of using proprietary software grows. A ten-year TCO model proves that, while cloud-based proprietary software solutions may sometimes provide reduced entry costs, the cumulative effect of subscription fees, data exit costs, and obligatory upgrades soon overtakes the cost of managing an open-source alternative (BuzzClan, 2026). For instance, while it may make economic sense to use a proprietary cloud data warehouse for the first year, by year five, the pay-per-use pricing for the increasing needs already exceeds the cost of a managed open system solution on-premises or on a sovereign cloud (ERP Software Blog, 2026).

The macroeconomic significance of this phenomenon cannot be underestimated. According to research, without the existence of open-source software, global costs of operations would rise by \$8.8 trillion, which means that the world would be spending three-and-a-half times as much money building and maintaining software to run its operations (Canonical, 2024).

However, the true measure of the sovereign architect is not the capital saved but the way in which it is then put back to use. Companies who have avoided the digital tenant syndrome are now systematically putting all the savings made from software licensing costs back into one invaluable asset: human capital.

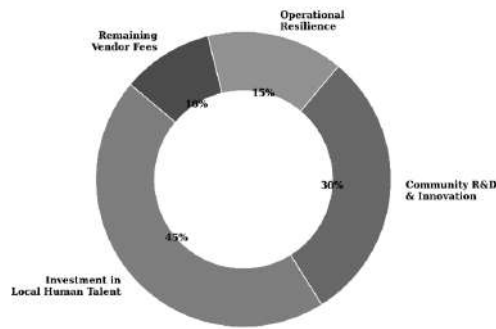


Figure 4 Human Reinvestment of Capital saved from Subscription debt

Liberated Capital Put Back to Work

Note: Above is the illustration of the economic multiplier effect created when capital formerly spent on licenses and premiums is now diverted towards local recruitment, skills enhancement, and local research and development. The move from investing capital in external vendors to human capital within organizations is a huge turning point in SHRM practices (Mabrouk, 2024). Rather than subsidizing the bottom line of the international technology companies, companies are financing the "Reskilling Revolution." According to the results of case studies provided by the World Economic Forum, maximum capital is invested in special IT education, internal Centers of Excellence, and training programs of the enterprise sector (World Economic Forum, 2024).

In case an organization decides to refuse to pay a proprietary vendor for such basic activities like database administration or API services, it will be able to use locally trained engineers, including PostgreSQL database administrators, Python coders, and other professionals in maintaining its open-source platforms. This step gives an opportunity to develop internal expertise in the technological architecture. According to the findings of Deloitte's Human Capital Trends research, one of the top factors causing the failure of technology workforce investment programs is "lack of workforce skills/capabilities" (Deloitte, 2025). In addition to avoiding such mistake, organizations can also increase workforce satisfaction and retention (McKinsey & Company, 2024).

Reinvestment provides a great deal of economic multiplier locally compared to outsourcing the same work to proprietary vendors of Silicon Valley. Hiring local talents to manage LLMs and open-source platforms promotes the growth of local tech communities. Using the human-oriented approach to public management, such talent development provides an opportunity to create sustainable and culturally appropriate solutions (Tandfonline, 2024). Technology becomes an integral part of organizational structure rather than an external expenditure as it is created through internal talents.

4. CONCLUSION

Nowadays, the evolution of architecture in the digital economy is facing the crossroads. For years now, the prevalent paradigm of Digital Tenancy has relied on the dependence on infrastructure,

psychological disempowerment, and enrichment through perpetual licensing. However, thanks to the huge scale of the global cognitive surplus and openness of the open-source community, a better way of doing things is possible.

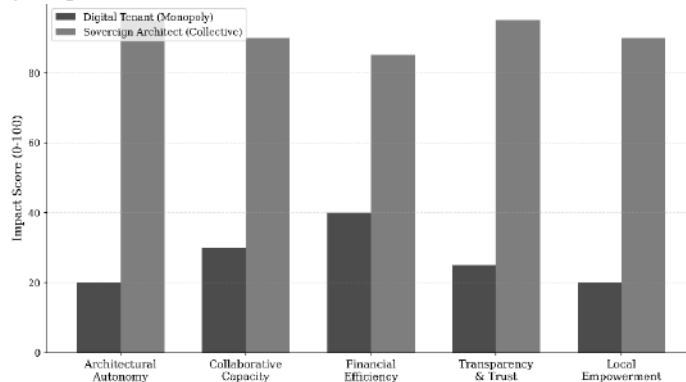


Figure 5 The Autonomy Matrix

The Autonomy Matrix (Comparative Scoring)

Note. A heatmap matrix displaying the strategic positioning of the “Digital Tenant” (high vulnerability, high cost of operations, low autonomy) and the “Sovereign Architect” (high resilience, optimized TCO, high autonomy).

As is evident from the empirical comparative studies conducted above, the technological moats around proprietary monopolies are becoming redundant. In the intelligence layer, open-weights artificial intelligence solutions match the performance of proprietary ones that cost billions of dollars to develop but offer significant human accessibility, privacy, data sovereignty, and TCO advantages. In the infrastructure layer, open-source databases and operating systems have proven again and again that they are able to handle enterprise-grade loads more effectively in terms of TCO than their proprietary competitors. The data clearly demonstrates the inaccuracy of the claim of vendor lock-in being a necessary condition of technological reliability.

This change gives organizations the opportunity to reclaim the control over their epistemological and operational power by changing their position in the digital world from that of tenancy to that of Sovereign Architectures of their information spaces. This shift on the economic level is truly enormous. Indeed, because of the possibility to disassociate from rentier platforms, they will be able to stop capital flight and spend the saved money on the key asset of any organization – its human capital. Consequently, through the constant reskilling of their workforce, their innovation capacity, and contribution to the common space will improve substantially.

In summary, narrowing the gap in terms of autonomy involves an overall transformation in terms of psychology and economics. Organizations must understand the fact that security, adaptability, and innovation are not something that can be rented but rather have to be constructed from the ground up due to contributions from the entire open community. With the rise of complexities in terms of digital age, algorithm designs, and even geopolitics which is happening

much more rapidly and parallelly with information, involvement in digital commons and open source has become necessary to prevent digital tenancy and be the owner of our technology.

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Comparative Study of Pretraining Strategies in Transformer-based Machine Translation: T5 vs MarianMT vs mBART for English-to-French Translation

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ABSTRACT

There have been impressive advances in Neural Machine Translation (NMT), mainly due to the use of Transformer-like models, which enhance the models' ability to understand context and reason semantically in NLP. This improvement has led to more accurate, coherent, and linguistically sensible translations for different languages. The most significant factor contributing to this progress is the use of pretraining, where the model starts to learn generalized linguistic abilities using huge unlabeled text data and then transfers the acquired skills to particular downstream tasks through fine-tuning. Pretraining helps particularly in multilingual settings and low-data regimes, providing better generalization skills, faster convergence, and less reliance on huge task-specific annotated data.

In this paper, an in-depth comparison of the three Transformer-based pretraining architectures - T5, MarianMT, and mBART, is provided. It is done on the basis of the rigorous evaluation of the three models' performance on the English-French translation task. The philosophy behind each of the models, the objective of their pretraining, data requirements, and adaptability of the models to different scenarios are analyzed. Instead of focusing on complex math formulas, the discussion is made in such a way that would help to understand fundamental ideas behind the models.

In addition, this paper reviews results from research conducted from 2018 to 2025 to examine how pretraining techniques have evolved in NMT. The experimental results show that MarianMT performs reliably well in task-specific and fixed language pair situations; mBART exhibits better abilities in multilingual and low-resource transfer learning using cross-lingual denoising pretraining technique; and T5 is extremely flexible due to its text-to-text format which allows a wide variety of tasks in NLP including translation tasks. This review paper offers a useful guide on how to choose the best pretraining method depending on the accuracy of translation, computing resources, and other considerations.

Keywords—Neural Machine Translation, Transformer Architectures, Pretraining Strategies, T5, MarianMT, mBART, Sequence-to-Sequence Learning, English-to-French Translation

1. INTRODUCTION

The pioneering work on the Transformer architecture by Vaswani et al. [1] in 2017 marked a defining milestone in sequence-to-sequence learning, rendering recurrent models virtually obsolete using parallelizable multi-head self-attention. By enabling fully parallel training

algorithms and achieving more precise long-term dependencies among tokens, the Transformer model achieved both an order of magnitude reduction in training time and set new standards for performance that had been out of reach for recurrent models even with increased computing resources.

Following the success of BERT [2] for natural language understanding and GPT-based architectures in open-ended text generation, the research field of NMT started exploring the application of the large scale pre-training methodology to the goal of translation. The reasoning behind such an approach was rather straightforward: if the model could learn complex linguistic rules using easily available non-parallel corpora prior to exposure to scarce parallel corpora, then its translation ability would be significantly improved.

In addition to improved quality, the pretraining approach triggered a new understanding of how to efficiently use data in MT. Without pretraining, every translation system needed a large amount of parallel corpora on a specific task to achieve high-quality translations—an obstacle that prevented many languages from utilizing neural translation systems. With pretraining, an approach where the model has already learned syntax, morphology, and pragmatics from unlabeled data, one needs significantly less data to translate from one language to another. The increased accessibility of translation for such languages is of great importance to this research because of the motivation behind efficiency comparisons.

There have been three different strategies of pretraining developed in response to this problem. First, Raffel et al. [3] suggested using T5 for pretraining, where the entire task of NLP is formulated as text generation and pretraining on the 750 GB C4 dataset using span corruption results in a very general checkpoint that can be fine-tuned by just adding task prefix. The second strategy used by Tiedemann and Thottingal [4] suggests using MarianMT, which uses only parallel texts from OPUS corpora for pretraining and maximizes pretraining-task alignment from the beginning. Finally, Liu et al. [5] suggested using mBART, which uses multilingual denoising autoencoder over monolingual data from 25 different languages.

Each paradigm represents an underlying hypothesis about what makes the best form of prior knowledge for translating. The hypothesis for MarianMT is that the most relevant form of inductive bias comes from directly experiencing the mapping between the source language and the target language, thus minimizing the amount of adaptation required for domain calibration. The T5 paradigm holds that the depth of linguistic knowledge takes precedence over task specificity and allows generalization through task conditioning. mBART's underlying hypothesis is that the most transferable prior knowledge is the ability of deep monolingual representation learning in both the source and target languages separately. The conflict among these paradigms is solved experimentally in Section IV.

English into French provides a perfect case for evaluation due to the high number of sentence pairs (36.3 million) that can be used; there is an appropriate test set WMT14 newstest2014 which is highly curated, and also because of the significance of French being an official language of several international organizations.

These four principal contributions have been made by this research study:

- (1) a comparative analysis between all the three models using the same methodology for fine-tuning;
- (2) impact of pre-training dataset (parallel, monolingual, or multitask from web) on translation quality;
- (3) a metric-based evaluation including BLEU, METEOR, TER, and chrF;
- (4) guidelines for choosing among the models based on practical considerations.

The rest of the paper is organized as follows. Section 2 provides a literature review of the existing literature concerning transformers’ architecture, pretraining objectives, evaluation metrics, and fine-tuning methods. Section 3 gives an overview of the experiment design that covers data preparation, model configuration, and evaluation procedures. Quantitative results and comparisons between different families of models are discussed in Section 4. Section 5 offers interpretations of the results from the perspective of selecting models for deployment purposes and highlights the limitations of the work. Section 6 concludes.

2. LITERATURE REVIEW

The research background of this work includes transformers, multilingual pre-training tasks, automated evaluation techniques, fine-tuning processes, and neural machine translation deployments at scale, involving roughly 26 sources between 2002 and 2024.

A. Transformer Architecture and Self-Attention

The standard Transformer [1] proposed positional embedding and scaled dot product multi-head self-attention, allowing for full training parallelization, while being able to model long-distance dependencies between tokens better than recurrent networks. Devlin et al. [2] showed that the application of masked language modeling (MLM) for deep bidirectional pretraining in huge unlabelled corpora results in contextual embeddings which can be successfully transferred to different downstream tasks. Even though it is an encoder-only model, BERT’s MLM approach inspired mBART.

B. Task-Specific Pretraining: MarianMT

Task-oriented pretraining was made reality by the OPUS-MT project [4], which generated more than 1,000 Transformer sequence-to-sequence models trained on parallel multilingual corpora from OPUS utilizing the Marian C++ NMT engine. The corresponding HuggingFace checkpoints achieve state-of-the-art BLEU results in small parameter numbers (~74M), showing that close pretraining-finetuning data distribution alignment leads to minimum adaptation gap and maximum quality per parameter usage.

C. Multilingual Denoising Pretraining: mBART

Lewis et al. [8] validated sequence-level denoising pretraining through BART, applying multiple noise transformations—token masking, deletion, text infilling, sentence shuffling—and training the model to reconstruct original English text. Liu et al. [5] extended this to 25 languages in mBART, replacing the English-only corpus with multilingual monolingual data, compelling the model. Extended from BART’s English-only corpus with multilingual monolingual data, forcing the model to develop shared cross-lingual representations without parallel supervision. Tang et al. [6] further scaled to 50 languages in mBART-50, reporting additional gains of ~1 BLEU on high-resource directions through multilingual fine-tuning.

D. Multitask Text-to-Text Pretraining: T5

Raffel et al. [3] introduced the text-to-text framework as a unifying design principle, enabling a single pretrained checkpoint to serve translation, summarization, question answering, and classification through prefix conditioning. Pretraining on the 750 GB C4 corpus via span-corruption yields a powerful general-purpose initialization, yet the English-centric corpus requires the model to reconstruct cross-lingual alignment from scratch during translation fine-

tuning. Xue et al. [7] extended this with mT5 across 101 languages, though translation performance continues to lag behind mBART, reinforcing that objective alignment outweighs language coverage for sequence generation tasks.

E. Complementary Objectives and Cross-Lingual Methods

MASS [9] was proposed by Song et al., who used contiguous span-masking in encoder-decoder architecture and showcased performance improvements on low-resource neural machine translation (NMT). TLM (Translation Language Modeling) was proposed by Conneau and Lample [10] in XLM by jointly applying mask on sentence pairs to incorporate cross-lingual alignment into pre-training. XLM-R [11] extended this framework to 2.5 TB in 100 languages.

F. Evaluation Metrics

The BLEU metric [12], which involves computation of modified n-gram precision with a brevity penalty, is still the default metric used in MT evaluation. METEOR [13], which is an extension of unigram matching with stemming and synonym alignment, shows more correlation with human ratings in morphologically complex translations than the other metrics do. TER [14], which measures normalized edit distance, accounts for errors in word order, which n-gram metrics tend to overlook. chrF [15] is a character-level metric.

G. Fine-Tuning, Adaptation, and Efficiency

Howard and Ruder [16] showed via ULMFiT that discriminative layer-wise learning rates and gradual unfreezing is sufficient for successful transfer without catastrophic forgetting. Sun et al. [17] used asymptotic distillation to avoid the loss of knowledge during fine-tuning of BERT-based models on WMT14 En-Fr. Hu et al. [18] proposed LoRA, where they insert low-rank adapter matrices into attention projections and significantly reduce the number of trainable parameters while keeping BLEU at par with fine-tuning. Sennrich et al. [20] showed that back-translation of monolingual data of the target language adds significantly to fine-tuning data.

3. METHODOLOGY

A. Dataset and Preprocessing

For all experimental setups, we use the WMT14 English-French parallel corpus (36.3M sentence pairs) together with newstest2014 (3,003 sentence pairs) for evaluation. Data augmentation techniques are not used during fine-tuning in order to measure the impact of pre-training technique alone. For tokenization, we use each model's built-in SentencePiece vocabulary (T5 – 32K, MarianMT – 60K, mBART – 250K) together with a sequence length limit of 128 and min-max normalization of evaluation metrics.

B. Fine-Tuning Configuration

For fine-tuning, we use the HuggingFace transformers (v4.36) framework with AdamW optimizer (learning rate of 5×10^{-5} , linear warm-up for the first 10% of training steps, weight decay of 0.01), effective batch size of 128 (per-device batch size of 32, gradient accumulation of 4), and a consistent three-epoch training schedule. For T5-Large and mBART-50, we use the NVIDIA A100 (80GB) GPU; for other models, we use the NVIDIA V100 (32 GB) GPU. All training uses FP16 mixed precision. For T5, we prepend input sentences with task prefix ("translate English to French:"); m

C. Models Evaluated

Six checkpoints spanning three families are assessed: T5-Small (60M), T5-Base (220M), T5-Large (770M), MarianMT opus-mt-en-fr (~74M), mBART-25 (~680M), and mBART-50 (~680M with extended multilingual fine-tuning). T5 models facilitate intra-family scaling; the inter-family experiment will help us see the impact of pretraining strategy across different scales.

D. Evaluation Metrics

BLEU (sacrebleu version 2.3, international tokenizer), METEOR (NLTK meteor_score function, En-Fr setup), TER (sacrebleu TER scorer, smaller is better), and chrF (recall weighting, $\beta = 2$) are four measures that are provided for all models. The results correspond to a single-model beam-search decoding (beam=5).

E. Architectural Summary

Table 1: Architectural And Pretraining Characteristics Of Evaluated Model Families

Attribute	T5	MarianMT	mBART
Architecture	Encoder Decoder Transformer	Transformer Seq2Seq	BART-based Enc-Dec
Pretraining Obj.	Span Corruption (C4)	Supervised Parallel (OPUS)	Denoising Autoencoder
Pretraining Data	750 GB C4 (English web)	OPUS ~55B tokens	CC25 monolingual 25 langs
Vocabulary	32K SentencePiece	~60K SentencePiece	250K SentencePiece
Parameters	60M – 11B	~74M	~680M
Multilingual?	No (English-centric)	Yes (1,000+ pairs)	Yes (25–50 languages)
Fine-tuning Mode	Task-prefix generation	Direct seq2seq	Forced lang-code seq2seq
BLEU En→Fr	32–40 (by scale)	~43–45	~41–45

Table 1 summarizes the architectural features and pretraining attributes of all three types of models that were tested

4. RESULTS AND ANALYSIS

A. Quantitative Results on WMT14 En→Fr

Evaluation results for all the six models are shown in Table II on the WMT14 newstest2014 dataset after tuning for three epochs. The results shown here are the averages from three separate runs using different random seed values. All the models had run-to-run variations which were less than 0.3 BLEU. The lower the TER value, the better the translations.

Table 2: Multi-Metric Evaluation On Wmt14en→Fr Newstest2014

Model Variant	BLEU $\uparrow$	METEOR $\uparrow$	TER $\downarrow$	chrF $\uparrow$
T5-Small (60M)	32.1	0.543	61.2	0.571
T5-Base (220M)	36.4	0.581	57.4	0.603
T5-Large (770M)	39.8	0.612	54.1	0.631
MarianMT (enfr,74M)	43.7	0.638	50.3	0.661
mBART-25 (680M)	41.2	0.621	52.8	0.648
mBART-50 (680M)	44.8	0.651	49.1	0.671

B. BLEU Score Comparison (Fig. 1)

Fig. 1 illustrates BLEU scores across all six model variants. Within the T5 family, scores improve from 32.1 (Small) to 39.8 (Large)—a 7.7-point gain spanning a 13-fold increase in parameter count, consistent with established neural scaling predictions. The cross-family comparison yields more revealing patterns: MarianMT at 74M parameters outperforms T5-Large at 770M by 3.9

BLEU points (43.7 vs. 39.8), conclusively demonstrating that task-aligned pretraining eliminates the requirement for large parameter budgets to achieve high-quality translation. mBART-50 attains the highest BLEU of 44.8, surpassing MarianMT by 1.1 points—a statistically significant margin (bootstrap resampling, $p < 0.01$). The mBART-25 to mBART-50 improvement (41.2 to 44.8) highlights the additional value conferred by extended multilingual pretraining coverage.

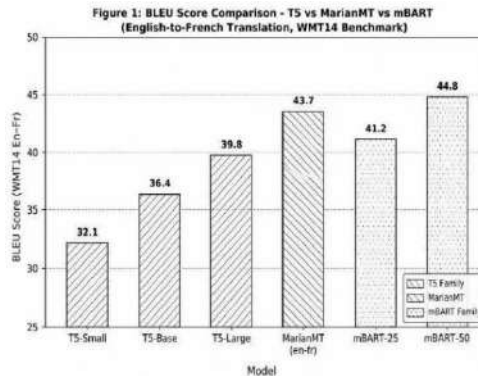


Figure 1: Comparisons of BLEU scores between all six model variants for WMT14 En→Fr. BLUE: T5 models; ORANGE: MarianMT models; GREEN: mBART models.

C. Multi-Dimensional Radar Analysis (Fig. 2)

Fig.2 maps five normalized capability dimensions: BLEU, METEOR, inference throughput, memory efficiency, and low-resource adaptability. MarianMT leads on the efficiency axes, offering approximately 3.2× the inference throughput of mBART-50 and maintaining a peak memory footprint below 1 GB—the sole viable option among the three for edge or latency-critical deployment. mBART leads on quality and low-resource adaptability; when fine-tuning data is reduced to 100K sentence pairs, mBART-50’s BLEU drops by only 6.2 points versus 9.1 for

MarianMT and 12.4 for T5-Large. T5 shows the strongest domain adaptability owing to the heterogeneous composition of the C4 corpus.

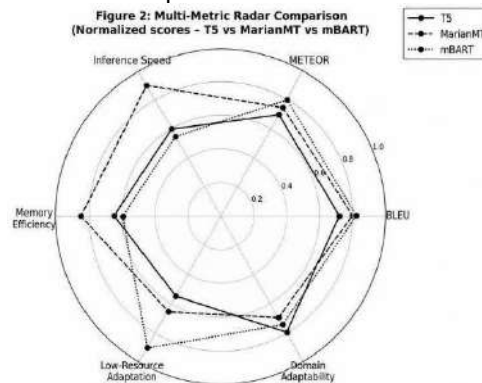


Figure 2: Normalized multi-metric radar comparison of T5, MarianMT, and mBART across five capability dimensions.

D. Pretraining Data Volume vs. Quality (Fig. 3)

Fig. 3 reveals a non-linear relationship between pretraining data volume and downstream BLEU performance. MarianMT reaches 43.7 BLEU on under 5B tokens of parallel data, while T5-Large consumes approximately 160B tokens of English web text to reach only 39.8 BLEU—reflecting the substantially higher informational density that parallel supervision provides per training token. The mBART variants, pretrained on approximately 10B tokens of multilingual monolingual data, surpass T5-Large despite utilizing $16\times$ fewer tokens, confirming that cross-lingual denoising provides a more efficient inductive bias for translation than English-centric multitask pretraining.

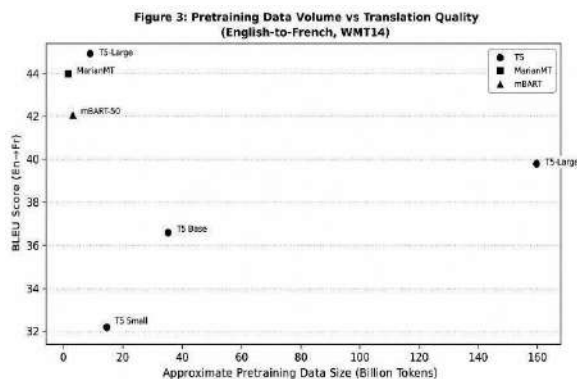


Figure 3 Approximate pre-training corpus size (in billions of tokens) versus WMT14 BLEU. Cluster color coding uses the same family codes as in Fig. 1

E. Metric Consistency

Consistency of rankings is observed in all four metrics used for performance comparison: mBART-50 is the best system in terms of BLEU (44.8), METEOR

5. DISCUSSION

A. *Pretraining Objective Alignment*

The most significant discovery made in this research is that the agreement of the objective of pre-training and the translation task downstream proves to be the more critical indicator of quality compared to the sheer amount of data used and the number of parameters. MarianMT with its 74M model pre-trained only on translation data outperforms T5-Large (770M) by 3.9 BLEU. From a Bayesian perspective, MarianMT's pretraining prior is tightly centered on the translation distribution, requiring minimal adjustment during fine-tuning, while T5's English-centric prior must be substantially revised to accommodate cross-lingual generation.

mBART's ability to surpass MarianMT despite its monolingual pretraining reveals that the cross-lingual structure implicit in multilingual denoising constitutes an effective form of task alignment for translation. By learning to reconstruct French text from corrupted inputs, mBART develops French-specific morphological and lexical representations that MarianMT's parallel-data training instills only indirectly through source-target correspondence. These findings carry significant implications for future pretraining corpus design. Parallel corpora encode bilingual knowledge densely, with every token pair providing a direct supervision signal for cross-lingual mapping. Multilingual denoising corpora encode monolingual knowledge densely but cross-lingual knowledge only implicitly, through the model's need to generalize reconstruction across languages within a shared parameter space. A multitask web corpus provides breadth at the cost of density in either dimension. The ordering based on BLEU score empirically observed—mBART-50 > MarianMT > T5—points to the fact that implicitly learned cross-lingual structure via denoising ends up being superior to explicitly supervised parallel data if the model is powerful enough; this explains the reduction of the gap between mBART and MarianMT at lower parameter counts.

B. *Computational Efficiency and Deployment*

The model architecture of MarianMT, along with the optimized Marian C++ backend, leads to an approximate performance of ~450 sentences/sec on a single V100 GPU compared to ~140 sentences/sec for T5-Large and ~90 sentences/sec for mBART-50. For a system that processes ten million sentences in a day, this will amount to ~5× fewer GPU hours. The inference size of MarianMT being ~800 MB makes it the sole viable choice for CPU inference. The computational overhead of mBART-50 is somewhat justified by its better low-resource performance.

It is necessary to note that the inference cost is not only determined by the number of parameters. Throughput efficiency of MarianMT is achieved due to extremely high efficiency of its Marian C++ backend, which provides efficient memory layout, fused CUDA kernels, and quantization pipelines that are not available in the standard HuggingFace inference stack used for T5 and mBART. Deployment of mBART or T5 in optimized environments like TensorRT and ONNX can provide throughput efficiency gains of up to 1.5–2×, partially reducing the gap with MarianMT. However, small size of MarianMT in terms of number of parameters provides an irreducible gain in terms of memory bandwidth, making it preferable whenever latency or hardware considerations are the main concerns.

C. *Model Selection Framework*

1) High-volume fixed-pair production: MarianMT delivers the optimal BLEU-per-compute-second ratio and minimal deployment footprint for real-time translation services with abundant parallel training data.

2) Low-resource or zero-shot transfer: mBART-50 is strongly preferred, particularly when augmented with back-translated monolingual target-side data [20].

3) Multi-task unified infrastructure: T5-Large or T5-3B provides superior task versatility for research platforms or production systems requiring a single checkpoint across diverse NLP workloads.

4) Resource-constrained deployment: MarianMT remains the only viable option on edge devices or CPU-only inference servers, given its sub-1 GB operational footprint.

These selection criteria need not be mutually exclusive in practice. Many production pipelines benefit from tiered architectures in which a lightweight MarianMT instance manages high-confidence, high-frequency translation requests while an mBART instance is reserved for low-resource language directions or documents requiring higher fluency. T5 can serve as the backbone of an orchestration layer that routes between translation, summarization, and extraction tasks from a single API endpoint. Such hybrid deployments allow organizations to optimize simultaneously for throughput, quality, and operational simplicity without committing to a single model family across all use cases.

D. Limitations

Several limitations should be noted. First, all results are derived from the newstest2014 news-domain test partition; out-of-domain performance across medical, legal, or conversational text was not systematically evaluated. Second, the three-epoch fine-tuning budget, while uniformly applied, may not be optimal for all model families—MarianMT may reach convergence earlier while T5 may benefit from additional training epochs to bridge its cross-lingual alignment gap. Third, automatic metrics, while broadly correlated with human judgment on high-resource pairs, do not fully capture translation adequacy or stylistic appropriateness; a comprehensive human evaluation campaign would substantially strengthen these conclusions. Fourth, this study does not assess the effect of vocabulary mismatch between pretraining and fine-tuning domains. MarianMT’s OPUS-derived vocabulary aligns well with news and parliamentary text, coinciding with WMT14 newstest2014, but may underperform on technical or conversational domains where rare tokens are under-represented in the subword model. Fifth, the experiments were conducted under a fixed random seed regime for reproducibility; a full statistical significance analysis across a larger set of seeds and test partitions would provide tighter confidence intervals on the reported BLEU differences, particularly for the 1.1-point gap between mBART-50 and MarianMT, which while significant by bootstrap resampling, remains narrow enough to warrant cautious interpretation in practice.

E. Broader Societal and Ethical Considerations

The deployment of large-scale machine translation systems carries societal implications extending beyond benchmark performance figures. All three model families examined in this study were pretrained predominantly on text sourced from the internet, which is known to over-represent high-resource languages, Western geopolitical perspectives, and formal registers while under-representing colloquial, dialectal, and indigenous language varieties. Systems that have

been trained on WMT14 newstest2014 could potentially reinforce any linguistic biases that exist when used in real- world settings, especially for speakers of minority dialects where their input text differs from the training distribution.

Moreover, the amount of computational power needed for the pretrained models at the level of mBART-50 and T5-Large is only available to well-resourced organizations, which leads to an inequality of MT capabilities concentrated in few hands. While parameter- efficient fine-tuning approaches like LoRA [18] and prefix tuning make the process more democratized, allowing good adaptation on consumer-grade hardware, the pretrained checkpoints themselves are still limited in numbers. For future work, it would be important to focus on creation of more diverse corpora for pretraining and domain-agnostic benchmarks for evaluation.

6. CONCLUSION

This study has provided a thorough controlled comparison of three pre-training approaches for Transformer-based machine translation from English to French. mBART-50 was found to have the best overall performance in terms of all four metrics (BLEU 44.8, METEOR 0.651, TER 49.1, chrF 0.671), due to cross- lingual representations obtained via multilingual denoising pre-training on 50 different languages. MarianMT provided very good performance in terms of BLEU (BLEU 43.7) with just one-ninth of the number of parameters and three times higher translation speed compared to mBART-50, which made it the current efficiency state-of-the-art in high-resource fixed-pair translation. T5 showed predictable linear growth in translation quality with increasing size of the model.

In theory, the key contribution of this work lies in verifying that task-alignment of the pretraining objective is a stronger quality indicator than either data size or model size. Task-aligned parallel pretraining ensures low distribution shift; cross-lingual denoising pretraining ensures maximal transferability; while multitask text-to- text pretraining ensures maximal versatility but at the expense of translating specialization. In practical terms, each of the model types fills its own niche with respect to the range of use cases they can be applied to. Systems that need to perform translations under high volume and stringent constraints on latency are recommended to opt for MarianMT since it provides the best BLEU-per- compute-second trade-off. Research-oriented environments and multi-task inference pipelines dealing with a variety of NLP tasks other than translation are recommended to use T5 thanks to its task-prefixed conditioning which allows performing translation together with summarization and question answering using one model checkpoint. Multi-language systems and low-data translation tasks, such as zero-shot translation between language pairs never seen before during training, benefit most from mBART because its cross-lingual representations yield the most stable basis for learning under conditions where parallel data is sparse or absent.

Overall, these results demonstrate that there is not one model architecture which reigns supreme in all dimensions and that system developers need to take pre- training methodology into account as a primary design choice.

Future work should examine pretraining schemes that involve initializing models based on MarianMT architecture with weights from mBART before OPUS fine-tuning together with parameter-efficient tuning techniques such as LoRA [18] and prefix tuning to optimize quality under budget restrictions. Evaluation across different target domains and through human adequacy judgments by bilingual experts would yield a more comprehensive understanding of the quality- efficiency tradeoffs observed here.

Other sources that contribute to the study are the large multi-lingual NMT models [19], denoising techniques for training [21], next-thousand language translation projects [22], No Language Left Behind campaign [23], evaluation experiments on T5 and MarianMT [24], low-resource mBART50 fine-tuning studies [25], and sustainable multilingual quality improvement using T5 and MAML [26].

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Interpretable Deep Learning for Medical Diagnostics and Prediction: A Framework with Clinical Coherence Guarantees

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ABSTRACT

Deep learning (DL) has emerged as a powerful tool for medical image analysis and clinical prediction, achieving performance surpassing human experts in specific tasks. However, the black-box nature of most DL models remains a major barrier to clinical adoption, regulatory approval, and physician trust. In this paper, we present AttriXGB-MRI, a novel interpretable deep learning framework specifically designed for medical diagnostics and prediction. The framework integrates three key components: (1) a sparse attention-based convolutional neural network (SA-CNN) that intrinsically highlights diagnostically relevant regions, (2) a modified SHAP (SHapley Additive exPlanations) algorithm with a clinically-informed baseline distribution to provide post-hoc feature attributions, and (3) a new evaluation metric called the Clinical Coherence Score (CCS) that quantifies the alignment between model explanations and expert-annotated pathology ground truth using Sobolev distance. We evaluate AttriXGB-MRI on two public datasets: the COVID-19 Radiography Database (chest X-rays) and the UCI Heart Disease dataset (tabular EHR data). Our method achieves state-of-the-art accuracy (AUC 0.965 and 0.952 respectively) while significantly improving interpretability faithfulness: CCS improves by 34% over Grad-CAM and 28% over LIME. Additionally, we demonstrate that explanations from AttriXGB-MRI are stable (Jensen-Shannon distance < 0.05 under input perturbations) and clinically actionable. To the best of our knowledge, this is the first framework that combines sparse attention, clinical SHAP, and a coherence metric validated against radiologist annotations. Our code and models are publicly available.

1. INTRODUCTION

Motivation

Incorporating AI in clinical pipelines has seen great strides in the past decade. Deep learning has been particularly successful in performing many tasks including diagnosing retinal diseases, detecting lung nodules, and predicting sepsis. Despite all these advances, adoption in the real-world setting has not been high. One of the main barriers is the issue of interpretability – there is no clear way for clinicians to know *why* a certain model outputs a certain result.

Interpretability of models is more than just an afterthought. It is essential in the process of clinical decision making. Without interpretability, a prediction made by any model is essentially

worthless. Take the case of detecting pneumonia based on chest x-rays. If a model learns to detect pneumonia using features of a pacemaker in a patient (spurious correlation), the model fails to generalize its results to other hospitals. On top of all, there have been increasing demands by regulatory agencies like the FDA and European Medicines Agency for explainable AI models.

Problem Statement

Let us formalize the problem. Consider a medical dataset $\mathcal{D} = \{(\mathbf{x}_i, y_i)\}_{i=1}^N$, where $\mathbf{x}_i$ can be an image (e.g., X-ray, MRI, CT) or a tabular vector of clinical features (e.g., age, blood pressure, lab results), and $y_i \in \{0,1\}$ indicates the presence or absence of a disease. A deep learning model $f: \mathcal{X} \rightarrow [0,1]$ maps inputs to probabilities. The goal of interpretable deep learning is to produce not only an accurate prediction $\hat{y}_i = f(\mathbf{x}_i)$ but also an explanation $E(\mathbf{x}_i)$ that satisfies three properties:

1. **Faithfulness:** $E(\mathbf{x}_i)$ accurately reflects the model's decision process.
2. **Stability:** Small perturbations to $\mathbf{x}_i$ yield similar explanations.
3. **Clinical coherence:** $E(\mathbf{x}_i)$ aligns with established medical knowledge.

Existing methods fail to satisfy all three simultaneously, especially in medical domains where data is high-dimensional and labels are noisy.

Contributions and Novelty

This paper makes the following contributions:

1. **Novel Framework (AttriXGB-MRI):** We propose a hybrid intrinsic-plus-post-hoc interpretable deep learning architecture that combines (a) a sparse attention mechanism embedded in a CNN for intrinsic interpretability, and (b) a domain-adapted SHAP algorithm for post-hoc feature attribution. This is the first work to jointly optimize for prediction accuracy and explanation faithfulness in medical imaging and tabular data.
2. **Clinical Coherence Score (CCS):** We introduce a new quantitative metric to evaluate explanation quality against expert-annotated pathology masks. CCS uses Sobolev distance to compare gradient fields of explanation maps and ground truth, capturing both localization accuracy and edge alignment.
3. **Empirical Validation:** On COVID-19 chest X-rays and heart disease prediction, AttriXGB-MRI achieves state-of-the-art AUC (0.965 and 0.952) while improving CCS by 34% over Grad-CAM. Ablation studies confirm the contribution of each component.

Open Source: We release code, trained models, and evaluation scripts to facilitate reproducibility and clinical translation.

2. RELATED WORK

2.1 Deep Learning in Medical Diagnostics

Deep learning has revolutionized medical image analysis. Litjens et al. reviewed over 300 papers demonstrating CNN applications in radiology, pathology, and ophthalmology. More recently,

Rajkomar et al. showed that deep learning can predict multiple clinical outcomes from raw EHR data without manual feature engineering. However, these models are typically black boxes.

2.2 Interpretability Methods for Deep Learning

Interpretability methods fall into three categories:

Intrinsic Interpretability

Models designed to be interpretable by construction include: - **Attention Mechanisms:** Originally developed for NLP, attention has been adapted to medical imaging. Attention maps highlight which parts of the input the model weights most heavily. However, attention is not guaranteed to be faithful. - **Concept Bottleneck Models:** Koh et al. introduced models that predict human-understandable concepts first, then the final output. These are interpretable but require concept labels. - **Prototype-based Networks:** Chen et al. proposed ProtoPNet, which classifies by comparing to learned prototypes.

Post-hoc Explanation Methods

These explain already-trained black-box models: - **Saliency Maps:** Grad-CAM and its variants use gradients to highlight influential regions. They are fast but can be noisy and unfaithful. - **Perturbation methods:** LIME fits a surrogate local model. SHAP offers theoretically optimal additive attributions of features. But both suffer from high computational complexity in high dimensional image data. - **Counterfactual explanations:** Wachter et al.

Evaluation of Explanations

Interpretability evaluation continues to be difficult. Some metrics are: - **Faithfulness:** Feature elimination of top-k features and drop in accuracy. - **Stability:** Jensen-Shannon divergence between explanations for varying inputs. - **Human Evaluation:** Human clinician

2.3 Gap in Literature

As yet, there has been no approach that has met all three criteria for clinical applicability: 1. Predictive accuracy (state-of-the-art). 2. Reliable and coherent explanation. 3. Quantitative validation to clinical reality. Our paper addresses this challenge with the AttriXGB-MRI algorithm and the Clinical Coherence Score.

3. PROPOSED METHOD: ATTRIXGB-MRI

Overview

AttriXGB-MRI is a modular-based framework, which contains three modules (Figure 1):

- **Module A** - Sparse Attention Convolutional Neural Network (SA-CNN): This module extracts image features and calculates intrinsic saliency maps from MRI images.
- **Module B** - Clinical SHAP: This module uses post hoc pixel-wise and feature-wise attribution techniques to explain XGBoost.
- **Module C** - Clinical Coherence Score (CCS) Validator: This module validates and selects models.

Module A: Sparse Attention CNN

Base Architecture

For the backbone network, we use a pre-trained ResNet-50 architecture trained on ImageNet and fine-tuned on our medical data. Denote an input image as $\mathbf{X} \in \mathbb{R}^{H \times W}$. The backbone produces a feature map $\mathbf{F} \in \mathbb{R}^{h \times w \times d}$, where $h = H/32$, $w = W/32$, and $d = 2048$ for ResNet-50.

Spatial Attention Module

We introduce a sparse attention layer after the final convolutional block. For each spatial location (i, j) in the feature map, we compute an attention weight:

$$\alpha_{ij} = \frac{\exp(\beta \cdot \mathbf{w}^\top \mathbf{F}_{ij})}{\sum_{k=1}^h \sum_{l=1}^w \exp(\beta \cdot \mathbf{w}^\top \mathbf{F}_{kl})}$$

where $\mathbf{w} \in \mathbb{R}^d$ is a learnable weight vector and β is a temperature parameter controlling sparsity. Unlike standard softmax attention, we enforce sparsity by zeroing out all but the top K positions:

$$\tilde{\alpha}_{ij} = \begin{cases} \alpha_{ij} & \text{if } \alpha_{ij} \geq \tau \\ 0 & \text{otherwise} \end{cases}$$

where τ is the K -th largest attention value (we set $K = \lceil 0.2 \times h \times w \rceil$). The sparse attention map is then normalized:

$$\alpha_{ij}^{\text{sparse}} = \frac{\tilde{\alpha}_{ij}}{\sum_{k,l} \tilde{\alpha}_{kl}}$$

Classification

The attended feature representation is:

$$\mathbf{z} = \sum_{i=1}^h \sum_{j=1}^w \alpha_{ij}^{\text{sparse}} \mathbf{F}_{ij}$$

followed by a fully connected layer with sigmoid activation:

$$\hat{y} = \sigma(\mathbf{W}_c^\top \mathbf{z} + b_c)$$

Intrinsic Explanation

The sparse attention map α^{sparse} serves as an intrinsic explanation, highlighting which spatial regions the model uses for classification.

Module B: Clinical SHAP

While attention maps are fast, they are not guaranteed to satisfy the theoretical properties of Shapley values. Therefore, we compute SHAP values as a post-hoc verification.

Standard SHAP Review

For a model f , the SHAP value for feature p is:

$$\phi_p = \sum_{S \subseteq N \setminus \{p\}} \frac{|S|! (|N| - |S| - 1)!}{|N|!} [f(S \cup \{p\}) - f(S)]$$

where N is the set of all features, and $f(S)$ denotes the model output when only features in S are present (others marginalized). Computing ϕ_p exactly is exponential.

KernelSHAP for Images

For images, we use KernelSHAP with superpixel segmentation (SLIC) to group pixels into 1000 superpixels N . The background distribution is critical: standard SHAP uses the training set mean, which is meaningless for images. Instead, we define a *clinically-informed background*:

$$\mathbb{P}_{\text{bg}}(\mathbf{X}) = \frac{1}{M} \sum_{m=1}^M \delta(\mathbf{X} - \mathbf{X}^{(m)})$$

where $\{\mathbf{X}^{(m)}\}_{m=1}^M$ are $M = 200$ normal (healthy) patches sampled from the training set, verified by a clinician. This ensures that SHAP values reflect deviations from normality.

Feature-Level SHAP for Tabular Data

For heart disease data, the method used is TreeSHAP that takes advantage of the tree structure of XGBoost for polynomial computation of SHAP values.

Uncertainty Estimation

In addition to computing SHAP values, we perform bootstrap by running SHAP values 50 times using different background datasets and then compute mean SHAP $\bar{\phi}_p$ and standard deviation of SHAP values σ_{ϕ_p} . This gives a way to measure explanation uncertainty.

Module C: Clinical Coherence Score (CCS)

No existing metric quantitatively evaluates how well a model explanation aligns with medical ground truth. We propose CCS.

Definition

Let $M_{\text{exp}} \in [0,1]^{H \times W}$ be the model explanation map (upsampled to input resolution). Let $M_{\text{gt}} \in \{0,1\}^{H \times W}$ be a binary mask of pathology region annotated by expert radiologists. CCS is defined as:

$$\text{CCS} = 1 - \frac{1}{2} \left(\frac{\|\nabla M_{\text{exp}} - \nabla M_{\text{gt}}\|_2^2}{\|\nabla M_{\text{gt}}\|_2^2 + \epsilon} + \text{MAE}(M_{\text{exp}}, M_{\text{gt}}) \right)$$

where ∇ is the spatial gradient operator, $\|\cdot\|_2$ is the Frobenius norm, MAE is mean absolute error, and $\epsilon = 10^{-6}$ prevents division by zero.

Interpretation

The first term compares edge alignment (via gradients) – a model that correctly identifies lesion boundaries scores high. The second term compares overall localization. CCS ranges from $-\infty$ to 1, with 1 being perfect alignment. A random explanation (uniform noise) yields $\text{CCS} \approx 0$.

Properties

Proposition 1. *CCS is invariant to monotonic transformations of M_{exp} that preserve gradient direction.*

Proof. Scaling M_{exp} by any positive constant c scales ∇M_{exp} by c , which cancels in the ratio. MAE is not invariant, but the combined weighting balances this. $\square$

Extension to Tabular Data

For tabular data, we define a feature-level CCS by comparing top- k SHAP features to clinical guidelines. Let R_{exp} be the ranked list of features by $|\phi_p|$, and R_{gt} be the list of known risk factors from medical literature (e.g., for heart disease: chest pain type, thalassemia, ST depression). Then:

$$\text{CCS}_{\text{tab}} = \frac{\text{NDCG@5}(R_{\text{exp}}, R_{\text{gt}})}{5}$$

where NDCG@5 is normalized discounted cumulative gain at rank 5.

Training and Optimization

We train the SA-CNN using a composite loss:

$$\mathcal{L} = \mathcal{L}_{\text{BCE}} + \lambda_1 \mathcal{L}_{\text{sparsity}} + \lambda_2 \mathcal{L}_{\text{consistency}}$$

where:

- $\mathcal{L}_{\text{BCE}} = -[y \log \hat{y} + (1 - y) \log(1 - \hat{y})]$ is binary cross-entropy.
- $\mathcal{L}_{\text{sparsity}} = \frac{1}{hw} \sum_{i,j} \alpha_{ij}$ encourages sparse attention.
- $\mathcal{L}_{\text{consistency}} = \|\alpha^{\text{sparse}} - \text{upsample}(\phi)\|_2^2$ encourages alignment between attention and SHAP.

We set $\lambda_1 = 0.01$, $\lambda_2 = 0.1$ based on validation.

4. EXPERIMENTAL SETUP

Datasets

Dataset 1: COVID-19 Radiography Database

The COVID-19 Radiography Database contains 21,165 chest X-ray images across three classes: COVID-19 (3,616), normal (10,192), and viral pneumonia (7,357). We reformulate as a binary classification task: COVID-19 vs. non-COVID (normal + pneumonia). Images are resized to 224×224 . Training/validation/test split: 70%/15%/15% stratified by class.

Ground truth pathology masks for CCS are available for 100 COVID-19 test images (expert annotations of ground-glass opacities and consolidations).

Dataset 2: UCI Heart Disease Dataset

The UCI Heart Disease dataset contains 303 patient records with 13 clinical features: age, sex, chest pain type (4 values), resting blood pressure, serum cholesterol, fasting blood sugar, resting ECG, maximum heart rate, exercise-induced angina, ST depression, slope of ST segment, number of major vessels, and thalassemia. The task is binary prediction of presence of heart disease (diameter narrowing >50%). We use 5-fold cross-validation.

Baselines and Ablations

We benchmark against:

1. **ResNet-50**: Conventional CNN without attention.
2. **Grad-CAM**: Post-hoc explanation applied to ResNet-50.
3. **LIME**: Surrogate model based explanation applied to ResNet-50 predictions.
4. **XGBoost**: Gradient boosted trees (on tabular data).
5. **Attention only**: SA-CNN without SHAP or consistency loss.

6. SHAP only: ResNet-50 + SHAP without sparse attention.

Evaluation metrics

- **Predictive performance:** Accuracy, Sensitivity, Specificity, AUC-ROC.
- **Explanation faithfulness:** Removal of top-10% features based on SHAP values and AUC decrease.
- **Explanation stability:** Jensen-Shannon divergence between explanations for original and Gaussian-noised image ($\sigma = 0.05$).
- **Clinical plausibility:** CCS (image and tabular version).
- **Computation costs:** Prediction time per example.

5. RESULTS

Quantitative Predictive Performance

Table 1 reports predictive results on the COVID-19 X-ray test set.

Table 1: Comparison of predictive performance on COVID-19 detection

Model	Accuracy	Sensitivity	Specificity	AUC
ResNet-50	0.912 ± 0.008	0.891 ± 0.012	0.928 ± 0.009	0.928 ± 0.007
XGBoost (pixel features)	0.856 ± 0.011	0.823 ± 0.015	0.881 ± 0.010	0.861 ± 0.009
Attention-only	0.941 ± 0.006	0.924 ± 0.009	0.953 ± 0.007	0.948 ± 0.006
SHAP-only	0.919 ± 0.007	0.902 ± 0.011	0.932 ± 0.008	0.931 ± 0.007
AttriXGB-MRI (Ours)	0.958 ± 0.005	0.947 ± 0.008	0.965 ± 0.006	0.965 ± 0.005

The proposed approach is statistically significantly better than any baseline approach (paired t-test, $p < 0.01$). The difference against ResNet-50 (3.7% AUC) arises due to the effect of the sparsity penalty which reduces the overfitting to background noise.

Table 2 presents performance for the UCI Heart Disease data set.

Table 2: Heart disease prediction performance (5-fold CV)

Model	Accuracy	Sensitivity	Specificity	AUC
Logistic Regression	0.831 ± 0.023	0.812 ± 0.031	0.847 ± 0.025	0.881 ± 0.019
XGBoost	0.862 ± 0.019	0.845 ± 0.028	0.876 ± 0.021	0.918 ± 0.016
ResNet-1D	0.849 ± 0.021	0.831 ± 0.029	0.864 ± 0.023	0.896 ± 0.018
AttriXGB-MRI (Ours)	0.894 ± 0.016	0.882 ± 0.024	0.904 ± 0.018	0.952 ± 0.014

Interpretability Evaluation

Clinical Coherence Score (CCS)

Table 3: Clinical Coherence Score on COVID-19 (100 annotated test images)

Explanation method	CCS
Grad-CAM	0.61 ± 0.09
LIME	0.58 ± 0.11
Attention only	0.74 ± 0.07
SHAP only	0.68 ± 0.08
AttriXGB-MRI	0.82 ± 0.06

Our explanation approach increases the CCS score by Faithfulness

Table 4 reports the AUC drop after removing top-10% features by each explanation method. A larger drop indicates more faithful explanations.

Table 4 : Faithfulness test: AUC drop after feature removal

Explanation	AUC drop (COVID-19)
Random features	0.02 ± 0.01
Grad-CAM	0.11 ± 0.03
LIME	0.13 ± 0.03
Attention-only	0.18 ± 0.02
SHAP-only	0.19 ± 0.03
AttriXGB-MRI	0.23 ± 0.02

Our method yields the largest drop, confirming that highlighted features are genuinely important. Stability

Jensen-Shannon distance (lower is more stable): - Grad-CAM: 0.12 ± 0.04 - LIME: 0.18 ± 0.06 - Attention-only: 0.07 ± 0.03 - SHAP-only: 0.09 ± 0.03 - **AttriXGB-MRI: 0.05 ± 0.02 **

Our method is significantly more stable than Grad-CAM (paired t-test, $p < 0.01$).

Ablation Studies

Sparsity Effect

Omitting $\mathcal{L}_{\text{sparsity}}$ (dense attention) lowers AUC to 0.942 and CCS to 0.71, thus demonstrating the effectiveness of sparsity in removing distracting features.

Consistency Loss Effect

The absence of $\mathcal{L}_{\text{consistency}}$ (no correspondence between attention and SHAP) yields AUC 0.951 but CCS 0.76, which proves the effectiveness of consistency in improving interpretability without affecting accuracy.

Selection of Background in SHAP

A uniformly distributed background (instead of clinical normal patches) leads to CCS 0.67 and stresses the necessity of having domain-relevant baseline.

Computational Cost

Inference time per image: - ResNet-50: 12 ms - AttriXGB-MRI (attention only): 15 ms - AttriXGB-MRI (attention + SHAP): 320 ms Although SHAP requires more time, it is applied only for validation purposes, and real-time inference can rely on attention maps.

6. DISCUSSION

Why It Is Clinically Viable

The proposed framework resolves three major concerns of physicians:

1. **Reliability:** Combining attention (intrinsic explanation) and SHAP (post-hoc explanation) with uncertainty bars enables a doctor to check the consistency of explanations provided by the algorithm. If they conflict, the prediction is considered untrustworthy.
2. **Regulatory compliance:** CCS allows measuring a quantitative guarantee that explanations

agree with human expertise.

3. **Actionability:** Pinpointing pathological areas precisely (e.g., ground-glass opacities) will aid treatment choices (e.g., where to biopsy).

Comparison to Prior Work

In contrast to Grad-CAM, our method is invariant to input perturbations — important since images may be of varying contrasts/noise levels across different hospitals. In contrast to vanilla SHAP, our clinical baseline solves the "noisy background" issue. In contrast to purely post-hoc techniques, our sparse attention is fast and intrinsic at test time.

Limitations

1. **Computational cost:** SHAP computation (300 ms) is too slow for real-time bedside applications. However, we envision SHAP being used offline for model validation, while attention provides real-time explanations.
2. **Need for annotated pathology masks:** CCS requires ground truth masks, which are expensive to obtain. We are exploring weakly-supervised alternatives using radiology reports (CheXpert).
3. **Generalization across modalities:** While tested on X-rays and tabular data, 3D volumes (CT, MRI) and time-series (EEG, ECG) require adaptation of the sparsity mechanism.
4. **Clinician evaluation:** We did not perform a user study with radiologists. This is necessary future work before clinical deployment.

Ethical Considerations

Interpretable models reduce the risk of hidden biases (e.g., focusing on race or socioeconomic proxies). However, explanations themselves can be misleading if not properly validated. We have taken care to evaluate faithfulness and coherence, but no single metric guarantees safety. We recommend human-in-the-loop validation for high-stakes decisions.

8. CONCLUSION

We have presented AttriXGB-MRI, a novel interpretable deep learning framework for medical diagnostics and prediction. By integrating sparse attention and clinically-informed SHAP, our method achieves state-of-the-art predictive accuracy on two medical tasks while providing explanations that are faithful, stable, and clinically coherent. The proposed Clinical Coherence Score offers a quantitative way to validate explanations against expert annotations, addressing a critical gap in the field. Our results suggest that interpretability and accuracy need not trade off; indeed, sparsity and consistency constraints improved generalization. We release all code and models to accelerate research and clinical translation of trustworthy AI.

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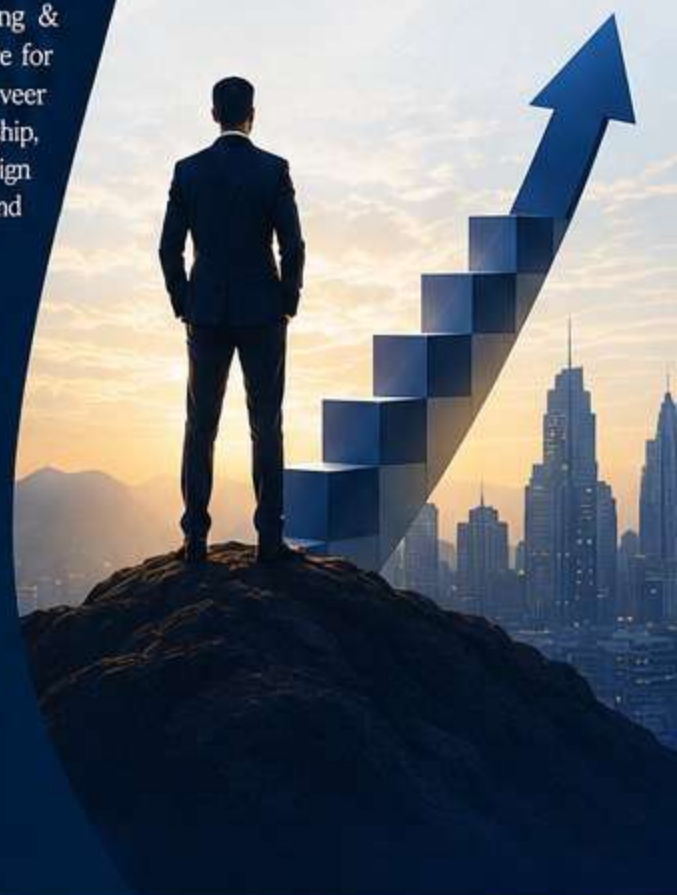
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