INTERDISCIPLINARY RESEARCH FOR SUSTAINABLE DEVELOPMENT (IRSD)

Volume 1, December 2025
ISBN: 978-81-984733-2-5

Edited by:

Dr. Charan Sai Raja Vennakandla
Dr. Pasuluri Bindu Swetha
Dr. S. Negi
A Kumar
Tanvir Singh

International Institute of Organized Research (I2OR)
www.i2or.com

Interdisciplinary Research for Sustainable Development (IRSD)

Editor(s): Dr. Charan Sai Raja Vennakandla, Dr. Pasuluri Bindu Swetha, Dr. S. Negi, A Kumar, Tanvir Singh

Vol. 1 December 2025

ISBN: 978-81-984733-2-5

Published By:

Number 3179, Sector 52, Chandigarh (160036) - India

Printed by
Green ThinkerZ
#530, B-4, Western Towers, Sector 126, Greater Mohali, Punjab (140301) – India

FOREWORD

Environment is the perdurable medium to create the best cultural modification, which is an unstoppable spirit for a fabulous fusion to enrich the elevating attainments of multifarious research in deed. With the multiple changes in the global scenario, Interdisciplinary Research for Sustainable Development (IRSD) now-a-days has its own significance. This book series will bring in research ideas of various people from different countries in a single forum and which certainly will be a fabulous opportunity for uniting the research fraternity. IRSD Book Series provide a fertile platform to exchange, deliberate and innovate, ideas resulting in possible future collaborations in pursuit of the United Nation's Sustainable Development Goals: The Global Goals, which will contribute to new research initiatives in the domain of Social & Environmental Sustainability for sustainable development of mankind. SDGs are adopted by all United Nations Member States in 2015 as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030. The first edition of the Book series is going to be truly thought provoking at all not to highlight the captivating research brilliance but to have the world-wide educational recognition in a very stimulating manner. It is one of the spellbinding Research alliances in all over the globe for the evergreen global actuality for creating an extensive hope of research eminence in deed.

Editor(s)

Dr. Charan Sai Raja Vennakandla
Director of Infrastructures at Y&L Technologies, San Antonia, USA.

Dr. Pasuluri Bindu Swetha
Professor, Department of ECE, Mentor, Best Innovation Ambassador,
G Pullaiah College of Engineering and Technology,
Kurnool, Andhra Pradesh, India.

Dr S Negi
Chief Editor, I2OR, India

A Kumar
Fulbright DAI Fellow,
Indiana University of Pennsylvania, PA, USA

Tanvir Singh
Spoken Tutorial, EduPyramids,
SINE, IIT Bombay

TABLE OF CONTENTS

The Impact of FinTech Innovations on Information Power & Financial Services

Dr. Udhaya. M[1], Dr. S. Marimuthu Kumar[2]
[1]*Assistant Professor,* [2]*Physical Director*
Department of Management, Rathinam College of Arts and Science, Coimbatore[1]
Nehru College of Arts and Science, Coimbatore[2]
drudhayam2025@gmail.com, smarimuthukumar79@gmail.com

Abstract: In this paper we focus on the development of FinTech, how is it evaluated and managed in selected areas, in the European Union, in China and in Hungary. Some of the pertinent questions in this field are the following: How can regulators keep up with the rapid pace of development? Can regulation be based on a precise definition and can a level playing field be ensured between traditional banks and FinTech start-ups? What are the risks? How can they be handled by supervision and regulation? We can conclude that FinTech is in the initial phase of a "revolutionary" process, and the definition of this phenomenon is broad and changing. Regulators and supervisors must influence the conditions in a way that a level playing field and risk assessment should be the same for traditional banks and FinTech companies. All of the actors have responsibility, including central banks, regulators, supervisors, incumbent banks, consumers and FinTech companies. Information is power, and several economists claim that digital is the new normal. In our paper we partly justify the first part of the sentence and we put a question mark at the end of the second part.

Keywords: Revolutions, Financial Institutions and Services, Technology, Diffusion Processes.

I. A NEW ROUND OF TECHNOLOGICAL AND DIGITAL REVOLUTION IS KNOCKINGS ON THE DOOR.

One of the most exciting phenomenon in the world right now is the development of digitalization. The space, emergence and social effects of this development are so rapid and so deep, that it is considered to be part of the 4th industrial revolution. One minor part of this phenomenon is the penetration of the financial and banking sector, which is mostly referred to as the FinTech hype, because of its important role.

In order to better understand this development, we briefly review the outcome of the second and third industrial revolutions and then focus on three areas – the European Union, China and Hungary – to study the present status and approach of the FinTech hype. The reason behind our research selection is that the European Union is playing a very important role not only in the development of FinTech, but also in the definition, its regulation and supervision aspects. The Chinese approach is also important since experience shows that China is facing the same or similar challenges in supervision and regulation, and on the other hand the support of FinTech development is strong. This is why we present the recent data on FinTech investment in Asia and in Europe below. The charts and figures support two important conclusions: FinTech investments are growing and reaching higher and higher levels both in Asia and in Europe (see *Figure 1* and *2*). It can also be seen that for the time being the European development is higher than in Asia. However, one must be careful making this comparison because the Asia line in the chart reflects the whole Asian region and we do not have equivalent data for

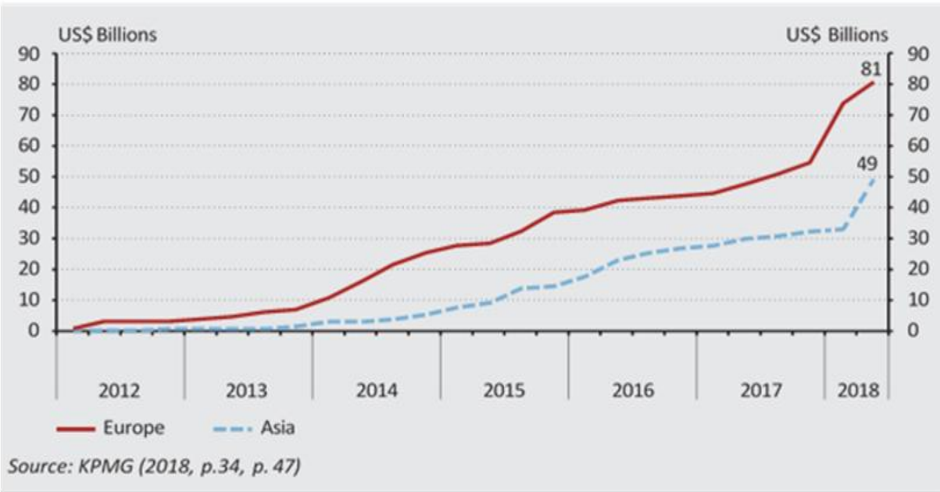
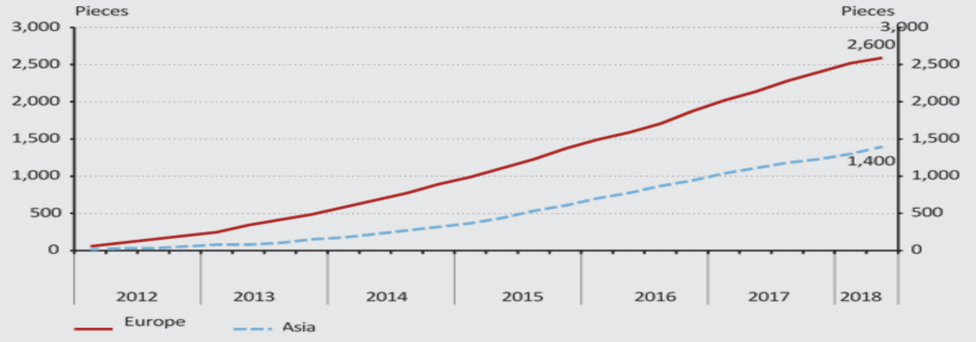


Figure 1: FinTech investment in Asia and in Europe

Figure 2
Cumulative FinTech closed deals in Asia and in Europe
(2012–2018)



Source: KPMG (2018, p.34, p. 47)

Since the beginning of the 21st century, we have been experiencing a digital transformation – changes associated with innovation in the field of digital technology in all aspects of society and the economy. The 4th industrial revolution is already underway. Industry 4.0 will be an answer to the challenges lying ahead. Several economists claim that digital is the new normal. We suggest putting a question mark at the end of this statement. In this period of rapid changes, we do not know what the final shape of "the new normal" will be. "In the news, financial technology is described as 'disruptive', 'revolutionary', and armed with 'digital weapons' that will 'tear down' barriers and traditional financial institutions" (World Economic Forum 2017). This revolutionary phenomenon is inexorably occupying more and more space in our everyday lives. Naturally, these changes – some revolutionary and others perceived as such – have also reached the financial and banking sector. Financial technology ('FinTech') is a broad concept. What are the main concerns of the European legislators and supervisors? First of all, the development of digital financial technology is very rapid. So rapid indeed that even the exact definition of the FinTech phenomenon is difficult. If the definition is broad and mostly an umbrella concept, then elaborating the legal framework and proper supervision is also difficult and cannot be sufficient. Supervisors are not ahead of the developments, but rather trailing behind them. For the time being, the principle of "same risk, same regulation" cannot be enforced.
Referring to the definition problem, examples of FinTech include digital ledger technology, robo-advice, RegTech (technologies that can be used for compliance and reporting requirements) and virtual currencies. This paper focuses on facilitating a better understanding of the FinTech phenomenon and the possible relations between traditional banks and FinTech start-ups.
Financial technology is one of the most innovative, increasingly important and potentially the most rapid change in financial services, and is revolutionising the way financial services firms operate. It is transforming debt and equity markets, payments, credit assessment, regulatory compliance, personal finance and many other facets of financial services. Although some may think that FinTech is just another "buzzword", we believe that technology creates the possibility to dramatically reshape finance as we know it. Digitisation is taking place in all areas of business and life, transforming services, and creating new ones accelerated by new FinTech companies (*Deloitte 2017*). The Golden Age of FinTech has come according to FinTech evangelists, but on the other hand the current hype about FinTech is not due to the allegedly revolutionary character of the technologies, but to their better visibility. Without questioning the tangible positive results, we would like to focus on the current situation of the FinTech phenomenon and its international assessment, the difficulties involved in forecasting its future prospects, and the necessity of a paradigm shift in the traditional banking system. In close relation to the latter, we review the expected evolution of the relationship between banks, FinTech companies and – last but not least – their current and future customers. Finally, the important question is whether or not there are risks related to the use of the FinTech services. If there are, how should these risks be mitigated or remedied by new regulatory and supervisory measures? One of the first questions to be answered is where do we stand in the digital technology process? Are we at the beginning or have we arrived at a balanced, calm phase of continuous development? Where is the place of the traditional banks in this process? In our opinion, the short and correct answer is: we do not know exactly. Answering this question could be helped by reviewing the lessons of the past.

Several decades after the beginning of the third industrial revolution philosophers were still trying to summarize the relation between machines and human beings and to depict their views on the impact of the machine age on human thinking and behaviour. In our view, these questions are or could be justified in the age of digital transition and are also valid when assessing the metamorphosis of traditional banks and their clients.
Technical progress is accelerating. The empirical observation known as Moore's Law states that technical development, or certain partial processes within it, can be described by a high exponential growth path (*Brock 2006*, *Kurzweil 2006*). Nowadays, the digital transformation of financial services is a common topic in the investigation and analysis of the financial system and the banking sector. Today, a financial conference would not meet the expectations of the mainstream if it missed an item on the agenda as the word

"FinTech" was not present. In many respects, the emerging opinions and findings agree: welcome the newcomer, the improving efficiency, the rising standard of consumer services, the acceleration and enforcement of competition. All of these unquestionable changes are warmly welcomed. There are, however, many aspects of the already ongoing developments and tendencies where the agreement and common understanding is not so great, and that is where important FinTech-related issues are not formulated (*Taylor 2019*).

However, in addition to established financial organisations, incumbent banks are also subject to structural inertia that limits their capacity to adapt to environmental change (*Buenstorf 2016*). Start-ups have certain advantages over financial behemoths. The legal capital requirements for their establishment, their small size, lean culture, technological progress, and ability to attract top talents give them a competitive advantage that is inherent in their very nature. New, more convenient, customer-centred services are changing the landscape. More and more experts are thus saying that the time has come to dramatically change the incumbent banks' attitudes. The main reasons for this change are the following:

- High penetration of mobile devices,
- Growing number of digitally native customers (so-called Millennials),
- Persistent distrust towards banks, let it be real or presumed,
- Customers in general are becoming more demanding,
- Growing inequality – the need to reduce financial illiteracy, and financial inclusion stimulus,
- The popularity of FinTech hubs, labs, accelerators by local and national politicians and financial institutions.

II. THE CHALLENGE OF APPROACHING FINTECH

There is no widely accepted definition of FinTech (financial technology) in the academic economic literature. The Basel Committee of Banking Supervision (BCBS) has opted to use the Financial Stability Board's (FSB) working definition for FinTech as "technologically enabled financial innovation that could result in new business models, applications, processes, or products with an associated material effect on financial markets and institutions and the provision of financial services". This broad definition is considered pragmatic by the BCBS in the light of the current fluidity of FinTech developments. That being so, the focus of the analysis and implications of this paper is on the effects of FinTech that are particularly relevant for banks, bank supervisors and – at the end of the day – their consumers. It is also worth noting that the term FinTech is used here to describe a wide array of innovations both by incumbent banks and entrants, be they start-ups or larger technology firms.

From the above it can be seen that the definitions of both the central banks and the Basel Committee have a common feature: that FinTech (financial services) are widely interpreted and defined in a way that permits continuous change and expansion.

The term FinTech also includes digital services and technological development- based business models that have already emerged in the financial market. The spread of the FinTech sector is a global phenomenon: the mass launch of new, non- bank participants and start-ups is being observed both in the developed markets (e.g. United States, United Kingdom) and in the dynamically developing markets (e.g. India, China). Service providers offering FinTech solutions have appeared in many banking fields, most frequently in payments, lending and investment advice.

As a matter of course, the permissive and broad definition outlined above has serious consequences. Since the definition does not precisely identify the content and scope of FinTech services, it creates difficulties in establishing a legislative framework to indicate the boundaries of supervisory controls, and in maintaining equal conditions for competition between traditional banks and FinTech companies.

FinTechs have an influence on how financial services are structured, provided and consumed, but have not successfully established themselves as dominant players.

Innovation is on the rise. As FinTechs have struggled to scale, banks have entered into a number of partnerships with them, and several are already bearing fruit. Banks have invested heavily for the satisfaction of their customers, and many are building compelling experiences that will meet customers' needs as never before. Furthermore, a number of institutions are effectively building new cultures, turning the page on disappointing experiences over the past decade (*McKinsey 2018*).

Many FinTechs came into existence with the goal of overtaking incumbents as the new dominant players in financial services, but they have shifted more towards building partnerships since they struggle with scale and customer adoption. Although FinTechs have failed to disrupt the competitive landscape, they have laid the foundation for future disruption. Some financial institutions have turned the threat of FinTechs into an opportunity (*WEF 2017*). Accepting the innovative importance of FinTechs, one key question is how the supervisory and regulatory institutions will approach this challenge.

As mentioned above, the FinTech phenomenon has emerged in the first phase of the fourth industrial revolution. Following the 2007–2008 international financial crisis, the primary task of traditional banks was to overcome the consequences of the crisis: they were forced to clean up their balance sheets, strengthen their capital base and cut NPL rates. They had to adapt to the strict and sometimes overly-eager regulatory conditions resulting from the crisis. They had to make significant cost reductions. As a result, traditional banks were only able to concentrate on internet services and digital developments with a delay, in recent years. Their primary focus was to recover and strengthen trust and confidence. In this situation, a market gap opened up for FinTech companies, as real market demand emerged. Less capital was needed to launch the operation of FinTech start-ups, and their development of financial technology in the field of payment services was fast. Furthermore, some traditional banks were open to outsourcing certain financial services and digital developments. Regulation and supervision of FinTech services mostly followed the rapid, changing events, consequently the regulation of third party payment (TPP) services was less strict then that of the incumbent banks.

Over the next ten years, banking will experience a higher degree of change than probably in the last 100 years. It is up to market incumbents to face this challenge. In particular, banks should rethink their business models and should look at the new wave of innovation as an opportunity to reach out to new customers, to increase efficiency, and to upgrade their business models.

However, there is a risk that the FinTech phenomenon could follow the already known pattern of shadow banking.

Speaking about the future of banking, *Hatami* (*2015*) considers five scenarios.

1. Scenario — The better bank. The digital revolution has run its course and almost all customers see digital as their main engagement mode with their bank. The incumbent big banks perceived the opportunity and reshaped their businesses to meet the new digital requirements. They restructured their IT platforms and processes, delivered new propositions internally and through partnerships, but most importantly they made the most of their key assets. They were able to retain most of their customers and retrained their people to become more digitally literate.
2. Scenario — The new bank. Incumbents were unable to survive the digital disruption. They were not able to meet the needs of their customers. These left in droves to go to the new challenger banks. These are new, full service banks built for the digital age. They provide services similar to those of the old banks, but they do it faster, cheaper and better that they ever could.
3. Scenario — The distributed bank. As the FinTech revolution progressed, large numbers of new businesses emerged to provide customers with better banking services. They did not attempt to be universal retail banks – they simply focused on providing specific products extremely well. They initially focused on payments, loans, savings products, forex, but slowly they moved into mortgages, investments, pensions and more.
4. Scenario - The relegated bank. In this scenario, banks become a back office service provider for front office customer-facing platforms, with banks providing the necessary licenses, access to payment networks and maintaining deposits and access to funding. There is a risk that banks and bank supervisors will have limited ability to monitor end-to-end transactions and systemic risk. The loss of the customer relationship and the dependence on these new platforms that channel financial products may have adverse consequences for risk management functions and revenue streams (revenues would need to be shared with the new intermediaries).\Scenario — The disintermediated bank. As customers became increasingly disenchanted with their bank, they became increasingly comfortable with going through their favourite social network or hardware provider to buy financial services. It started with payments, followed by sales finance, then investment advice, loans and savings products, until eventually all of the banks' products could be accessed by these providers. Customers felt that going through a provider they love and trust was a guarantee that they wouldn't be taken advantage of, like they felt they had by the banks (Hatami 2015, BCBS 2018).

For the traditional banks, there is also a present challenge on the human side. How do they close the digital gap in their services and also in relation to FinTech service providers?

The shortage of digital skills pits company against company in the fight to fill positions in data analytics, user experience design, artificial intelligence, cybersecurity and other areas. Half of banking institutions have a difficult or very difficult time accomplishing that task.

One new aspect of the same question is revealed in the annual banking reports of McKinsey. In 2015, they documented the potential for FinTechs and digital platform companies to erode banks' margins. However, according to their last report banks have made a lot of good news for themselves recently. One area where McKinsey is seeing radical compression is in remittances — a profit centre for banks worldwide. New firms such as Azimo, TransferWise and TransferGo have built superior technology and are able to price their services as much as 78 per cent below incumbents. As they struggle to compete, incumbents' margins are taking a pounding. Over the past two years, in markets around the world, digital entrants and new analytical firms have gained a foothold, and banks' margins are indeed falling — despite their massive cost-cutting efforts.

The digital entrants are changing too. With most retail businesses (except investing) already fully explored, at least for now, FinTechs are moving into commercial and corporate banking. McKinsey's Panorama FinTech database, which tracks over 1,000 financial start-ups, shows that one of the fastest-growing segments is acquisitions between retail banks and FinTechs has helped to solidify the notion that the land grab is over. FinTechs are also making strides in capital markets and investment banking, especially advisory — although here, the emphasis is more on enabling traditional business processes, rather than disrupting them. The threat from platform companies is real and must be addressed. McKinsey's analysts do not think, however, that it is existential for the global banking industry. The long history of banking strongly suggests that there will always be a need for financial intermediation and a profit to be made by providing capital to others, although it may take many years for the industry to return to profitability in a global economy that is undergoing profound changes. As a first step, banks can take advantage of a range of actions over the next three to five years to reclaim their rightful ownership of the customer relationship, improve productivity and industrialise their operations using digital tools. In essence, banks can deploy some of the same technologies that digital companies are using against them. These steps can lift revenues, improve capital usage, and, especially, cut costs (*McKinsey 2018*).

III. THE APPROACH TO FINTECH IN THE EUROPEAN UNION

In the European Union, the importance of digital technology has been realised and it is considered an issue of paramount strategic, economic and social importance. The European Commission declared that the new digital technology will be a key element in the future competitive edge of the EU.

As a consequence of this development, since May 2015 the European Union has been delivering on an ambitious and comprehensive Digital Single Market Strategy which was accomplished by 2017. The SDM Strategy is built around improving access to goods, services and content, creating the appropriate legal framework for digital networks and services, and reaping the benefits of a data-based economy.

It has been estimated that the Strategy could contribute €415 billion per year to the EU economy and create hundreds of thousands of new jobs. Thus, it would be hard to understate the importance of timely implementation (*European Commission 2017*).

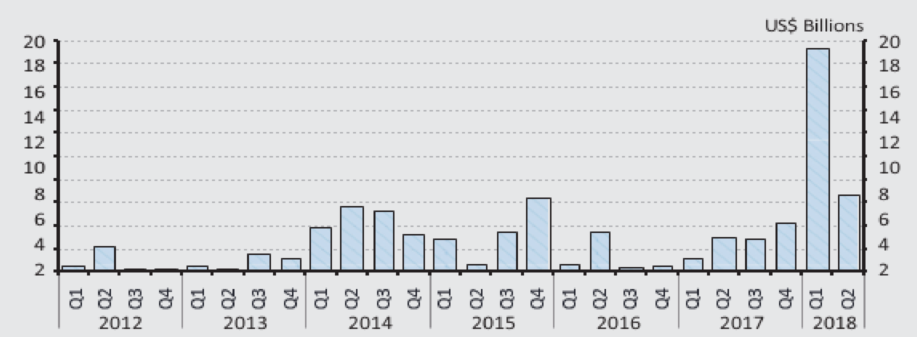
With the strategic aim of building a more competitive, innovative financial market, in March 2018 the European Commission unveiled a

"Europe should become a global hub for FinTech, with EU businesses and investors able to make most of the advantages offered by the Single Market in this fast-

moving sector. As a first major deliverable, the Commission is also putting forward new rules that will help crowdfunding platforms to grow across the EU's single market. The Action Plan envisages to enable the financial sector to make use of the rapid advances in new technologies, such as blockchain, artificial intelligence and cloud services. At the same time, it seeks to make markets safer and easier to access for new players. This will benefit consumers, investors, banks and new market players alike. In addition, the Commission is proposing a pan-European label for platforms, so that a platform licensed in one country can operate across the EU. The Action Plan is part of the Commission's efforts to build a Capital Markets Union (CMU) and a true single market for consumer financial services. It is also part of its drive to create a Digital Single Market. The Commission aims to make EU rules more future-oriented and aligned with the rapid advance of technological development" (*European Commission 2018*).

This strong intent of the European Union to support and motivate FinTech development is confirmed by the data below, where we can see an immense growth after 2017, when the SDM concept was accepted (see *Figure 3*).

Figure 3
Total European FinTech investment activity
(2012–2018)



Source: KPMG (2018, p.34)

The importance of the FinTech issue in Europe is clearly reflected by the next development: the day after the EU FinTech Action plan was published, in March 2018 the European Banking Authority published its FinTech Roadmap under the title "Designing a Regulatory and Supervisory Roadmap for FinTech."

The EBA Roadmap is an important summary of the necessary and envisaged regulatory approach related to the services provided by the incumbent banks and FinTech start-ups.

"Most of the current regulatory approaches are situated between these two extremes: "let it happen" and "regulate and restrict". They are generally based on three components:

(i) monitoring of innovation,
(ii) assessment of risks vis-à-vis the public interest (micro-prudential, financial stability, consumer protection and market integrity), and
(iii) selective application of the existing rulebook, where needed adapted to capture the innovation.

In general, this pragmatic attitude revolves around a tiered regulatory structure, with differentiated regulatory requirements according to the risks for the firms, their customers, the financial sector and the economy at large. In principle, the objective is to deliver "same risk – same rules" expectations.

Let us quote another important view of this document: "Even though FinTech firms may offer some bank-like products and compete with banks for the same customers, this doesn't necessarily mean that they should be licensed, regulated and supervised as banks. We need to make a key distinction, here, between the cluster of services that represent the essence of banking, and as such should be reserved to licensed banks, and those additional services that may be offered, on a standalone basis, also by other intermediaries, in competition with regulated banks". The EBA's FinTech Roadmap describes its priorities for 2018/2019 and provides an indicative timeline for the completion of these tasks. The priorities are:

- monitoring the regulatory perimeter, including assessing current authorisation and licensing approaches to FinTech firms, and analysing regulatory sandboxes and innovation hubs in order to identify a set of best practices to enhance consistency and facilitate supervisory coordination;
- monitoring emerging trends and analysing the impact on incumbent institutions' business models and the prudential risks and opportunities arising from the use of FinTech;

In a paper "*Sound Practices on the implications of FinTech developments for banks and bank supervisors"*, in February 2018 the Basel Committee's Financial Stability Board summarised "how technology-driven innovation in financial services, or 'FinTech', may affect the banking industry and the activities of supervisors in the near to medium term".

This extensive analysis provides an excellent understanding of financial technology developments and the presently known FinTech business models. "Against this backdrop, current observations suggest that although the banking industry has undergone multiple innovations in the past, the rapid adoption of enabling technologies and emergence of new business models pose an increasing challenge to incumbent banks in almost all the banking industry scenarios considered".

The Basel Committee summarised the ten most important possible implications of the suggested supervisory approach related to the relations of traditional banks and FinTech service providers:

1. the overarching need to ensure safety and soundness and high compliance standards without inhibiting beneficial innovation in the banking sector;
2. the key risks for banks related to FinTech developments, including strategic/ profitability risks, operational, cyber- and compliance risks;
3. the implications for banks of the use of innovative enabling technologies;
4. the implications for banks of the growing use of third parties, via outsourcing and/or partnerships;
5. cross-sectoral cooperation between bank supervisors and other relevant authorities;
6. international cooperation between bank supervisors;
7. adaptation of the supervisory skill set;
8. potential opportunities for supervisors to use innovative technologies ("suptech");

IV. THE APPROACH TO FINTECH IN CHINA

"Competition in the FinTech space is developing at the global level. As often occurs in innovative markets, the key to success lies in a large domestic market, which allows successful companies to achieve a scale enabling them to aim for global leadership. In the long term, European FinTech players would be at a significant disadvantage vis-à-vis their US and Chinese competitors, if the European markets remain segmented along national borders, with different sets of rules and uncoordinated actions by local authorities" *(Enria 2018).*

In this chapter on the Chinese experience, we survey FinTech in three dimensions: the Chinese government, the People's Bank of China (the Chinese central bank) and the financial supervision authority Chinese Banking Regulation Committee (CBRC)3, and the Chinese commercial banks.

In order to make a short summary we refer to the FinTech approach of China, which was presented by excellent high-level financial experts at the AFCA CEE Financial Summit Forum – New Chapter of Asia-Europe Financial Cooperation in Budapest, Hungary in November 2017. The FinTech sector in China has been developing rapidly and is the global leader by several measures. The country's digital payments account for almost half the global volume and online peer-to-peer (P2P) lending accounts for three quarters of the global total. China's FinTech sector is now at a critical juncture. The Chinese government's attitude towards FinTech has become progressively more complex, as risks have piled up around P2P platforms and the number of underground fund raising and financing activities have grown. The authorities remain generally supportive, despite some recent tightening measures (*Hu – Yin – Zheng 2016*, *PWC China 2017*).

In relation to internet finance, Premier Li Keqiang made some important statements: "We will encourage internet finance to seek a healthy development path with the backing of proper regulatory coordination and supervisory mechanisms" and "We will work to see that internet finance develops in line with regulations". The Chinese government gave players a free hand to experiment. Light-touch – or, more accurately, late-touch – regulation of digital activities and players in China has encouraged entrepreneurship and experimentation. While the response of regulators lagged behind market developments, China's internet giants were relatively free to test and commercialise products and services and to gain critical mass. For example, regulators took 11 years after Alipay introduced online money transfers in 2005 to set a cap on the value of the transfers. It was five years after Alipay introduced barcode-based payment solutions that Chinese regulators produced an official standard on management requirements (*McKinsey 2017*).

On the side of the commercial banks let us quote the approach of some of the major Chinese financial institutions. Liu Qiang, Vice

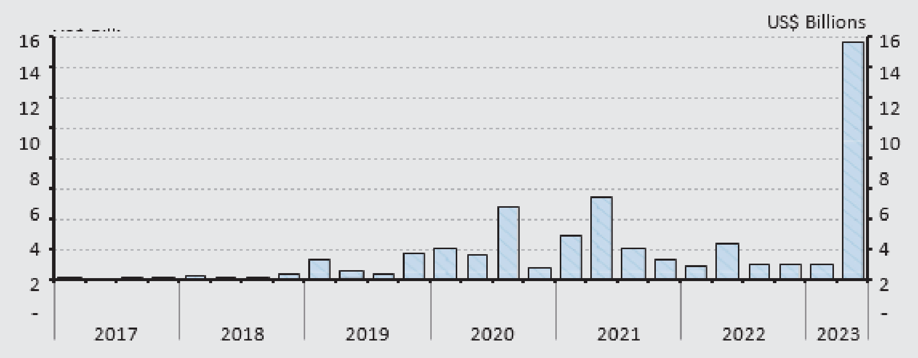
President of the Bank of China urged to take the lead in technological innovation and improve the efficiency of financial services. FinTech can improve the quality serving the real economy. The development of FinTech has enriched the content of finance and expanded the market. The combination of new technologies, capital and market can create astounding power. Banks on both sides should vigorously step up innovation and cooperation in technology and promote the transformation and upgrading of banking service efficiency. Everyone can see that technical progress is continuously pushing forward the resolving of information asymmetry, which is of great importance to financial development. FinTech has rich connotations, and will become a trend of financial development within the ceaseless technical progress.

While the growth phenomenal of traditional and non-traditional digital financial services has been fostered in recent years by technological innovation, advancement, rapidly changing consumer behaviour and adaptation to forms of finance, China's regulatory environment has also provided fertile conditions for growth. This statement is confirmed by te data below (see *Figure 4*).

Mr Huang Yi, Executive Vice President of China Construction Bank, delivered a speech titled Financial Technology and Strategic Transformation of the Banking Industry in China. According to Yi, instead of leading to a shrinkage of the banking industry, the rapid development of China's internet finance has brought about competitive and cooperative development through two-way interaction and complementation of advantages. The breakthrough and maturity of technical fields laid a solid foundation for the technology-driven transformation of the banking industry. He also mentioned that financial technology was a more direct, powerful and effective driving force for transformation. Intuitively, the development of financial technology first broke through physical limitations effectively, and drove the integration of banking channels. Besides, the application of financial technology drove the reform of banking business modes, and gradually popularized the service modes based on scenarios and platforms. Furthermore, financial technology had enriched risk control means, making risk management more effective. He continued as follows: as financial technology had advantages, China could work to develop core technologies and set patent standards. China's commercial banks and some large internet enterprises stayed ahead in the international market in terms of financial technology practices. They should take the advantage to integrate related technologies and make these technologies their patents, and use these patent advantages to change the process of the international financial industry, to form new industrial standards and to enhance the core competitiveness of China's banking industry (*Kerényi – Müller 2018*).

Strengthening regulation and supervision is the focus of the CBRC, the Chinese Banking Regulatory Committee. Based on the framework, the fundamental principles governing the regulation of Digital Finance are "tolerate, encourage, guide and standardise" and the associated supervisory requirements can be summed up as "comprehensive, timely, professional and effective" (*Varga 2017:134*)

Figure 4
Total FinTech investment in Asia
(2012–2018)



Source: KPMG (2018, p. 47)

In 2018, at the Budapest Renminbi Initiative Conference Mr Ren Zhe, Representative of the Peoples Bank of China, spoke about the recent development of FinTech Regulation in China. He emphasised that the definition of internet finance is broad, and internet payments, digital currencies and digital infrastructure require different approaches. Changes are needed in the regulatory and supervisory requirements and related changes in business incentives of incumbents and new players. In his opinion, "there is no unified approach to FinTech activities; improvement the ecosystem of FinTech can help mitigate some significant risks; The approach to FinTech in Hungary

After reviewing the EU and Chinese approaches to the FinTech development, we briefly summarize the Hungarian attitudes.

As a matter of course, the Hungarian FinTech approach is closer to that of in the European Union and rather to that within the euro area. However, there are some country-specific features. The global financial crisis also impacted the Hungarian financial sector: lending activity and profitability decreased, NPL rates rose, there was a heavy burden of FX-denominated retail loans, and internal hard budget constraints were faced within the banks. Due to the absorption of these developments, the banking sector could return to the normal development of IT and other services. Digital innovations and FinTech expansion was started in the past three to four years. Although foreign ownership is relatively high in the banking sector, at around 50 per cent, most of the FinTech developments are made at Hungarian subsidiaries and are not taken over from the parent banks. It is also a special, although not unique feature, that the Magyar Nemzeti Bank (MNB), as Hungary's central bank, has both the supervisory and regulatory competence.

Against this background, FinTech regulation is high on the MNB's agenda. When the idea of regulating FinTech first appeared to the MNB, their first step was to look for information on the best practices of other central banks around the world. The MNB considers the support of FinTech development so important that "the MNB established an Innovation Center (Multilateral Consultation Platform) to help FinTech start-ups in the initial phase, or even those already on the market, to navigate regulatory issues" (*Thurzó 2017*).

The MNB also prepared a targeted questionnaire to assess the attitude and proposals of market participants which are developing and offering FinTech innovations. According to this survey "banks believe that they will continue to play a central role in financial intermediation. On the other hand, the overwhelming majority of FinTech firms are in regular contact with banks or have turned to banks since their launch. This is due to the fact that in addition to financial support, banks can also provide assistance through the expertise gained during their operations. Access to banks' extensive datasets is crucial for newly established FinTech firms and banks have thorough knowledge of the detailed legal requirements pertaining new ideas and approaches to improve regulation efficiency should be incorporated".

V. SUMMARY AND CONCLUSION

Since the beginning of the 21st century, we have been experiencing a digital transformation – changes associated with innovation in the field of digital technology in all aspects of society and the economy. The fourth industrial revolution is already underway. Financial Technology represents one of the most innovative, increasingly important and potentially the most rapid change in financial services revolutionizing the way financial services firms operate and transforming debt and equity markets, payments, credit assessment, regulatory compliance, personal finance and many other aspects of financial services. For a better understanding of this process, we have briefly compared the lessons from the previous three industrial revolutions. We can see similarities, as revolutions have a sudden start and mostly end up with positive changes and transformational powers, but they also have disruptive effects. In the initial phase it is difficult to predict the outcome, to foresee what will be a lasting positive effect and to assess the potential risks involved and their management.

In our day and age, one of the greatest challenges for the banking sector, for the regulators and for supervisors is the digital transformation of financial services. In this context, the future of traditional financial intermediation and the relationship between incumbent banks and FinTech start-up companies is a relevant question. These developments and the new actors on the market raise the question of potential risks, thus how regulation and supervision should be changed, and whether fair competition and a level playing field can be ensured and maintained.

REFERENCES

[1]. Arner, D.W. – Barberis, J. – Buckley, R.P. (2015): *The Evolution of FinTech: A New Post-Crisis Paradigm?* in University of Hong Kong Faculty of Law Research Paper No. 2015/047, October.

[2]. Authority of the House of Lords (2018): *AI in the UK: ready, willing and able?* HL Paper 100. https://publications.parliament.uk/pa/ld201719/ldselect/ldai/100/100.pdf. Downloaded: 24 May 2018.

[3]. Basel Committee on Banking Supervision (BCBS) (2018): *Sound Practices. Implications of FinTech developments for banks and bank supervisors*. https://www.bis.org/bcbs/publ/ d431.pdf. Downloaded: 24 May 2018.

[4]. Buenstorf, G. (2016): *Schumpeterian incumbents and industry evolution*. Journal of Evolutionary Economics, 26(4): 823–836. https://doi.org/10.1007/s00191-015-0423-7

[5]. Brock, D.C. (ed.) (2006): *Understanding Moore's Law: Four Decades of Innovation*. Philadelphia: Chemical Heritage Press.

[6]. Deloitte (2016): *FinTech in the CEE region.* https://www2.deloitte.com/ce/en/pages/about- deloitte/articles/fintech-cee-region.html. Downloaded: 24 May 2018.

[7]. ECB (2017): *Guide to assessments of fintech credit institution licence applications*. Banking Supervision, European Central Bank.

[8]. https://www.bankingsupervision.europa.eu/legalframework/publiccons/pdf/licensing_and_fintech/ssm.guide_on_assessment_for_ licensing_of_fintech_credit_insts_draft.en.pdf. Downloaded: 24 May 2018

Sustainability and Development Across Disciplines

Simran Aulakh
83603-37527
simranaulakh293@gmail.com

Abstract - Sustainability and development are no longer isolated issues tied solely to environmental or economic concerns. In today's interconnected world, they are multifaceted challenges requiring insights from numerous academic and professional disciplines. This paper explores how various fields—including environmental science, economics, political science, sociology, engineering, urban planning, health sciences, education, agriculture, and law—contribute uniquely to the understanding and advancement of sustainable development. The study underscores the need for interdisciplinary collaboration to address the complex and interrelated goals outlined in the United Nations Sustainable Development Goals (SDGs). By drawing on the strengths of different disciplines, society can develop holistic solutions that are both inclusive and effective.

I. INTRODUCTION

In recent decades, the twin concepts of sustainability and development have gained global prominence. Development, in its traditional sense, has been equated with economic growth, infrastructure expansion, and industrialization. However, this approach often came at the expense of environmental integrity and social equity. With the publication of the Brundtland Commission's report in 1987, a new paradigm emerged: *sustainable development*, defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

This definition triggered a shift in how governments, organizations, and academic institutions approach development. No longer confined to economics or environmental science, sustainable development has become a **multidisciplinary endeavor**, demanding insights from various fields to ensure that progress is economically viable, socially inclusive, and environmentally responsible.

II. MULTIDISCIPLINARY ENDEAVOR

1. Environmental Science: The Ecological Foundation

Environmental science plays a foundational role in the sustainability discourse. It focuses on understanding ecosystems, biodiversity, and the impacts of human activity on the natural world. Through methods like environmental impact assessments, climate modeling, and resource audits, this discipline helps identify the ecological limits within which development can safely occur.

Environmental scientists also inform strategies for reducing pollution, conserving biodiversity, and mitigating climate change—critical components of long-term sustainability. Their data-driven approaches provide the scientific basis for sustainable land use, water management, and energy transitions.

2. Economics: Rethinking Growth and Value

Economics offers vital tools to analyze the trade-offs and incentives that influence sustainable behavior. Traditional economic models often prioritized GDP growth over long-term ecological health. In contrast, modern sustainability economics promotes concepts like the **green economy**, **circular economy**, and **natural capital**.

By assigning value to ecosystem services and incorporating environmental costs into market systems, economists encourage more responsible consumption and production patterns. Instruments like carbon pricing, environmental taxes, and sustainability reporting are examples of how economic tools can drive progress toward the SDGs.

3. Political Science and Public Policy: Power and Governance

The role of political science in sustainability lies in shaping effective governance systems. Policy frameworks at local, national, and international levels are essential to regulate environmental use, allocate resources equitably, and enforce development plans. Political scientists examine how power, institutions, and ideologies affect environmental and development outcomes.

International agreements like the **Paris Climate Accord** and national strategies for renewable energy and poverty reduction reflect how policy can align with sustainability goals. Moreover, public policy plays a crucial role in managing conflicting interests and fostering collaboration among stakeholders.

4. Sociology and Anthropology: Understanding Social Dimensions

Sustainability is as much about people as it is about the environment. Sociology and anthropology provide insights into human behavior, cultural practices, and social structures that influence how communities interact with their surroundings. These disciplines explore issues of **environmental justice**, **gender equality**, and **community resilience**.

Understanding local traditions, power dynamics, and social inequalities helps in designing development programs that are culturally appropriate and socially inclusive. Indigenous knowledge, often undervalued, can offer sustainable practices rooted in centuries of ecological stewardship.

5. Engineering and Technology: Innovating for Sustainability

Engineering and technological innovation are vital for implementing practical solutions to sustainability challenges. From renewable energy systems and water purification technologies to sustainable construction materials and smart city infrastructure, engineers design systems that reduce environmental impact and improve quality of life.

The emerging field of **sustainable engineering** integrates lifecycle thinking into product and process design, ensuring minimal waste, efficient energy use, and resilience to environmental stressors.

6. Urban Planning and Architecture: Building Sustainable Spaces

Urban areas are at the heart of sustainable development due to their growing population densities and resource demands. Urban planners and architects contribute by designing **sustainable cities** that promote energy efficiency, low-carbon transport, and green public spaces.

Concepts like **transit-oriented development**, **mixed-use zoning**, and **green building certification (e.g., LEED)** show how spatial planning can support both human well-being and environmental conservation.

7. Health Sciences: Sustainability and Human Well-being

The link between sustainability and health is direct and profound. Environmental factors such as air and water quality, food security, and climate change significantly affect human health. Health sciences contribute by identifying risks, developing resilient healthcare systems, and promoting access to essential services.

Public health frameworks increasingly integrate sustainability principles—such as promoting active transportation, reducing pollution, and preparing for climate-related health emergencies like heatwaves or disease outbreaks.

8. Education: Enabling Change Through Knowledge

Education is a key enabler of sustainable development. Through **Education for Sustainable Development (ESD)**, schools and universities equip learners with the knowledge, skills, and values needed to create a more sustainable future.

ESD fosters critical thinking, global citizenship, and systems thinking—skills necessary for tackling complex sustainability challenges. Educational institutions also serve as hubs for research, innovation, and community engagement.

9. Law and Human Rights: Framing Justice and Responsibility

Legal frameworks are crucial for holding entities accountable and ensuring that development respects both environmental limits and human rights. Environmental law regulates resource use, pollution, and conservation, while human rights law ensures protection from displacement, discrimination, and exploitation.

Emerging legal movements, such as granting legal personhood to rivers or forests, represent innovative approaches to environmental protection. Law ensures that sustainability is not just a goal but a legal and ethical obligation.

10. Agriculture and Food Systems: Feeding the Future Sustainably

Agriculture is central to sustainable development, touching on food security, livelihoods, and land use. Sustainable agricultural practices—such as **agroecology**, **permaculture**, and **organic farming**—aim to produce food while preserving ecosystems and reducing chemical inputs.

Food systems must also address challenges like waste reduction, equitable distribution, and climate resilience. Integrating science with traditional farming knowledge can support productivity without degrading natural resources.

III. CONCLUSION

Sustainability and development are complex, multidimensional challenges that demand an interdisciplinary approach. No single discipline can address the full scope of issues such as poverty, climate change, urbanization, and inequality. By drawing from the strengths of environmental science, economics, politics, sociology, engineering, education, health, and law, we can build integrated solutions that are more effective and equitable.

The future of sustainable development depends on breaking down silos and fostering collaboration among disciplines. Only by doing so can we achieve the shared vision of a just, prosperous, and environmentally stable world for current and future generations.

REFERENCES

[1]. Brundtland, G. H. (1987). *Our Common Future: Report of the World Commission on Environment and Development*. United Nations.

[2]. Sachs, J. D. (2015). *The Age of Sustainable Development*. Columbia University Press.

[3]. United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development*.

[4]. Raworth, K. (2017). *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*. Chelsea Green Publishing.

[5]. IPCC. (2021). *Sixth Assessment Report*. Intergovernmental Panel on Climate Change.

Analyzing Student Engagement Patterns Using Machine Learning Techniques in Virtual Learning Environments

Dr. Dipti H. Domadiya
Professor& Principal, National Computer College-Jamnagar, Gujarat, India
(E-mail: diptipunjani@gmail.com)

Abstract –The digital transformation of education has revolutionized learning processes worldwide, making virtual learning environments (VLEs) central to modern pedagogy. Understanding student engagement in these settings is crucial for ensuring educational quality and equity. This conceptual paper examines how Machine Learning (ML) techniques can be employed to analyze and enhance student engagement patterns in online education. Drawing from recent developments in learning analytics, educational data mining, and artificial intelligence (AI)-enabled pedagogy, this study develops a conceptual model linking ML algorithms to the three core dimensions of engagement: behavioural, cognitive, and emotional. Through a review of empirical and theoretical literature, the paper outlines how algorithms such as Random Forest, Support Vector Machines (SVM), Neural Networks, and Natural Language Processing (NLP) can detect and interpret engagement behaviours in digital learning contexts. The discussion highlights both the transformative potential and ethical challenges of ML-based engagement analytics, emphasizing the need for interpretability, fairness, and transparency in AI-driven educational systems. This work provides a comprehensive foundation for researchers and practitioners seeking to design intelligent, data-informed, and ethically grounded learning ecosystems.

Keywords – *Machine Learning, Student Engagement, Virtual Learning Environments, Learning Analytics, Educational Data Mining, Predictive Modelling, Adaptive Learning, Online Education*

I. INTRODUCTION

Over the past decade, educational systems across the world have witnessed a paradigm shift from traditional face-to-face instruction to digitally mediated learning ecosystems. The emergence of Virtual Learning Environments (VLEs) such as Moodle, Blackboard, and Canvas has transformed the delivery of educational content and interaction patterns between students and educators. However, the success of such systems depends heavily on one key factor — student engagement (Henrie et al., 2018; Fredricks et al., 2004).

Engagement is widely recognized as a multidimensional construct encompassing behavioural, emotional, and cognitive involvement in learning tasks (Redmond et al., 2018). Engaged students are more motivated, demonstrate higher retention, and achieve better academic outcomes. Yet, measuring engagement in digital environments poses unique challenges, as student interactions occur asynchronously and are mediated through complex technological interfaces.

Machine Learning (ML) provides innovative means to address these challenges. ML's ability to process large datasets, recognize hidden patterns, and predict future behaviours makes it particularly suitable for analyzing engagement in online education (Romero & Ventura, 2020). By examining clickstreams, discussion posts, and time-on-task metrics, ML algorithms can generate actionable insights that educators can use to personalize learning experiences and provide timely interventions (Aljohani, 2021; Zawacki-Richter et al., 2019).

Despite these promising applications, much of the research to date remains fragmented and lacks a unified conceptual framework. This paper aims to fill that gap by presenting a comprehensive conceptual model that links ML techniques with engagement dimensions in VLEs. It also discusses the ethical, pedagogical, and technical implications of adopting ML for educational decision-making.

II. LITERATURE REVIEW

A. Defining Student Engagement

Student engagement is an enduring construct that captures the quality of learners' interaction with educational activities and their emotional and cognitive investment in learning (Fredricks et al., 2004). In virtual contexts, engagement is not limited to classroom participation but extends to metrics such as time spent on learning platforms, interactions with multimedia content, and peer collaboration (Henrie et al., 2018).

Redmond et al. (2018) categorize engagement into five interrelated domains: behavioural, cognitive, affective, social, and collaborative. For this paper, these are consolidated into the three dominant engagement dimensions widely used in machine learning analytics—behavioural**,** cognitive, and emotional engagement.

B. Machine Learning in Educational Analytics

Machine Learning has become an integral component of Learning Analytics (LA) and Educational Data Mining (EDM)**.** Through supervised and unsupervised learning, ML models can classify students, predict dropout risks, and recommend personalized learning paths (Siemens & Long, 2019; Romero & Ventura, 2020). Supervised methods such as Random Forest and SVM predict outcomes using labelled data, while unsupervised methods like K-Means Clusteringidentify hidden engagement patterns (Chiu & Hew, 2023).

Recent studies show that ML can accurately predict academic success and identify at-risk learners before traditional assessments can (Peña-Ayala, 2021). Deep learning models have been particularly effective in analyzing unstructured data such as discussion text or facial expressions during online learning sessions (Liu et al., 2022). However, despite these advancements, many studies focus narrowly on performance metrics rather than holistic engagement.

C. Integrating Pedagogy and Data Science

The educational application of ML should extend beyond technical sophistication to address pedagogical concerns. Ifenthaler and Yau (2020) argue that data-driven models must align with learning theories to ensure interpretability and ethical soundness. The constructivist learning paradigm emphasizes the learner's active role in constructing knowledge, which ML systems should support by providing adaptive feedback and scaffolded instruction. Moreover, explainable AI (XAI) frameworks can make ML predictions more transparent, fostering trust among educators (Holmes et al., 2021; Ferguson et al., 2022).

D. Research Gaps and Future Directions

While a growing body of literature explores the predictive potential of machine learning (ML) in education, few studies have systematically conceptualized how multifaceted engagement metrics—encompassing behavioural, cognitive, emotional, and social dimensions—can be effectively integrated with ML models to form comprehensive engagement analytics ecosystems**.** Most existing frameworks remain fragmented, focusing on either data processing or outcome prediction, without adequately linking technological capability with pedagogical intentionality. This disconnect limits the potential of ML to provide actionable insights that can truly enhance learning design and instructional decision-making.

To bridge this gap, the current paper advances a conceptual modelthat aligns machine learning methodologies with pedagogical objectives to create a holistic framework for student engagement analytics**.** This proposed model emphasizes the synergy between data-driven intelligence and human-centered pedagogy**,** illustrating how algorithmic predictions can support educators in identifying at-risk learners, personalizing instruction, and fostering deeper engagement. Furthermore, this research highlights the necessity of embedding ethical and interpretive layers within ML systems—ensuring transparency, fairness, and accountability in the educational use of predictive technologies.

By synthesizing existing theoretical and technological perspectives, the study contributes to closing a critical gap in educational data science research. It lays the foundation for a scalable, ethically grounded, and pedagogically aligned ML-based engagement ecosystem, setting the stage for future empirical validation and interdisciplinary collaboration.

III. CONCEPTUAL FRAMEWORK

The conceptual framework proposed in this study integrates multiple dimensions of student engagement with machine learning (ML) methodologies, creating a holistic ecosystem for data-driven pedagogical decision-making. The framework is designed to bridge the gap between technological capability and instructional intentionality, ensuring that ML models are not only predictive but also interpretable, ethically grounded, and pedagogically meaningful.

The framework comprises six interrelated layers: Data Collection, Engagement Indicators, Machine Learning Analytics, Insight & Interpretation, Pedagogical Action and Ethical& Governance**.** Each layer plays a specific role in capturing, analyzing, and acting upon engagement data to enhance online learning outcomes.

TABLE I
CONCEPTUAL MODEL OF ML-BASED STUDENT ENGAGEMENT ANALYTICS ECOSYSTEM

Layer	Components	Function / Purpose	Example ML Techniques
Data Collection Layer	Raw VLE data: login frequency, clickstreams, forum participation, assignment submissions, quiz scores	Captures student activity and behaviour in online platforms	Data pre-processing, feature extraction
Engagement Indicators Layer	Behavioural, Cognitive, Emotional, Social	Converts raw data into meaningful engagement metrics	Feature engineering, dimensionality reduction
Machine Learning Analytics Layer	Supervised & unsupervised algorithms for prediction and classification	Detects patterns, predicts at-risk students, clusters engagement levels	Random Forest, SVM, K-Means Clustering, Neural Networks, NLP for sentiment analysis
Insight & Interpretation Layer	Visual dashboards, interpretable outputs, XAI integration	Provides educators with actionable, understandable insights	SHAP, LIME, interpretability tools
Pedagogical Action Layer	Adaptive feedback, personalized learning paths, intervention strategies	Uses ML insights to guide instructional design and improve engagement	Recommender systems, adaptive learning algorithms, targeted intervention rules
Ethical & Governance Layer	Privacy, fairness, transparency, ethical compliance	Ensures responsible use of ML in education	GDPR-compliant data handling, bias mitigation algorithms

A. *Explanation of the Framework*

- Data Collection Layer: This layer serves as the foundation, capturing all digital traces of student activity within a VLE. Data includes login frequency, content access patterns, discussion forum participation, assignment submissions, and quiz performance. Comprehensive data collection enables the extraction of both behavioural and cognitive indicators of engagement.
- Engagement Indicators Layer: Raw data is processed and converted into meaningful metrics across behavioural, cognitive, emotional, and social dimensions. Behavioural metrics may include frequency of logins and time-on-task; cognitive indicators might involve quiz performance or depth of resource interaction; emotional and social indicators can be derived using sentiment analysis of forum posts and peer interactions.
- Machine Learning Analytics Layer: This layer applies appropriate ML algorithms to analyze engagement metrics. Supervised learning methods like Random Forest and SVM can classify engagement levels, while unsupervised methods such as K-Means Clustering reveal hidden patterns in student behaviour. Neural Networks and NLP techniques help interpret complex and unstructured data, including textual discussion contributions and affective signals.
- Insight & Interpretation Layer: ML outputs are transformed into interpretable insights for educators. Using Explainable AI (XAI) tools such as SHAP or LIME, educators can understand the rationale behind predictive classifications, ensuring transparency and facilitating actionable decisions.
- Pedagogical Action Layer: Insights generated through ML guide instructional strategies and personalized interventions. This layer supports adaptive feedback, tailored content recommendations, and targeted interventions for students identified as at-risk, promoting engagement and learning outcomes.
- Ethical & Governance Layer: Responsible deployment of ML in education requires adherence to privacy regulations (e.g., GDPR), fairness, and bias mitigation. Ethical oversight ensures that predictive analytics respect student rights and contribute to equitable learning experiences.

B. *Integration and Flow*

The framework operates as a continuous cycle**:** data collected from VLEs is transformed into actionable engagement metrics, analyzed through ML models, interpreted via transparent tools, and applied through pedagogical interventions. Ethical and governance considerations overlay every layer, ensuring responsible use of AI in educational contexts. By integrating these components, the framework provides a scalable, human-centered, and ethically grounded model for understanding and enhancing student engagement in virtual learning environments.

IV. METHODOLOGY (CONCEPTUAL APPROACH)

As a conceptual study, this research does not involve primary data collection. Instead, it synthesizes existing theoretical and empirical literature to propose a structured model illustrating how Machine Learning (ML) techniques can enhance student engagement analysis in Virtual Learning Environments (VLEs). The methodology focuses on linking multidimensional engagement metrics with suitable ML approaches, while emphasizing interpretability, ethical considerations, and pedagogical relevance.

A. Conceptual Workflow

The proposed methodology follows a stepwise conceptual workflow**,** integrating data collection, feature extraction, ML analysis, interpretation, and pedagogical action (Siemens & Long, 2019; Romero & Ventura, 2020):

- Data Collection Layer: Learner activity data is collected from VLEs, including login frequency, time-on-task, forum participation, assignment submissions, quiz scores, and multimedia interaction. This layer captures both behavioral and cognitive traces, providing a foundation for engagement analysis (Henrie et al., 2018).
- Feature Extraction Layer: Raw data is transformed into meaningful engagement indicators. Behavioural metrics quantify participation patterns, cognitive metrics evaluate learning effort and knowledge acquisition, and emotional metrics assess motivation and affect through sentiment analysis of discussion posts and peer interactions (Fredricks et al., 2004; Redmond et al., 2018).\
- Machine Learning Analysis Layer: ML algorithms are applied to the processed engagement data for classification, prediction, and clustering. Decision Trees and Random Forests are used for classifying behavioural engagement levels, while Neural Networks and Gradient Boosting predict cognitive effort and learning depth. Natural Language Processing (NLP) and sentiment analysis extract emotional and social engagement patterns from unstructured text data (Liu et al., 2022; Peña-Ayala, 2021).
- Interpretation & Insight Layer: Outputs from ML models are translated into actionable insights for educators. Tools from Explainable AI (XAI), such as SHAP and LIME, ensure transparency, allowing educators to understand model decisions and make informed pedagogical interventions (Ferguson et al., 2022).
- Pedagogical Action Layer: Based on ML-driven insights, educators can implement adaptive learning strategies, provide personalized feedback, and design targeted interventions to enhance student engagement and performance (Aljohani, 2021). This layer ensures that technological outputs are meaningfully applied to improve learning experiences.

B. Mapping Engagement Dimensions to MLTechniques

TABLE II

CONCEPTUAL MODEL OF ML-BASED STUDENT ENGAGEMENT ANALYTICS ECOSYSTEM

Engagement Dimension	Sample Indicators	Suitable ML Techniques	Analytical Purpose
Behavioural	Login frequency, assignment submissions, time-on-task	Decision Trees, Random Forest	Classify engagement levels and identify at-risk students
Cognitive	Quiz attempts, resource views, interaction patterns	Neural Networks, Gradient Boosting	Predict cognitive effort, learning depth, and knowledge retention
Emotional	Sentiment in discussion posts, feedback tone	NLP, Sentiment Analysis	Detect motivation, affective states, and social engagement

This mapping serves as a conceptual blueprint for adaptive learning systems capable of real-time engagement monitoring. By systematically linking engagement dimensions with appropriate ML techniques, the methodology provides a framework for identifying engagement patterns, predicting outcomes, and guiding interventions in VLEs.

C. Rationale for Selected ML Techniques

- Decision Trees & Random Forest: Effective for handling structured data like logins, assignment submissions, and time-on-task. They offer interpretability and high accuracy for classification tasks.
- Neural Networks & Gradient Boosting: Well-suited for capturing nonlinear relationships and predicting cognitive engagement levels, especially when datasets are complex and multidimensional.
- NLP & Sentiment Analysis: Ideal for analyzing unstructured text data from forums, chat logs, and reflective submissions to detect emotional and social engagement patterns.

V. DISCUSSION

The integration of Machine Learning (ML) techniques into Virtual Learning Environments (VLEs) offers transformative potential for enhancing student engagement. This discussion examines the theoretical and practical implications of the proposed conceptual framework, highlighting how ML can bridge the gap between learner behaviour, cognitive effort, and emotional investment.

A. ML as a Catalyst for Personalized Learning

The proposed framework emphasizes ML's capacity to move beyond traditional, one-size-fits-all approaches by enabling personalized learning pathways. By classifying students based on behavioural engagement (e.g., login frequency, time-on-task), predicting cognitive effort (e.g., quiz attempts, resource interactions), and analyzing emotional engagement through sentiment analysis, ML models can provide educators with actionable insights (Aljohani, 2021; Peña-Ayala, 2021).

For example, Random Forest and Decision Trees effectively categorize behavioural engagement levels, allowing educators to identify students at risk of disengagement in real time. Neural Networks and Gradient Boosting can predict cognitive workload and highlight students who may require additional resources or scaffolding. Meanwhile, NLP techniques enable the extraction of emotional and social signals from discussion forums, offering a nuanced understanding of learners' affective states (Liu et al., 2022). Integrating these ML outputs into adaptive interventions fosters a learning environment tailored to individual needs, enhancing both retention and academic performance.

B. Pedagogical Implications of ML-Driven Engagement Analytics

By linking engagement metrics to ML algorithms, educators can implement evidence-based pedagogical strategies. For instance, students identified as under-engaged in the behavioural dimension might receive targeted prompts or reminders, while learners demonstrating low cognitive engagement may benefit from adaptive learning pathways or supplementary exercises. Emotional engagement insights can inform collaborative activities, discussion facilitation, or mentorship interventions.

The framework highlights the synergy between technology and pedagogy, ensuring that data-driven insights are translated into meaningful educational action. This aligns with constructivist learning theory, which emphasizes active, personalized, and socially interactive learning experiences (Fredricks et al., 2004; Redmond et al., 2018).

C. Ethical Considerations and Responsible AI

While ML offers powerful tools for engagement analysis, it introduces ethical challenges that must be addressed. Privacy, fairness, bias, and interpretability are critical considerations in educational AI applications. The framework incorporates an Ethical & Governance Layer to ensure compliance with data protection regulations (e.g., GDPR), mitigate algorithmic bias, and maintain transparency (Ferguson et al., 2022).

Explainable AI (XAI) tools, such as SHAP and LIME, enhance interpretability by clarifying how ML models generate predictions. This transparency fosters trust among educators and students, supporting responsible use of AI while enabling informed pedagogical decisions.

D. Bridging Research Gaps

The proposed conceptual model directly addresses several research gaps identified in prior studies. First, it integrates multidimensional engagement metrics—behavioural, cognitive, emotional, and social—into a cohesive ML-driven ecosystem, overcoming the narrow focus of earlier research that emphasized only quantitative or performance-based measures (Siemens & Long, 2019; Romero & Ventura, 2020).

Second, the framework emphasizes interpretability and ethical oversight**,** ensuring that predictions are transparent, fair, and actionable. This addresses a critical limitation of black-box ML models in education, which often hinder trust and adoption. Third, by providing a scalable blueprint, the model encourages application across diverse disciplines, learning platforms, and cultural contexts, enhancing generalizability and future empirical validation.

E. Potential Challenges and Future Directions

Despite its strengths, the framework also acknowledges limitations. Conceptual integration does not equate to empirical validation; real-world implementation is necessary to test the accuracy, reliability, and scalability of ML-based engagement analytics. Furthermore, data heterogeneity**,** varying VLE architectures and differences in student demographics may impact model performance.

Future research should focus on:

- Empirical testing of the framework using cross-institutional datasets to assess predictive performance.
- Integration of multimodal data, including video interactions, biometric feedback, and collaborative behaviour, to enhance the richness of engagement analysis.

- Interdisciplinary collaboration among data scientists, educators, and ethicists to refine ML applications, ensuring they are pedagogically meaningful, interpretable, and ethically responsible.

F. Implications for Educational Practice

The proposed ML-based engagement ecosystem equips educators with actionable insights for real-time interventions. It transforms engagement analysis from reactive evaluation to proactive instructional design**,** allowing institutions to implement adaptive learning strategies that are responsive to student needs. By embedding ethical and interpretive considerations, the model also ensures responsible and transparent use of AI, fostering trust and adoption in educational contexts.

VI. CONCLUSION

This conceptual study presents a comprehensive framework for leveraging Machine Learning (ML) to enhance student engagement in Virtual Learning Environments (VLEs). By integrating behavioural, cognitive, emotional, and social engagement metrics with suitable ML techniques, the proposed model provides a structured, human-centered, and ethically grounded approach to learning analytics.

The study highlights how ML can transform traditional engagement monitoring into a dynamic, adaptive, and interpretable process, enabling educators to identify at-risk learners, personalize instruction, and implement targeted interventions in real time. The conceptual workflow—from data collection to pedagogical action—demonstrates the synergy between technological capability and pedagogical intentionality, ensuring that data-driven insights translate into meaningful educational practices.

Importantly, the framework addresses critical gaps in existing research, including the need for multidimensional engagement analysis, interpretability of ML models, ethical oversight, and cross-context generalizability. By embedding Explainable AI (XAI) and ethical considerations throughout, the model promotes transparency, fairness, and responsible application of AI in education.

While empirical validation remains a future step, this conceptual study lays a solid foundation for adaptive, scalable, and ethically responsible ML-based engagement ecosystems. It offers both theoretical insights and practical guidance for educators, researchers, and policymakers aiming to enhance learning experiences in increasingly digital and data-rich educational contexts.

In conclusion, this study reinforces the potential of ML to bridge the gap between technology and pedagogy, providing a roadmap for creating intelligent, inclusive, and effective learning environments that respond dynamically to students' engagement patterns.

REFERENCES

[1] Aljohani, N. R. (2021). *Predictive analytics in adaptive learning: Using machine learning to enhance online education.Journal of Educational Technology Systems, 49*(4), 471–489. https://doi.org/10.1177/00472395211021984

[2] Chiu, T. K. F., & Hew, T. K. F. (2023). *Learning analytics and machine learning in online learning environments: A systematic review.Educational Research Review, 38*, 100492. https://doi.org/10.1016/j.edurev.2022.100492

[3] European Commission. (2022). *Ethics guidelines for trustworthy AI in education.* Publications Office of the European Union.

[4] Ferguson, R., Clow, D., &Macfadyen, L. (2022). *Explaining learning analytics predictions: Transparency and trust in educational AI systems.Computers & Education, 179*, 104403. https://doi.org/10.1016/j.compedu.2021.104403

[5] Fredricks, J. A., Blumenfeld, P. C., & Paris, A. H. (2004). *School engagement: Potential of the concept, state of the evidence.Review of Educational Research, 74*(1), 59–109. https://doi.org/10.3102/00346543074001059

[6] Henrie, C. R., Halverson, L. R., & Graham, C. R. (2018). *Measuring student engagement in technology-mediated learning: A review.Computers & Education, 90*(1), 36–53. https://doi.org/10.1016/j.compedu.2015.09.005

[7] Holmes, W., Bialik, M., & Fadel, C. (2021). *Artificial Intelligence in Education: Promises and implications for teaching and learning.*Center for Curriculum Redesign.

[8] Ifenthaler, D., &Yau, J. Y. K. (2020). *Utilising learning analytics for study success: Reflections on current empirical findings.Research and Practice in Technology Enhanced Learning, 15*(1), 1–13. https://doi.org/10.1186/s41039-020-00132-4

[9] Liu, R., Zhang, Y., & Chen, S. (2022). *Deep learning applications in educational data mining: A systematic review.IEEE Access, 10*, 11238–11255. https://doi.org/10.1109/ACCESS.2022.3142237

[10] Peña-Ayala, A. (2021). *Learning analytics: A survey of machine learning methods used to analyze educational big data.Computers in Human Behavior, 120*, 106728. https://doi.org/10.1016/j.chb.2021.106728

[11] Redmond, P., Heffernan, A., Abawi, L., Brown, A., & Henderson, R. (2018). *An online engagement framework for higher education.Online Learning Journal, 22*(1), 183–204. https://doi.org/10.24059/olj.v22i1.1175

[12] Romero, C., & Ventura, S. (2020). *Educational data mining and learning analytics: An updated survey.Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery, 10*(3), e1355. https://doi.org/10.1002/widm.1355

[13] Siemens, G., & Long, P. (2019). *Learning analytics: The emergence of a discipline.AmericanBehavioral Scientist, 57*(10), 1380–1400. https://doi.org/10.1177/0002764213498851

[14] Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). *Systematic review of research on artificial intelligence applications in higher education: Where are the educators?International Journal of Educational Technology in Higher Education, 16*(1), 39. https://doi.org/10.1186/s41239-019-0171-0

Dr. Dipti Hasmukhbhai Domadiya is a Professor and I/C Principal at National Computer College, Jamnagar. She holds a Ph.D. in Computer Science from Saurashtra University and has over two decades of teaching and research experience. Her research interests include Machine Learning, Artificial Intelligence, Data Mining, Natural Language Processing and Educational Technology. Dr.Domadiya has published extensively in Scopus-indexed, UGC-approved, and international journals.She has also contributed book chapters with reputed publishers such as IGI Global and Springer.As an active reviewer and technical committee member, she has served in multiple IEEE and international conferences. She has successfully supervised Ph.D. scholars in the field of Computer Science.

Virtual Paint Application by Motion Tracking and Color Recognition using OpenCV

Suzan Rizvi[1], Syed Amaan Abbas Rizvi[2], Asfia Aziz[3], Imran Hussain[4], Aqeel Khalique[5]
Department of Computer Science & Engineering, SEST, Jamia Hamdard, New Delhi
(E-mail: [1]suzanrizvi100@gmail.com,[2]amaanabbas413@gmail.com,[3]asfiaaziz@jamiahamdard.ac.in [4]ihussain@jamiahamdard.ac.in [5]aqeelkhalique@jamiahamdard.ac.in)

***Abstract*—** Virtual Paint Application is an interactive tool that allows users to draw digitally without touching a mouse, pen, or screen. It uses computer vision techniques to track the movement of a coloured object and converts that motion into brushstrokes on a virtual canvas. With the help of OpenCV, the system detects specific colours, follows their position in real time, and maps the trajectory as drawing lines. This hands-free approach makes digital art more accessible and engaging, offering a creative way to control on-screen painting through simple gestures and colour recognition.

***Keywords*—** *OpenCV; Object Tracking; Color Recognition*

I. INTRODUCTION

Virtual Paint Application using OpenCV [1] and C++ is designed to provide a creative, innovative platform for artistic expression by leveraging computer vision, real-time object motion tracking, and color recognition. Users can draw virtually in the air using objects such as colored markers, making it suitable for artistic and educational purposes. The Virtual Paint Application uses a webcam to capture real-time video, which serves both as a canvas and input for the system. The application tracks objects (e.g., colored markers) to determine brush motion and color, allowing users to paint directly on the webcam feed. Multiple objects and colors can be detected simultaneously, enabling collaborative and dynamic painting. This application aims to provide an immersive experience for artists, students, and educators.

II. RELATED WORK

This section presents the related work in Table 1 with reference to Virtual Paint Application using OpenCV library [2].

TABLE I. Related Work Summary

Ref. No.	***Year***	***Summary***
[3]	2020	Demonstration of the image processing capabilities of OpenCV. The ultimate goal to create a computer vision machine learning application that promotes. Human computer interaction (HCI) also named Man- Machine Interaction (MMI)] refers to the relation between the human and the computer or more precisely the machine, and since the machine is insignificant without suitable utilize by human there are two main characteristics should be deemed when designing a HCI system: functionality and usability.
[4]	2023	A meticulously crafted color detection algorithm implemented in C++ and OpenCV achieves up to 97.4% accuracy in identifying specified hues from live video feeds. The detected colors are seamlessly translated into vibrant brush strokes rendered on a digital canvas in real- time. Optimization strategies involving parallel processing and code optimizations provide further performance gains.
[5]	2021	The required language for this project is python due to its more exhaustive libraries and easy to make use of the syntax and but understanding the basics as well as it can be implemented in any open cv supported languages The color tracking and detection processes are used to achieve the goal of this project. The color marker here used is detected and mask is produced. The next steps of morphological operations on the mask produced those are Erosion and Dilation.

III. METHODOLOGY

A. Product Perspective

This application is a standalone desktop program leveraging OpenCV for image processing and object tracking. It provides a virtual drawing platform where users can interact with the system using physical objects like markers of specific colors. The application is built using C++ for performance and cross- platform compatibility.

B. Product Features

- Real-time Video Capture: Captures live video from the webcam
- Object Tracking: Tracks the motion of user-defined objects in the video feed.
- Color Recognition: Identifies the color of the tracked objects to set brush colors.
- Virtual Drawing: Allows users to draw on the webcam feed using tracked objects [3].
- Multiple Object Support: Enables simultaneous tracking and drawing with multiple objects.
- Customizable Brush Sizes: Provides options to change brush stroke sizes.

C. User Classes and Characteristics

- Artists: Individuals seeking innovative digital tools for creative expression.
- Educators: Teachers using the application for interactive lessons or demonstrations.
- Students: Learners exploring digital art or computer vision technologies.
- Hobbyists: Technology enthusiasts experimenting with computer vision.

D. Assumptions and Dependencies

A functional webcam is required for the application to work. The system assumes proper lighting conditions for accurate object tracking and color recognition. OpenCV library and required dependencies are correctly installed.

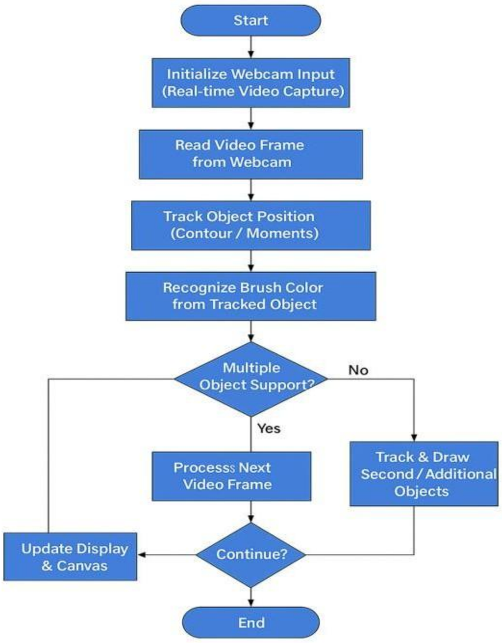


Fig. 1 Flow Model of Virtual Paint Application

IV. RESULTS

This section presents the virtual paint application in execution. Fig. 2 capture picture of the user going to use the virtual paint application.

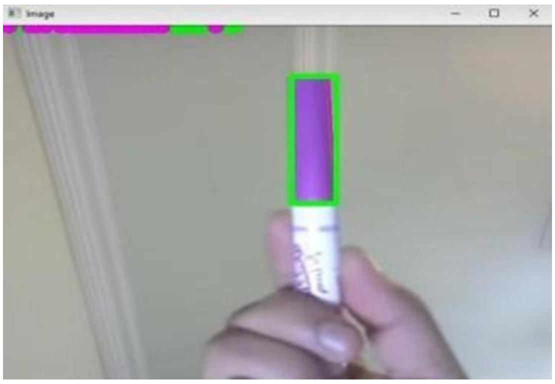


Fig. 2 Color Marker with Bounding Box Indicating Object Detection

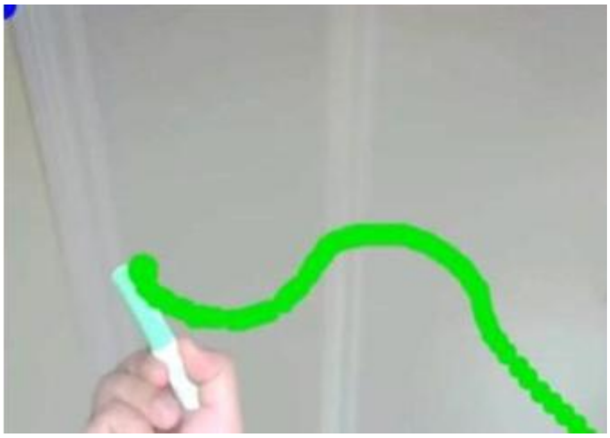


Fig. 3 Drawing with A Singular Marker On Webcam

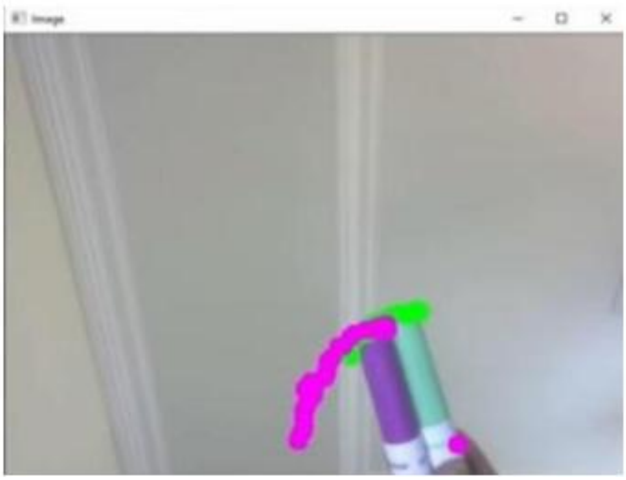


Fig. 4 Drawing with 2 Markers of Different Colors On Webcam In A Single Session

Fig. 5 Drawing with multiple markers of different colors on webcam in a single session

V. CONCLUSION

In this paper, we explore the concept of Virtual Painting using OpenCV and C++, demonstrating computer vision can transform simple gestures into digital artwork. By combining real-time motion tracking and color recognition, the system enables users to draw freely in the air with any colored object, eliminating the need for physical tools. This approach not only enhances creativity but also opens opportunities for educational demonstrations, interactive learning, and innovative UI designs. The study highlights the effectiveness of vision-based interaction and provides a foundation for more advanced virtual drawing or gesture-controlled applications in the future.

REFERENCES

[1] https://www.computervision.zone/

[2] I. Culjak, D. Abram, T. Pribanić, H. Džapo, and M. Cifrek, “A brief introduction to OpenCV,” in *Proc. 35th Int. Convention MIPRO*, Opatija, Croatia, May 2012, pp. 1722–1726. doi: 10.1109/MIPRO.2012.6240859.

[3] Y. Patil, M. Paun, D. Paun, K. Singh, and V. K. Borate, “Virtual Painting with OpenCV Using Python,” *International Journal of Scientific Research in Science and Technology* (IJSRST), vol. 5, no. 8, pp. 189–194, Nov.–Dec. 2020.

[4] S. Mishra, V. D. Trung, L. A. Ngoc, P. T. Vi, and S. Mishra, “Immersive Virtual Painting: Pushing Boundaries in Real-Time Computer Vision using OpenCV with C++,” in *Proc. 2023 8th Int. Conf. Research in Intelligent Computing in Engineering*, Pradeep Kumar et al. (eds.), *Annals of Computer Science and Information Systems*, vol. 38, ACSIS, 2023, pp. 41–50. doi: 10.15439/2023R58.

[5] P. Srungavarapu, E. P. Maganti, S. Sakhamuri, S. P. K. Veerada, and A. Chinta, “Virtual Sketch using Open CV,” unpublished manuscript, Jun. 2021.

Lane Departure Warning System using Deep Learning

Gosia Sandal Parveen[1], Asfia Aziz[2], Aqeel Khalique[3], Imran Hussain[4]
Department of CSE, Jamia Hamdard, New Delhi, INDIA
Email: [1]gosiasandal@gmail.com
[2]asfiaaziz@jamiahamdard.ac.in
[3]aqeelkhalique@gmail.com
[4]ihussain@jamiahamdard.ac.in

Abstract— In todays' modern generation every individual owns a vehicle making it a necessity than luxury. Consequently, huge numbers of vehicles crowd the roads and highways which resulted into hours long traffic jams, reckless driving and road accidents. One of the major reasons behind these accidents is lane indiscipline. Lane indiscipline means when drivers unintentionally or recklessly shift lanes without notifying other vehicles. Lane indiscipline is risky for young learners, elderly drivers and others. Advance Driving Assistance System (ADAS) has a feature to alert driver if he/she does not follow lane discipline. This paper proposes a real-time lane detection and lane departure warning (LDW) system using computer vision techniques implemented with OpenCV. The LDW system detects road lane markings using Canny edge detection and Hough Line Transform and the system identifies the vehicle's position relative to the lanes. The system immediately triggers an audio beep alert, warning the driver to correct their lane as it detects that the vehicle is veering out of its lane even slightly. The proposed LDW system is a useful feature and application of ADAS and improves safety, comfort, efficiency and assisting new drivers, elderly individuals, or driving school trainees.
Keywords— *Lane departure warning, Lane detection warning, LDW, ADAS.*

I. Introduction

Road safety has become a major global concern due to the rising number of vehicles and the increasing frequency of road accidents. To promote safe and orderly driving, and to prevent traffic congestion, it is essential to adhere to traffic rules and regulations enforced by authorities. Some important guidelines include maintaining proper lane discipline on multi-lane roads—vehicles must remain in their assigned lanes, and erratic lane switching or straddling lanes is a traffic offense. Drivers are also expected to use indicators before changing lanes and use the right lane only for overtaking or when instructed by traffic signs. Under poor visibility and low lighting, where the markings are faded, following proper lane discipline can play a crucial role in reducing road accidents, improving traffic flow, offering clear guidance, and reduce sudden braking or turning. Safe driving requires constant focus on the lane markings, traffic signals, and boundaries, all at the same time. This could be particularly challenging for new drivers and older individuals, those who aren't familiar with the area or with the concept of driving overall.

To address this problem, a technology was developed called ADAS, Advanced Driver Assistance System. They are technologies that help humans drive safer, more conveniently, and ultimately enhance overall driving experiences. ADAS uses a network of cameras, sensors, and user-friendly interfaces to detect traffic signals, lane markings, and predict potential danger to assist the driver respond correctly to whatever problem is occurring. These systems are built to reduce accident and human error while driving. Some standard ADAS features include adaptive cruise control, collision detection, lane departure alerts, lane centering, satellite navigation, real-time traffic information, mobile-based route guidance, automatic headlight control etc. This paper introduces a real-time lane departure warning system, developed using computer vision methods with Python and OpenCV. The system captures live video from a mounted camera, identifies road lanes using Canny edge detection and Hough Line Transform, and determines the vehicle's position in relation to the lanes. If the vehicle deviates from its lane, the system issues an audible alert to prompt corrective action from the driver. This solution is particularly beneficial for novice drivers, seniors with slower reaction times, and driving institutions. It serves as a low-cost assistance tool aimed at improving lane discipline, preventing road mishaps, and promoting safe driving practices on Indian roads.

Related Work

This section contains the description about the authors of the related work literature. Authors of [2] proposes an algorithm that was developed to determine the appropriate time to issue a warning when the vehicle is departing the lane. They employed a combination of method, Lucas–Kanade (L-K) optical flow method and the Hough Transform to track vehicle movements accurately. To address lane detection on both straight and curved roads under noise and outlier conditions, [3] introduces a effective and reliable algorithm with high detection accuracy, that employs the Least Median of Squares (LMedS) method to enhance the elasticity of line fitting. Author of [4] builds a system that utilizes the RANSAC algorithm for robust line detection in constantly changing driving environments, and implements a real-time lane departure alert system on a BeagleBoard embedded platform. Author of [5], integrate the Euclidean distance metric, Probabilistic Lane Shape Fitting (PLSF), and the Hough Transform for effective lane detection under difficult lighting conditions and noise. They focuses on accident prevention through the application of advanced computer vision techniques. Author of [6], presented an embedded lane detection system built on a Raspberry Pi platform, where they combined Canny edge detection and the Hough Transform to enable real-time performance on resource-constrained hardware.

To overcome issues of poor road conditions and faded or missing lane lines, author of [7] proposes an enhanced detection algorithm, where they integrate image warping, adaptive thresholding, and pixel summation techniques to identify lane lines even under worse light conditions. A different method is adopted in [8], employing MATLAB for image processing and utilizing a combination of Canny edge detection to applying bird's-eye transformation to road images, Hough Transform, and Kalman filtering to achieve precise and stable lane detection. In [9], authors present a comparative study of existing lane detection and departure warning systems, they discuss and evaluates the strengths and weakness of current approaches, and provide insights for improvement. We present the related work in Table 1.

II. METHODOLOGY

A. *Related Work*

In this section, we present the techniques, algorithms, flowchart for the proposed lane departure warning system.

TABLE I. RELATED WORK.

Reference No.	**DETAILS**		
	Year	Algorithm Used	Summary
[2]	2014	Lucas-Kanade (L-K) optical flow, Hough transform methods	The paper presents an algorithm that determines whether to issue a warning based on the vehicle's current position when it begins to drift from its designated lane.
[3]	2015	Least Median Square method	The paper introduces a lane line detection method that works effectively on both straight and curved roads, offering reliable detection and a high rate of accuracy.
[4]	2015	RANSAC algorithm, Beagle board	The paper describes a real-time lane departure alert system implemented on a BeagleBoard, functioning on a compact embedded system running an open-source Linux platform.
[5]	2018	Euclidean distance, PLSF algorithm, Hough transform	The paper explains the use of advanced computer vision algorithms for lane detection, aimed at preventing road accidents, it' is suitable for straight and curved roads and performs well under various lighting conditions.
[6]	2019	Hough transform, canny edge detection	The paper discusses the implementation of a lane detection system on an embedded development platform using a Raspberry Pi.
[7]	2021	Image warping, thresholding and pixel summation	The paper proposes an algorithm capable of detecting lanes even when road markings are faded or unclear, and when road conditions are poor.
[8]	2024	Canny edge detection, Hough transform, MATLAB, and Kalman filtering	The paper outlines an approach that uses MATLAB to process road images, transforming them into a bird's-eye perspective and utilizing a Kalman filter for precise lane detection.

Reference No.	DETAILS		
[9]	1996	Kalman filter, Covariance matrix	The presents an improved model-based approach where width of search area is narrowed to reduce noise, then filters/ parameter are applied to robustly detect lane lines.
[10]	2023	Confusion matrix, ROC curve, DET curve	The paper provides a comparative study of lane detection and lane departure technologies, highlighting their current limitations and areas needing improvement.
[11]	1997	Hough Transform, canny edge, parabolic model	The paper presents an algorithm that operates across different types of road/lane surfaces/structures and weather condition to detect lane boundaries modeled as parabolas.

B. ADAS

Advanced Driver Assistance System (ADAS) [12], is designed to make driving safer and more convenient, ultimately enhancing overall driving experience. They encompass an extensive range of advanced features like Adapting Control Crews, Lane Departure Warning, Automated Parking, and collision Avoidance, all working together to support the driver and reduce all the chances of accidents and risks. These systems rely on a network of components including cameras, radars, ultrasonic sensors, and lidars, along with high precision computers to understand and interpret the vehicle surrounding in real time. A key component of ADAS is sensor fusion where the data from different several sensors is combined together to form a clear and more complete picture of the surrounding of the car or vehicle. They analyze the sensor data in real time and provide support for decision making processes. These tasks are carried out or performed by electronic control units, ECUs, using complex algorithms and powerful processes. In addition, ADAS benefits from artificial intelligence and machine learning to allow the system to adapt over time. By learning from previous data, the system learns to adjust to different road condition, improve object detection and recognition. Therefore, through the integration advanced hardware with intelligent software, ADAS plays a key role towards development of self-driving cars and reducing human errors, making roads safer. Common ADAS features are collision avoidance, adaptive cruise control blind spot monitoring, pedestrian detection, driver monitoring, traffic sign recognition, automatic parking and lane departure warning.

C. OpenCV

Open-Source Computer Vision Library, (OpenCV) [13], is a widely used and flexible library for computer vision and machine learning projects. It was originally developed by Intel but now it’s maintained by the foundation of OpenCV, along with contributions from the global developer community. OpenCV has a large collection of tools and optimized algorithms that assists while working with images, videos, especially for real-time applications. Some of the algorithms are object detection, facial recognition, motion analysis, image segmentation, etc. Key feature of OpenCV is that it works across different platforms and supports multiple programming languages that makes it easier for developers and researchers to work with any language.

D. Canny Edge Detection

Canny edge detection is a popular and reliable method used for identifying edges in images [14]. In 1986 John F. Canny introduced Canny edge detection and is still widely used today because its accuracy rate of filtering out noises while still keeping the important details is very high. This technique was developed to detect the boundaries of objects digital images by spotting areas where the brightness changes sharply, this abrupt change indicates that there is a boundary between two different regions, likely here one object ends and another object begins. canny edge detection has high precision and consistency, it several phases helps highlight borders of things in a picture, reducing mistakes and avoid false positives.

The several phases are:

- Put Gaussian filter to reduce image noise
- Calculate intensity gradients in all directions (both horizontal & vertical)
- To thin out detected edges execute non-maximum suppression
- Apply double thresholding to categorize strong and weak edges
- Conduct edge tracking by hysteresis to finalize edge selection

Canny edge detection has several advantages. It removes all the false or duplicate responses to a single edge, provides strong resistance to noise interference, low probability of missing important edges and high precision of localization of edges.

E. Greyscale conversion

A grayscale image consists of just one channel [14], the grayscale image is basically a version of a picture that shows only shades of green without any color. Each pixel just represents how bright or dark it is. This simplification reduces complexity, makes things easier, and increases the processing speed while image processing. By removing color, we can only focus on the brightness, which is usually enough to identify the edges and shapes in the image. The conversion process includes calculating the intensity of each pixel by using a mix of its red, green, and blue (RGB) values. And then the calculated intensity values are allocated to the equivalent pixel in the grayscale output. During the conversion process, it ensures that the key features remain visible even without any color information. This not only makes image processing easier but also helps edge detection techniques.

F. Hough Transform

The Hough Transform is a technique in the computer vision domain [15] for detecting geometric shapes like lines, circles, and eclipses in digital images. In 1962, it was introduced by Paul Hough and has now evolved into a better method for detecting patterns and shapes even when the images are not perfectly clear or have noise or are blurry. In Hough transform we essentially look for shapes in a different space called Hough Space, where shapes are defined by specific values like angles and distance instead of looking in the regular image spaces. For example, as shown in Figure 1, when looking for lines, instead of thinking in terms of slope and intercept, the method often uses angle (θ) and distance from the center (ρ), which tends to be more stable. This method typically starts by identifying points of interest in the image, and then, for each of these edge points, algorithms figure out all the possible shapes that could go through it and then plots it in the Hough Space. Each plotted shape gets a vote in the Hough Space, and the shapes with the most votes are likely to be present in the original image.

Applications of the Hough Transform are:

- Identification of edges in images,
- Recognizing of objects in images,
- Detecting road lanes in autonomous vehicle systems,
- Analyzing medical images,
- Supporting machine vision in industrial inspection tasks.

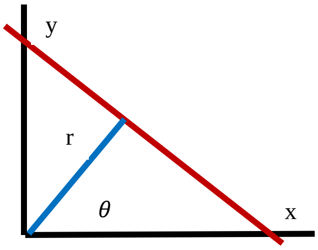


Fig. 1. Hough transform line

G. Gaussian Filter

The Gaussian Blur is an image preprocessing technique that is used extensively in image editing and computer vision to soften or blur images [16]. It helps reduce noise and improve the clarity of the image. Those random spots or sharp changes in brightness that can show up due to camera issues or lighting problems are called noise. The noise is the leading cause of false edge detection during image analysis. The method works by applying a special filter called Gaussian Kernel, which is based on smooth bell-shaped curve. The key feature of this kernel is that all its values sum up to be 1. This filter averages out the pixel values around each point in the image, giving more importance to pixels closer to the center. It is a simple but powerful trick to clean up images and make details easier to work with. This method softens the images while still preserving the important details and brightness level. This reduces fine details and minor intensity fluctuations, helping eliminate insignificant edges and create a more uniform image appearance. The degree of blurring depends on the size of the kernel—the larger it is, the stronger the blur effect. Beyond aesthetic improvement, Gaussian blur is also an essential preprocessing tool in machine learning and deep learning workflows. By filtering out irrelevant details and reducing noise, it contributes to more accurate and efficient model performance [14], especially when dealing with image-based data**.**

Mathematically, the Gaussian kernel is defined as

$$G(x, y) = \frac{1}{2\pi\sigma^2} \cdot exp\left(-\frac{x^2+y^2}{2\sigma^2}\right) \qquad (1)$$

Advantages of blurring are:

- It is effective in reducing noise from images. Since noise typically contains high-frequency components, applying a low-pass filter kernel suppresses these unwanted signals.
- It contributes to producing a smoother and more uniform image appearance.
- It eliminates faint or low-contrast edges, enhancing clarity by focusing on prominent structures.
- It is useful for obscuring image details when needed—for instance, law enforcement may intentionally blur a victim's face to protect their identity.

In this paper, we convert the input image into grayscale to simplify further processing. Gaussian filter is applied on the grayscale image to reduce noise and ensuring smoother edges. The Canny edge detection algorithm is then used to compute image gradients and identify strong edges, based on a low-to-high threshold ratio (1:3), resulting in a clear outline image. Next, we define a Region of Interest (ROI) by plotting points using Matplotlib, forming a polygonal area where the lanes are expected. This creates a mask where the ROI is white, and the rest is blacked out, producing another image. A bitwise AND operation is performed between canny image and edge image to isolate only the relevant lane features. Hough Transform is then applied to detect straight lines within this masked region. These detected lines are drawn onto a black background and then blended with the original-colored image, so the lane lines appear neatly highlighted on the road. Extending this method to video, the same processing is performed frame-by-frame to detect lanes in real time. Finally, an alert system is integrated, where a beep sound is triggered if no lane lines are detected, it warns the driver of a potential lane departure, thus promoting safer driving behavior. The methodology of our work is presented in Figure 2.

H. Libraries Used

We use the following libraries to implement LDW system:

- OpenCV
- Winsound
- NumPy (Version – 2.2.3)
- Matplotlib (Version – 3.10.1)

The various videos of vehicle moving on roads were used as input in our proposed work and the video feeds were downloaded from YouTube channel PHAZMID [17] and pexel.com [18].

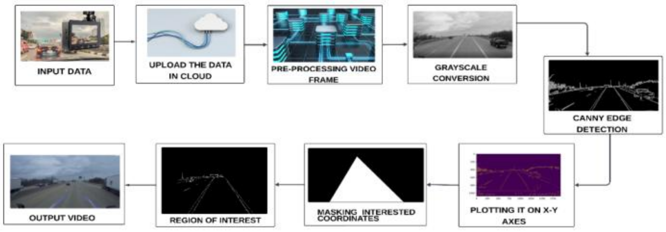


Fig. 2. Methodology of proposed LDW system.

III. RESULTS

This section presents a series of key frames extracted from the output video generated by the proposed lane detection system. The program highlights the detected lane lines in real time and emits an audible alert (a beeping sound) whenever the vehicle deviates from its lane, thereby notifying the driver of unintended lane departure. Figure 3 represents a Gaussian filter applied image a which effectively reducing noise and producing smoother edges. Subsequently, edge detection is performed using the Canny algorithm, yielding a sharp edge line image, as shown in Figure 4. In Figure 5, this Canny output is plotted within an x–y coordinate space, enabling the identification of the region of interest (ROI) for further processing. Once the coordinates of the ROI are selected, a mask is applied to hide the whole image and isolating the area of interest seen in Figure 6..The masked and edge-detected images are then combined, as shown in Figure 7. This composite is imposed on the original-colored frame to highlight the lane lines appearing the ROI which is represented in Figures 8, 9 and 10.

In addition, the system provides textual output on the console. When a lane change is detected, the message "Lane change detected" is printed. Similarly, if the system fails to identify lane lines, it reports "No lines detected." These two cases are illustrated in Figures 11 and 12, respectively.

Fig. 3. Gaussian Blurred applied on video frame

Fig. 4. Canny Edge Detection applied on video frame

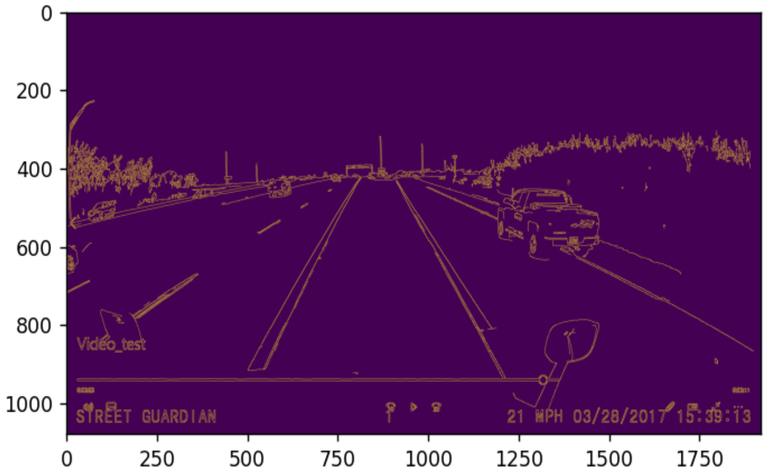


Fig. 5. Image along with x and y axis to find interested coordinates

Fig. 6. Snapshot from the output of video 1

Fig. 7. Snapshot from the output of video 1

Fig. 8. Snapshot from the output of video 2

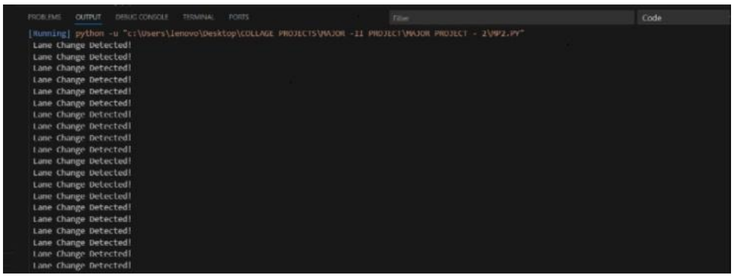


Fig. 9. Message alert in terminal when lanes are switched

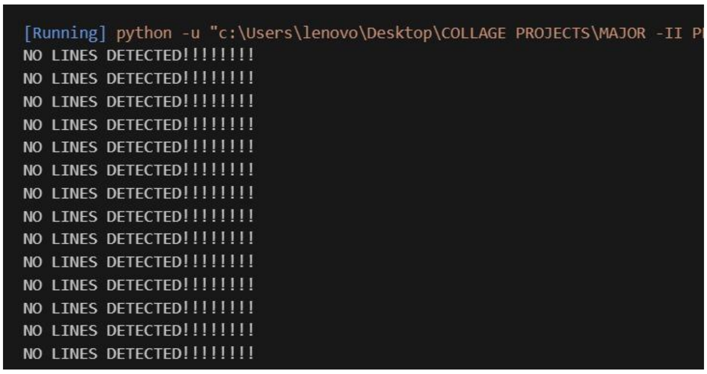


Fig. 10. Message alert in terminal when couldn't detect lanes.

IV. CONCLUSION

Lane departure warning is a feature of ADAS assisting drivers with the safe operation of a vehicle. ADAS encompasses a wide range of features designed to support drivers through automation and enhanced perception, such as lane departure warnings, adaptive cruise control, collision avoidance etc. Integrating lane detection within the broader ADAS framework significantly improves the reliability and responsiveness of the vehicle's safety systems. In this paper, we develop lane departure warning and alert system using Canny edge detection, Gaussian blur, Hough Transform and OpenCV. The system detects the lane lines in the input video and generates an output video that displays the lane line highlighted. It alerts the driver when the vehicle switches lanes with a beeping alert sound. This can be especially helpful for young learners, elderly drivers, and even everyday drivers who may sometimes lose focus on the road. By providing immediate feedback, the system acts as an extra layer of awareness, encouraging drivers to maintain better control and discipline while driving. The system shows strong potential with future such as handling curved roads, detecting multiple lane types, or adapting to different weather and lighting conditions. As we move toward a future of semi-autonomous and fully autonomous vehicles, systems like these will play a pivotal role in reducing road accidents, enhancing traffic flow and increasing driver comfort.

REFERENCES

[1] Hamid, U.Z.A., et al.: Autonomous emergency braking system with potential field risk assessment for frontal collision mitigation. In: 2017 IEEE Conference on Systems, Process and Control (ICSPC), pp. 71–76. IEEE, Meleka, Malaysia (2017). https://doi.org/10.1109/SPC.2017.8313024

[2] Taubel, G., Sharma, R., Yang, J.: An experimental study of a lane departure warning system based on the optical flow and Hough transform methods. WSEAS Trans. Syst. 13, 105–115 (2014)

[3] Zhang, L., Xu, Y.: Research on lane detection technology based on OpenCV. In: 3rd International Conference on Mechanical Engineering and Intelligent Systems, pp. 994–997 (2015)

[4] Balaji, N., Babulu, K., Hema, M.: Development of a real-time lane departure warning system for driver assistance. In: Satapathy, S.C., et al. (eds.) Emerging ICT for Bridging the Future – Volume 1, Advances in Intelligent Systems and Computing, vol. 337, pp. 463–471. Springer, Cham (2015)

[5] Kamble, A., Potadar, S.: Lane departure warning system for advanced drivers assistance. In: Second International Conference on Intelligent Computing and Control Systems (ICICCS), pp. 1775–1778 (2018)

[6] Surti, M., Chourasia, B.: Real time lane detection system using Python and OpenCV on Raspberry Pi. Int. J. Res. Eng. Appl. Manag. (IJREAM) 5(6), 100–104 (2019)

[7] Devane, V., Sahane, G., Khairmode, H., Datkhile, G.: Lane detection techniques using image processing. In: ITM Web of Conferences, vol. 40, ICACC-2021, 03011 (2021)

[8] Megalingam, R.K., Pradeep, N.C., Reghu, A., Sreemangalam, S.A.: Lane detection using Hough transform and Kalman filter. In: International Conference on E-mobility, Power Control and Smart Systems (ICEMPS) (2024)

[9] Takahashi, A., Ninomiya, Y.: Model-based lane recognition. In: Proceedings of Conference on Intelligent Vehicles, IEEE, ISBN 0-7803-3652-6 (2002)

[10] Nigam, S., Pareek, H., Vishwakarma, A., Pareek, R., Lolage, R.: Lane detection system using OpenCV for self-driving cars. Int. Res. J. Innov. Eng. Technol. (IRJIET) 7(4), 115–118 (2023)

[11] Yu, B., Jain, A.K.: Lane boundary detection using a multiresolution Hough transform. In: Proceedings of International Conference on Image Processing, IEEE, ISBN 0-8186-8183-7 (2002)

[12] National Instruments: What is ADAS? https://www.ni.com/en/solutions/transportation/adas-and-autonomous-driving-testing/what-is-adas.html, last accessed 2023/10/25

[13] GeeksforGeeks: OpenCV Python tutorial. https://www.geeksforgeeks.org/opencv-python-tutorial/, last accessed 2023/10/25

[14] Educative: What is Canny edge detection. https://www.educative.io/answers/what-is-canny-edge-detection, last accessed 2023/10/25

[15] GeeksforGeeks: Hough transform in computer vision. https://www.geeksforgeeks.org/hough-transform-in-computer-vision/, last accessed 2023/10/25

[16] GeeksforGeeks: Python image blurring using OpenCV. https://www.geeksforgeeks.org/python-image-blurring-using-opencv/, last accessed 2023/10/25

[17] YouTube: Lane detection tutorial. https://www.youtube.com/watch?v=tBWq-2TBvH8&list=PPSV, last accessed 2023/10/25

[18] Pexels: Driving video dataset. https://videos.pexels.com/video-files/16385743/16385743-hd_1920_1080_30fps.mp4, last accessed 2023/10/25.

IoT based Mental Health Monitoring

Jenifer Bano[1], Fauzy Iraqi[2], Asfia Aziz[3], Aqeel Khalique[4], Imran Hussain[5]
[1,2,3,4,5]Department of CSE, SEST, Jamia Hamdard, New Delhi
(E-mail: jeniferbano2@gmail.com
mefauzia786@gmail.com
asfiaaziz@jamiahamdard.ac.in
aqeelkhalique@gmail.com
ihussain@jamiahamdard.ac.in)

Abstract—The global rise in mental illness has developed as an urgent public health threat, with around 500 million of individuals affected by disorders such as depression, schizophrenia and dementia. These conditions create a significant challenge worldwide, more complicated by the limitations of traditional management approaches that depend heavily on subjective self-reports and infrequent professional evaluations, which often fail to capture the evolving nature of mental health. Advances in the Internet of Things (IoT) have introduced new possibilities for continuous and passive monitoring with the help of networked sensors worn on the body or embedded in everyday environments, enabling the collection of comprehensive data reflective of both physical and psychological states. This paper surveys existing research at the intersection of IoT and mental health, identifying how sensor-based systems can support real-time classification and personalized visualization configured to individual sensitivity profiles. Preliminary findings demonstrate optimistic outcomes, including high accuracy, scalability, and the ability to generate functional insights through dynamic feedback loops that support continuous improvement. At the same time, we can see many challenges, such as difficulties in data acquisition among certain patient populations, lack of interoperability and self-organization among devices, service-level agreement issues, and critical concerns surrounding privacy, security and informed consent. By connecting environmental conditions with mental health care, IoT-driven solutions represent an impactful shift from reactive treatment to proactive and predictive systems, developing the foundation for more personalized, preventive, and sustainable models of global mental health support.

Keywords—*Mental health, Internet of things, IoT, Predictive systems.*

I. Introduction

Mental health disorders depict one of the most serious global health challenges, affecting hundreds of millions of people worldwide and applying significant social and economic burdens. The World Health Organization (WHO) identifies conditions such as depression, anxiety, schizophrenia, and dementia as leading causes of disability. Despite increasing awareness, current management strategies remain insufficient, often utilize subjective self-reports and periodic evaluations that lack urgency and objectivity. In this context, the Internet of Things (IoT) offers transformative potential for mental health monitoring and management.
This introduction is structured into five key points that defines the motivation and direction of this research:

1. Global Burden of Mental Health Disorders

Mental illnesses such as depression and anxiety are throughout the leading causes of disability worldwide. More than 500 million people suffer from mental health conditions, with frequency rising due to factors such as the COVID-19 pandemic. The societal and economic costs are immense, underscoring the immediate need of developing innovative monitoring and intervention strategies.

2. Limitations of Traditional Mental Health Management

Current approaches depend heavily on self-reports and professional evaluations, which are often subjective and infrequent. These methods fail to collect real-time changes in emotional states, limiting the effectiveness of interventions. Resource-constrained environments face additional challenges in providing immediate and personalized care.

3. Emergence of IoT in Healthcare

IoT technologies combine sensors, actuators, and software to provide continuous, data-driven services. IoT has already evolved industries such as agriculture, supply chains, smart homes, and healthcare. In mental health, however, IoT applications remain underexplored, focusing mainly on a significant research gap.

4. Importance of Environmental Factors

Currently monitoring systems focus primarily on internal physiological and behavioural data (e.g., heart rate, sleep patterns). External environmental conditions such as temperature, humidity, air quality, and lighting strongly influence emotional wellbeing. Excluding these factors reduces the comprehensiveness and accuracy of current monitoring solutions.

5. Potential of IoT and Big Data for Mental Health Monitoring
IoT devices when integrated with environmental sensors can continuously collect real-time data at scale. When it is combined with big data analytics, fuzzy logic, and machine learning, these systems can detect patterns and deliver personalized recommendations. This integration allows proactive care, early detection of adverse conditions, and tailored interventions to improve mental health outcomes.

6. Stress-Related Disorder
Stress can affect individuals with long term negative effects, and in some cases, develop in other mental disorders, such as depression or anxiety . IoT related technologies, such as smartphones, wearables, or external sensing devices, provide new possibilities for addressing and treating stress-related disorders. Physiological characteristics such as voice features can be used to determine levels of stress in individuals. Smartphones' microphones can be used to collect voice-related data, which have been reported to have a link with individuals' stress levels. However, devices have limitations (i.e., battery duration, phone memory usage) can represent a challenge in continuous voice tracking.

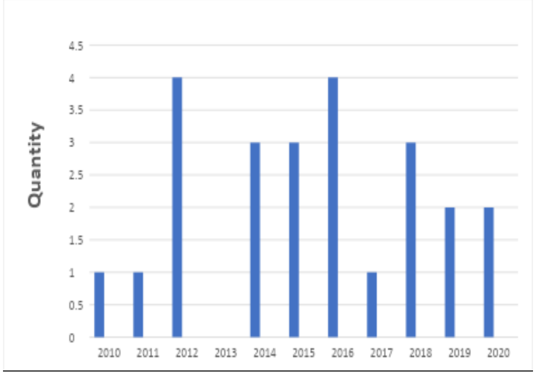


Figure 1: Number of studies related to IoT and mental health published per year

In Figure 1, we present the number of studies related to IoT and mental health published per year that derives from this survey.

II. METHODOLOGY

This research uses a mixed-method approach that combines a systematic survey of existing IoT applications in mental health with the foundational design and evaluation of a prototype monitoring framework. The approach begins with the identification and review of current sensor-based systems, focusing on their ability to capture physiological, behavioural, and environmental data relevant to mental health. Developing on these insights, the suggested IoT framework integrates wearable devices such as smartwatches and EEG headbands to monitor heart rate variability, sleep cycles, and galvanic skin response, alongside environmental sensors embedded in smart homes or workplaces to measure temperature, humidity, air quality, and lighting conditions.

Data collected from these sources are transmitted through mobile gateways to provide security to cloud platforms, where big data analytics, fuzzy logic, and machine learning algorithms are applied to classify mental health states and uncover hidden patterns. Continuous monitoring over several months enables the detection of temporary variations, while personalized dashboards provide real-time visualization and feedback specialized to individual sensitivity profiles. The system is evaluated using metrics such as accuracy, precision, recall, scalability, and user acceptance, with initial trail studies conducted among individuals diagnosed with depression or anxiety as well as control groups. Ethical evaluations are central to the methodology, with the strict observance of informed consent protocols, anonymization of sensitive data, and observation with international standards such as GDPR and HIPAA. Finally, repetitive validation through patient and clinician feedback ensures that the framework remains user-centered, scalable, and adaptable to diverse populations, preparing the foundation for predictive and preventive mental health support.

III. RESULT AND DISCUSSION

Data Privacy and Security in Healthcare IoT - Data privacy is a fundamental concern for any healthcare system. Reliable cybersecurity measures, including encryption and access management, are essential to protect sensitive user health and disability information. The collection and use of this data for research and treatment purposes must be governed by transparent policies and require explicit user consent. For the current prototype, a strict enforcement of user role and permission management was implemented as a fundamental measure to prevent unauthorized data access. System design maintenance for IoT-based Healthcare. An IoT-based healthcare system needs high standards for reliability, accuracy, response time, and data privacy. The systems design must carefully combine all components, including AI models, IoT devices, and computing platforms. The quality of Electroencephalography (EEG) data is crucial for the accurate classification and prediction tasks performed by modern AI models. This study utilized commercially available devices for measuring and transmitting EEG data to the cloud server. While these devices

provided validated accuracy suitable for a feasibility prototype, they present drawbacks for a full-scale Edge Device implementation, specifically. Devices reduce overall hardware efficiency.
Interference Issues - Possible interference between the integrated Bluetooth and Wi-Fi modules exists. Suboptimal Hardware Efficiency and Compactness: Using separate commercials.
Device Integration and Resolution of Limitations - The main limitation is the current lack of continuous integration, which could be addressed by developing an application-specific device. This device would integrate the brainwave sensing module and the Wi-Fi communication component into a single unit.
Scalability and System Response Time -It maintains efficient system response time is essential for a positive user experience. While significant investment in cloud computing infrastructure such as clustered servers connected by high-speed lines currently addresses this need and it enhances scalability, it can also lead to network traffic repetition. For future sustainability, better utilization of edge computing is recommended to reduce the server load. This shift will enable the system to accommodate a larger user volume.
Addressing Persistent Limitations in Previous Sleep Monitoring Research - Even with advancements in IoT technologies for sleep monitoring through previous research, several key limitations still continue like lack of multi-platform deployment, many existing systems support only one platform (cloud, web, or mobile), limiting accessibility and usability across different environments. Absence of Open-Source Code like the lack of open-source code limits system adaptability, customization, and further development by the research community. Insufficient Focus on Scalability and Extensibility makes a limited emphasis on these aspects constrains the ability to incorporate new features or expand system capabilities. Inconsistent Data Security and Privacy, sensitive user information protection remains a concern due to inconsistent security and privacy measures.
Impact of Environmental Factors - The analysis has identified a strong correlation between environmental factors temperature, humidity and stress levels. These findings correspond with existing research, confirming that high temperatures and humidity levels are associated with higher stress. The limit identified for temperature and humidity provide usable insights for designing interventions, particularly in enclosed environments such as offices and homes. These results underscore the importance of addressing environmental conditions as a critical factor in emotional well-being.
Future Directions - Establishing on the current findings, several opportunities for future research and development are recommended, dataset expansion, collecting larger datasets from different environments and populations will enhance model accuracy and scope for generalization.
Feature Improvement: It expands input features which includes physiological signals, activity data, or contextual information will provide a more comprehensive understanding of stress factors.
Edge Device Deployment: It develops lightweight versions of the models for deployment on edge devices which can access real-time stress monitoring and feedback in resource-constrained settings.
Adaptive Models: It designs adaptive models that learn individual users stress responses over time can improve the systems privacy and accuracy.
Integrated Intervention Systems: It combines stress monitoring with intervention mechanisms which are environmental adjustments or relaxation prompts, and can create a holistic stress management solution.
Data Augmentation and Class Imbalance Mitigation: It helps to address the challenge of class imbalance in stress detection systems, and incorporating techniques such as oversampling, synthetic data generation, or cost-sensitive learning to create more number of robust models, which can improve performance and fairness, especially when dealing with neglected stress levels in the data. These directions aim to refine the system and broaden its applicability, ensuring a more impactful contribution to the area of stress management and mental well-being.

IV. LIMITATIONS

The limitations of this study should be recognized. External validity and dataset scope, the dataset was restricted to tropical cities, which limits the extent to which the findings can be applied to diverse climates and populations. To increase the model's robustness and applicability, future research should broaden the dataset to include its huge array of environmental conditions and user demographics. Model Simplicity and Predictor Variables: While the models successfully classified stress levels, depending exclusively on temperature and humidity as predictors might oversimplify the complex nature of stress.
A more systematic understanding of emotional states could be achieved by incorporating additional variables such as air quality, noise levels, or physiological data. Individual variability and personalization, the current approach of identifying stress based on predefined temperature and humidity thresholds may fail to account for individual differences in stress responses. Future work is recommended to develop personalized models that adapt to users' unique sensitivities to environmental factors, thereby improving the system's relevance and accuracy.

V. CONCLUSION

IoT and AI are known as fundamental areas of future technology, which attract significant interest across a wide range of industries. The combination of these technologies into healthcare is predicted to enhance health protection. Simultaneously, advancements in brainwave sensors are making efforts to better understand brain activities. In this paper, we introduced the architecture of a mental healthcare system that utilizes IoT and AI technologies to analyze brainwave signals collected from sensing devices, thus providing health tracking capabilities. We have detailed the design of each component within the architecture and to develop a prototype system to validate it. Although the prototype system primarily focuses on sleep state monitoring, the proposed architecture is adaptable to other mental healthcare aspects. Mental health disorders are becoming a global issue. For example, due to the current COVID-19 pandemic, social isolation and stress-related situations have become more common, thus leading to mental health tolls in the majority of people who are carrying their day-to-day tasks from home [119,120]. In addition to this, people who are concerned about their future and their families, specifically those for whom the pandemic resulted in the loss of jobs or at worst, the loss of a close tie, are prone to suffer mental health-related problems, such as anxiety, depression, or stress-related conditions.

This paper formally introduces an innovative system architecture that leverages the combined capabilities of IoT and AI specifically personalized for mental healthcare applications. The core of this system lies in its capacity for the continuous and non-invasive surveillance of a user's health status through the analysis of real-time brainwave signals acquired directly from connected sensors. This continuous data stream, applied to processing by advanced AI algorithms, facilitates the detection of subtle physiological and neurological shifts that may signify emerging mental health concerns.

Significantly, the main architecture of this mental healthcare system has been engineered with integral scalability and modularity. While initially validated for sleep surveillance, the framework is intentionally developed to be highly adaptable, permitting smooth integration and expansion to encompass a wide spectrum of other mental health applications, including, but not limited to, the detection of stress, the tracking of mood disorders, and the assessment of cognitive function. This scalability positions the proposed system as a versatile and future-proof platform for next-generation personalized mental health monitoring and intervention.

REFERENCES

[1] Khan, S.F: Health care monitoring system in Internet of Things (IoT) by using RFID. In Proceedings of the 2017 6th International Conference on Industrial Technology and Management (ICITM 2017), Cambridge, UK, 7–10 March 2017. [Google Scholar] [CrossRef]

[2] Arnrich, B.; Osmani, V.; Bardram, J. : Mental Health and the Impact of Ubiquitous Technologies. Personal and Ubiquitous Computing: London, UK, 2013. [Google Scholar] [CrossRef] [Green Version]

[3] W. D. Killgore:Effects of sleep deprivation on cognition. Prog. Brain Res., vol. 185, pp. 105–129, Jan. 2010.

[4] Kong, G.; Li, C.; Peng, H.; Han, Z.; Qiao, H:EEG-based sleep stage classification via neural architecture search. IEEE Trans. Neural Syst. Rehabil. Eng., vol. 31, pp. 1075–1085, 2023.

[5] World Health Organization. Urban Green Spaces and Health; WHO/EURO: 2016-3352-43111-60341; World Health Organization, Regional Office for Europe: Copenhagen, Denmark, 2016. [Google Scholar]

[6] Cianconi, P.; Betrò, S.; Janiri, L. The impact of climate change on mental health: A systematic descriptive review. Front. Psychiatry 2020, 11, 490206. [Google Scholar] [CrossRef] [PubMed]

[7] Pan, J.; Tang, M.; Caniza, J.-M.; H'eraud, E.; Koay, H.K.; Lee, C.K.; Lee, Y.; Li, A.N.; Ruiz, C.; Santillan-Salas, F.; et al. Correlating Indoor and Outdoor Temperature and Humidity in a Sample of Buildings in Tropical Climates. Indoor Air 2021, 31, 2281–2295. [Google Scholar] [CrossRef]

[8] Extreme Heat Can Take a Toll on Mental Health. Available online: https://www.psychiatry.org/news-room/apa-blogs/extreme-heat-can-take-a-toll-on-mental-health (accessed on 18 December 2024).

[9] Sherstinsky's article, "Fundamentals of recurrent neural network (RNN) and long short-term memory (LSTM) network," appeared in Physica D: Nonlinear Phenomena, volume 404, in March 2020, with Article number 132306.

[10] An item by Zhou, X., Liu, C., Zhai, L., Jia, Z., Guan, C., and Liu, Y. from April 2023 is titled "Interpretable and robust AI in EEG systems.".

A Review on the Phyto-therapeutic potential of the wonder tree, *Prosopis cineraria*

Preeti Sharma[1], Chetna[2]
[1,2]*Kumari Vidyavati Anand College for Women, Karnal-132001, India*
(04sep.preeti@gmail.com, chetna150712@gmail.com)

Abstract— *Prosopis cineraria*, widely revered as the "wonder tree" of arid and semi-arid regions, holds significant ecological, cultural, and medicinal importance across several traditional medicinal systems. This chapter provides a comprehensive overeview of the phyto-therapeutic potential of *P. cineraria*, beginning with its botanical characteristics, distribution, and ethnobotanical relevance. The phytochemical profile of the species is examined in detail, highlighting key bioactive constituents such as alkaloids, flavonoids, tannins, steroids, saponins, and phenols which forms the basis of its broad pharmacological spectrum. The chapter further cites current evidence on its therapeutic properties, including antioxidant, anti-inflammatory, antimicrobial, antidiabetic, hepatoprotective, and immunomodulating properties. Special emphasis is placed on recent pharmacological studies that validate traditional uses and explore potential mechanisms of action. Overall, this review underscores *Prosopis cineraria* as a promising source of natural therapeutic agents and encourages further scientific exploration, standardization, and development of plant-based formulations derived from this resilient and medicinally valuable species.

Keywords— *Antioxidants, Anti-inflammatory, Prosopis cineraria, Phytochemicals, Phytomedicine, Anti-bacterial, Medicinal Plants.*

I. INTRODUCTION

The 'king of the desert', commonly known as Khejri (*Prosopis cineraria)* grows predominantly in dry and arid regions, performs a vital role in preserving the ecosystem. All the parts of the plant are used for numerous medicinal purposes. Leaves of *P. cineraria*, commonly called as "Loong", are formed into paste and applied on blisters, boils, mouth ulcers in livestock [1]. *P. cineraria* (the king of desert) has an extensive deep-root system and it is often considered as an aridity-loving tree because it possesses an ability to withstand drought and adverse climatic conditions. Its tap root system can penetrate vertically to more than 20 m hence, *P. cineraria* is popularly referred to as the "wonder tree" [2]. It is a multipurpose tree owing to the fact that all the parts of *P. cineraria* are useful for medicinal purposes and hence, it is referred as "kalpvriksha" in the ancient literature of India [3]. *Prosopis cineraria* is an evergreen, small to moderate sized thorny tree. It has slender branches with conical thorns and dark-green coloured leaves which are bipinnately compound. This tree is a legume and has the ability to fix atmospheric nitrogen thereby, plays a remarkable role in enhancing soil fertility and promotes the growth of other surrounding trees [4].

II. DISTRIBUTION

The wonder tree, *Prosopis cineraria*, is predominantly found in arid areas of Indian subcontinent, including India, Iran, Afghanistan, Saudi Arabia, Pakistan, Oman, UAE and Yemen. In India, it is native to the several parts of Rajasthan, Uttar Pradesh, Gujarat, Haryana and Tamilnadu [5].

A. Taxonomic Classification

Kingdom: Plantae
Order: Fables
Family: Fabaceae
Genus: *Prosopis*
Species: *cineraria*

Vernacular Names

Table 1. Representation of Vernacular names of *Prosopis cineraria.*

S. No.	*Different Languages*	*Vernacular Names*
1.	Arabic	Ghaf
2.	Bengali	Shami
3.	Gujarati	Khijado, Sumri, Semru, Sami, Karma
4.	Hindi	Banni, Chonksa, Shami, Khejiri, Janti, Sangria, Jand, Chaunkra
5.	Sanskrit	Jhind, Jhand

S. No.	*Different Languages*	*Vernacular Names*
6.	Tamil	Perumbay, Vanni, Jambu
7.	Urdu	Jandi, Thand, Kandi

Trade Names
Jand, kandi, khejri.

B. Botanical Description

The experimental plant, *Prosopis cineraria*, has the following salient features[1,6,7].

- It is an evergreen tree.
- The bark of the tree is thick and rough gray with very deep fissures (Figure 2.6).
- The branches of the medicinal plant are slender, glabrous and with compressed, straight and scattered prickles of 3-4 cm length.
- Flowers of the plant are in the form of axillary spikes.
- The flowers posses yellow corolla and thereby, attract huge number of insects and various other wild bees.
- The tree has 'bipinnately compound leaves' which are alternate in their arrangement (Figure 2.6).
- The leaflets are in the pairs of 15–18, and they have oblong shape with an entire margin and the petiole is normally 0.5–4 cm long.
- The average size of the leaves of the tree is 2.5 cm (in length) and 1 cm (in breadth).
- The freshly procured leaves of the tree are usually green in colour, odourless and bitter in taste.

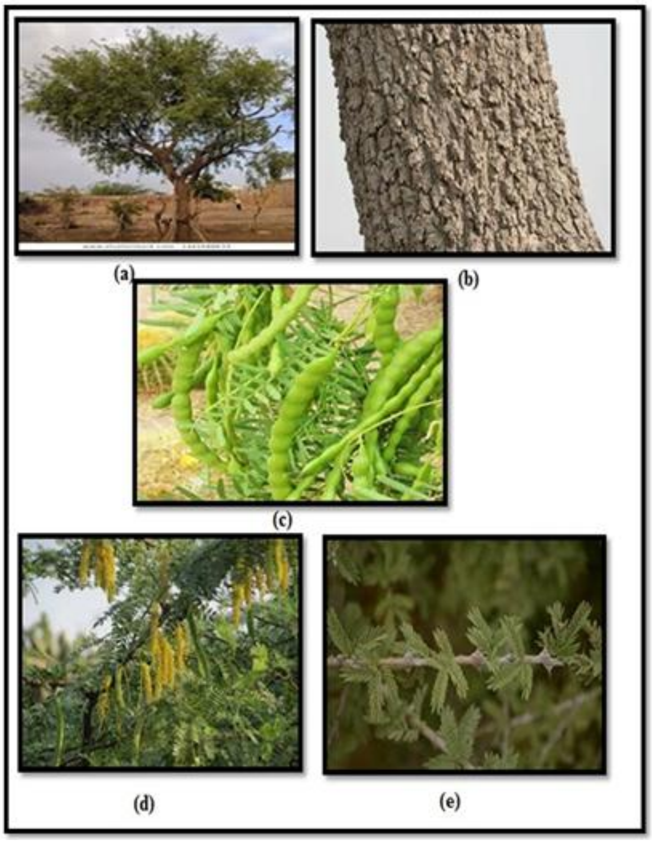


Figure 1. Different parts of *Prosopis cineraria* [The tree of Prosopis cineraria **(a)**; Stem-Bark **(b)**; Pods **(c)**; Flowers **(d)**; Leaves **(e)**]

C. Phytochemistry of Prosopis cineraria: A Potential Herb

Prosopis cineraria is a store-house of numerous active chemical entities that possess nutritional value and play a pivotal role in the treatment of many serious diseases. Numerous chemical entities are present in several parts of the experimental plant, *Prosopis cineraria* are mentioned below:

Part of the Plant- Prosopis cineraria	***Phytochemicals***
Flowers	• Patuletin glycoside patulitrin • Sitosterol • Spicigerine • Prosogerin A and Prosogerin B (Flavone derivatives)[8,9]
Leaves	• Steroids- campesterol, cholestrol, sitosterol and stigmasterol • Actacosanol • Piperidine alkaloid 'spicigerine' • Hentriacontane • Methyl docosanoate[10,11]
Seeds	• Prosogerin C • Prosogerin D • Prosogerin E • Gallic Acid • Patuletin • Patulitrin • Luteolin • Rutin [12,13]
Dried Pods	• 3-benzyl-2-hydroxy-urs-12-en-28-oic acid • Maslinic acid 3-glucoside • Linoleic acid • Prosphylline [14]
Bark	• Hexacosan-25-on-l –ol, a new keto alcohol along with ombuin and a triterpenoid glycoside • Vitamin K1 • n-octacosyl acetate-the long chain "aliphatic acid" • Presence of glucose, rhamnose, sucrose and starch has also been reported [15]

D. Therapeutic Properties of 'The Wonder Tree'

P. cineraria (the king of desert) has an extensive deep-root system and it is often considered as an aridity-loving tree because it possesses an ability to withstand drought and adverse climatic conditions. Its tap root system can penetrate vertically to more than 20 m hence, it is also popularly referred to as the "wonder tree" [16]. *Prosopis cineraria* has therapeutic importance and it is used for curing serious diseases and possess important activities like anti-fungal, anthelmintic, anti-cancer, anti-bacterial,anti-viral,anti-hyperglycaemic,anti-hyperlipidemic, anti-oxidative [17].

Flowers of *P. cineraria* are orally administered in order to prevent miscarriage. Bark of *P. cineraria,* has been utilized in the cure of various serious ailments such as asthma, leprosy, wandering of mind, fever, dyspepsia, dysentery, rheumatism, muscle tremors, bronchitis, piles, leucoderma [18,19]. Dried pods of the plant have a vital role in the treatment of protein calorie malnutrition (PCM) and deficiency of calcium and iron in blood [20]. The leaflets of the plant are rich in nutritive value and the smoke of leaves is considered as a remedy to cure eye-troubles [11].

Leaves of *P. cineraria,* commonly called as 'Loong', are formed into paste and applied on blisters, boils, mouth ulcers in livestock [1]. Phytochemical screening of the leaflets unravelled the presence of phenolic acid derivatives and hydrocarbons [11,21]. The studies carried out on the extracts of leaves of *P. cineraria* reported their antihyperglycemic, antihyperlipidemic and antioxidative potential [17]. The alkaloids present in the extracts of *P. cineraria* showed remarkable anti-bacterial potential against gram-positive and gram-negative bacterial species comparable to the commonly used antibiotics like penicillin, streptomycin and tetracycline [22]. The leaves of the plant were collected to study their prominent antimicrobial compounds. The research study highlighted the potential utilization of this plant leaves as antimicrobial agents. Dried leaves were extracted with aqueous ethanol. Antimicrobial activity tests were performed for the extracts and fractions obtained by preparative TLC. Tannins constitute the major compounds in the plant extracts. The leaves revealed the significant antimicrobial activity and highlighted its potential for the treatment of infectious diseases. The developed TLC solvent system may further be applied on column chromatographic separation of pure active compounds from *P. cineraria* [23].

In search of safe and effective therapeutic agents as an alternative to synthetic chemotherapeutics for the treatment of leukaemia, the research work was conducted to isolate and identify the active compounds from the leaves of *P. cineraria*. Dose and time-dependent cytotoxicity of the isolated compounds were studied against leukaemia cells and their anticancer mechanism such as cell wall damage, nuclear damage, ROS and NO generation, SOD level, LDH release and lipid peroxidation were investigated. Based on anti-proliferative activity, the isolated phytocompound vitexin from *P. cineraria* could be developed as a natural drug for treating leukaemia [24].

The study demonstrated that an ethanol extract of *Prosopis cineraria* pods can reduce serum cholesterol when fed to hypercholesterolemic rabbits. The extract also reduced the level of atheromatous plague in the aorta. Notably, the extract can improve antioxidant enzyme activity and inhibits HMG-Co reductase activity. Therefore, the use of an ethanolic extract of *Prosopis cineraria* pods could be further investigated as an alternative therapeutic agent to statins and other drugs, but one that does not have adverse side effects for the treatment of cardiovascular diseases [25]. The studies conducted on the stem-bark demonstrated the antihyperglycemic, antihyperlipidemic and antioxidative properties [26]. It is also considered to possess laxative and abortifacient properties [18]. The bark of this plant provides relief in case of scorpion sting [27].

Anti-inflammatory activity has been exhibited by the water-soluble extract obtained from the residue of methanolic extract of *P. cineraria* [27,28].Flowers have anti-diabetic potential and their powder is used to prevent miscarriage. Patulitrin, a cytotoxic principle has been isolated from the flowers of *P. cineraria* [8]. The gum of the tree is highly nutritive and used at the time of delivery by pregnant women. The pods of the plant are commonly known as 'sangar' or 'sangri' and have high nutritive value. Pods of *P. cineraria* are considered astringent by people of Punjab and they are highly nutritive hence, their consumption helps in curing mineral deficiency [20]. Studies conducted on the pods showed their 'LPO, COX-1 and COX-2' enzyme inhibitory activities [29].

The study was planned to explore the biological properties (antioxidant, antibacterial and lipoxygenase) and phytochemical investigation of extracts of stem, leaf and bark. Results showed that the plant has significant antioxidative potential and it is active against lipoxygenase enzyme. Antibacterial potential of the plant extracts was shown against- *Escherichia coli*, *Salmonella typhi*, *Pseuodomonas aeroginosa*, *Bacillus subtilis*, *Staphylococcus aureus* and presence of various bio-active constituents like alkaloids, glycosides, flavonoids, saponins, tannins, steroids and terpenoids was detected [30]. The hydro-alcoholic extracts of plant parts like leaf and stem-bark of *P. cineraria* were investigated by trypan blue exclusion method and MTT assay to explore the cytotoxic effects against human cancer cell lines such as HeLa and MCF-7. Hence, it was postulated that the plant extracts of the plant possess potent anticancer activity [31].

The extract (methanolic) obtained from the stem-bark of *P. cineraria* was evaluated for hepatoprotective activity and the study revealed that the extract rendered protection to the hepatic cells against carbon tetrachloride induced hepatotoxicity [32]. Numerous phytoconstituents like tannins, steroids, flavone derivatives (namely Prosogerin A, B, C & E), Rutin, Patulitrin, Luteolin, Patuletin, alkaloids etc. have been isolated from various parts of this medicinal plant [33]. Two new compounds methyl 5-tridecyloctadec-4-enoate and nonacosan-8-one, together with three known compounds (lupeol, β-sitosterol and stigmasterol) were isolated from chloroform fraction of *P. cineraria* stem bark. The chloroform fraction of stem bark was investigated in STZ-stimulated experimental diabetic rats, at doses of 50 and 100 mg/kg b.w. for 21 days. A marked reduction in blood glucose levels, glycosylated haemoglobin was observed, and it was also able to restore body weight, liver glycogen content and serum insulin level in diabetic rats, in a dose-dependent manner. Furthermore, a decrease in serum lipid profile and elevation in HDL after administration of the chloroform fraction was found, revealing that chloroform fraction has potential to protect from "diabetes-associated" complications [34].

E. Pharmacological activities of Prosopis cinerari

Anti-bacterial Activity

Stem-bark extracts (aqueous and methanolic) of *Prosopis cineraria* exhibited antibacterial potential at 250 µg/ml in comparison with Ciprofloxacin (Standard at 100mg/ml) against eight bacterial strains- *Streptomyces griseus*, *Salmonella typhi*, *Bacillus subtilis*, *Bacillus Lintus*, *Staphylococcus aureus*, *Klebsiella pneumonia*, *Staphylococcus albus*, *Escherichia coli*. Significant potent action of methanolic extract of the plant has been analyzed against all pathogens. It was postulated that flavonoids and tannins contribute and render the antibacterial activity to *Prosopis cineraria*. Antimicrobial potential of different extracts of dried unripe pods of *P. cineraria* was investigated by using the method-Agar well diffusion. However, negligible activity was reported by petroleum ether extract [35].

Anti-hyperglycaemic Activity

Prosopis cineraria has significant capacity in lowering the levels of blood sugar. Numerous studies were investigated and on the basis of the research study it has been postulated that the reduction in body weight and elevation in blood sugar level in diabetic rats were normalized when the extract of *Prosopis cineraria* was administered. *Prosopis* extracts presumably restore the survival of the β cells of the islets of langerhans and thereby, blood sugar level is lowered down by generating an "insulin genic effect." The reduction in body weight isprominently because of heightened glucose uptake in muscles which results in preventing tissue loss [36]. Hydro-alcoholic extract (50%) of *P. cineraria* stem bark was researched for its "anti-hyperglycaemic activity" by using Alloxan induced Hyperglycaemia Model. The research study was conducted by administering orally plant extract at the dose of 300 mg/kg body weight to hyperglycaemic mice once in a day for 45 days. It was reported that the fasting blood glucose level was lowered down by 27.3%, in comparison to that of standard glibenclamide which rendered 49.3% decline and the content of liver glycogen was significantly elevated in comparison to the control group. Loss of body weight in experimental mice was managed (significantly) in comparison to control group. Reduced concentration of non-enzymatic antioxidants and activity of antioxidant enzymes were also restored by drug administration, thereby, curing the oxidative damage in the cells of experimental animals and hence pointing out the anti-diabetic and antioxidant activity of the extract [26].

Analgesic Activity

Ethanol, ethyl-acetate, Petroleum ether extracts of stem bark were prepared (by soxhlet apparatus). Among the studied extracts- ethanolic extract was studied to possess significant analgesic activity when evaluated by using Eddy's hot plate model at a dosage of 300 mg/kg body weight in rats. Petroleum ether extract showed a significant antipyretic activity using Brewer's yeast induced hyperpyrexia model at same dose [37]. Analgesic activity of aqueous extract of leaves by using glacial acetic acid (GAA) induced writhing test model was investigated. The analgesic activity of the extract exhibited at a dose of 200 mg/kg body weight of Swiss albino mice was found to be significant in comparison to control. The leaf extract analyzed by using Brewer's yeast induced hyperpyrexia model demonstrated a significant antipyretic activity at the dose of 200 mg/kg body weight [38].

Anti-convulsant Activity

Prosopis cineraria stem bark was evaluated against maximal electro shock (MES) and Pentylenetetrazole (PTZ) induced convulsions in Swiss albino mice to study anticonvulsant activity. It was unravelled that the methanolic extract suppressed hind-limb tonic extensions (HLTE), those induced by MES and a protective effect in PTZ-induced seizures in a dosage dependent manner was exhibited. Methanolic extract of the wonder tree, *Prosopis cineraria*, at doses of 200 and 400 mg/kg and standard Phenytoin (25 mg/kg) have shown significant decline in duration of convulsions [39].

Anti-oxidant Activity

Elucidation of anti-oxidant activity of different extracts of the leaves of *Prosopis cineraria,* scavenging capability of the plant extracts for radicals like DPPH, hydrogen peroxide, hydroxyl, superoxide, nitric oxide and ABTS were performed. It was revealed that the leaves extract of *P. cineraria* which is a storehouse of numerous compounds that are capable of donating hydrogen to a free radical for the removal of odd electron which is detrimental for radical's reactivity. Six extracts of leaves of *P. cineraria* were analyzed and among them ethyl acetate and methanolic extracts showed maximum scavenging activity followed by chloroform and aqueous extracts [40].

Apoptotic Activity

Methanolic extract of the leaves of the wonder tree, *P. cineraria*, was analyzed in non cancerous cell line HBL 100 and breast cancer cell line MCF -7. Various staining techniques were adopted namely, ethidium bromide, Giemsa, Propidium iodide and Hoechst both in cancerous and noncancerous cell line. The plant extract rendered a steep elevation in apoptotic ratio in cancer cell line in contrast to HBL 100. This study unravelled that *P. cineraria* leaves possess the ability to inhibit the proliferation of MCF-7 breast cancer cells by involving apoptosis or programmed cell death. *P. cineraria* is a promising anti-cancer agent in treatment of cancer [41].

Anti-tumor Activity

Extract of leaves and bark (hydro-ethanolic) of *P. cineraria* were examined for anti-tumor activity against Ehrlich ascites carcinoma tumor model. Both the extracts of the plant at doses of 200 and 400 mg/kg body weight exhibited significant antitumor activity [42]. The extract (methanolic) of leaves of *P. cineraria* was investigated for ameliorative potential against *N*-nitrosodiethylamine (DEN, at dose of 200 mg/kg) induced experimental liver tumours developed in male Wistar rats. Treatment with DEN has elevated the lipid peroxidation (LPO) levels in mitochondria and weight of the liver which was reduced by the treatment of extract (200 and 400 mg/kg) in dose-dependent manner. Levels of CAT, SOD, GPx and GSH increased in comparison to animals having liver tumours. The study revealed that extract of *P. cineraria* may attribute its curative activity by modulating the levels of lipid peroxidation and activating antioxidant defence system [43].

F. Prospective of Phyto-therapeutic Application of Prosopis cineraria

In recent years it has been witnessed, that the research for drugs derived from plants has increased tremendously, due to the growing usage of plant-based medicines and their worldwide increasing popularity. The available research data on *Prosopis cineraria* provides sufficient experimental support for the clinical development of *P. cineraria*, a potential herb, as adjuvant therapy. Thus, given the literature reports, *Prosopis* has positive impact on the human diet and general health. In this sense, the present review provides an in-depth overview of the literature data regarding *Prosopis* plant's chemical composition, pharmacological and food applications, covering from pre-clinical data to upcoming clinical studies.

The analysis of the literature reports markedly highlights the promising beneficial health effects of *Prosopis cineraria*, given the advances reached with concerns to their biological activities. The multiple pre-clinical studies conducted so far clearly emphasize the use of *Prosopis* as a rich source of extremely useful phytochemicals, particularly phenolic compounds. In addition, clinical studies are extremely scarce to effectively support the pharmacological effects of *P. cineraria*. On the other hand, despite their traditional uses, toxicological reports available advice for more in-depth studies on this matter to improve the overall knowledge, safety windows, quality and widespread use of the plant. Thus, more in-depth pre-clinical studies are needed to further support and confirm the effective biological effects of *Prosopis* with scientific evidence.

P. cineraria successfully fulfil the criteria and can be considered for the development of plant-based medicines due to its potent therapeutic potential, and also its easy availability. Many researchers have attempted to draw the attention towards this beneficial tree for the development of phytomedicines. The pharmacological activities of *P. cineraria* could be associated, towards a possibility of its incorporation into the present healthcare system.

III. ACKNOWLEDGMENTS

The authors express their sincere gratitude to all researchers and scholars whose work has contributed to the understanding of *Prosopis cineraria* and its medicinal significance. We also extend our appreciation to our colleagues for their valuable guidance, constructive suggestions, and encouragement throughout the preparation of this chapter. Finally, we acknowledge the support of our families and institutions, whose constant encouragement has enabled us to do this work.

REFERENCES

[1] Nandkarni KM. (2000) Indian Materia Medica, Vol. 1, Popular Prakashan, Mumbai.
[2] Felekar P, Bandurski RS. (1979) Use and potential of leguminous trees for minimal energy input. Agriculture Economic Botany; 33: 172-84.
[3] Mahoney D. (1990) Trees of Somalia- A field guide for development workers. Oxfam/HDRA, Oxford; 133-136.
[4] Gupta RK, Prakash I. (1975) Environmental analysis of the Thar Desert. English Book Depot, Dehradun.
[5] Pareek AK, Garg S, Kuma M. (2015) *Prosopis cineraria*: a gift of nature for pharmacy. Int. J. Pharma Sci. Res; 6(6): 958-64.
[6] Jongbloed MVD, Feulner GR, Böer B, Western AR, Environmental Research and Wildlife Development Agency. (2003) The comprehensive guide to the wild flowers of the United Arab Emirates. Environmental Research and Wildlife Development Agency (ERWDA), Abu Dhabi, 1–574.
[7] Ansari SH. (2006) Essentials of pharmacognosy, 1st ed. Birla publications Pvt. Ltd.New Delhi.
[8] Sharma RC, Zaman A, Kidwai AR. (1964) Chemical examination of *Prosopis spicigera* Linn. Indian J Chem; 2(2): 83-4.
[9] Bhardwaj DK, Bisht MS, Mehta CK, Sharma GC. (1979) Flavonoids of *Prosopis spicigera* flowers. Phytochemistry; 18: 355-66.
[10] Jewers K, Nagler MJ, Zirvi KA, Amir F. (1976) Lipids, sterols and a piperidine alkaloid from Prosopis SPICIGERA leaves. Phytochemistry; 15: 238-40.
[11] Malik A and Kalidhar S. (2007) Phytochemical examination of *Prosopis cineraria* L. (druce) leaves. Indian Journal of Pharmaceutical Sciences; 69(4): 576–78.
[12] Bhardwaj DK, Gupta AK, Jain RK, Sharma GC. (1981) Chemical examination of *Prosopis spicigera* seeds. J NAT Prod; 44(6): 656-59.
[13] Ukani MD, Limbani NB, Mehta NK. (2000) A review of ayurvedic herb *Prosopis cineraria* (L) druce. Anc. Sci. of Life; 20(1): 1-13.
[14] Bhardwaj DK, Bisht MS, Jain RK. (1980) Prosogerin-D, a new flavone of *Prosopis spicigera* seeds. Phytochemistry; 19: 1269-70.
[15] Bahuguna Upendra, Shukla RN. (2010) A study on investigation of the chemical constituents and milled wood lignin analysis of *Lantana camara* and *Prosopis chinnsis*. International Journal of Applied Biology and Pharmaceutical Technology: 1(3): 830-835.
[16] Felekar P, Bandurski RS. (1979) Use and potential of leguminous trees for minimal energy input. Agriculture Economic Botany; 33: 172-84.
[17] Velmurugan V, Arunachalam G, Ravichandran V. (2011) Anthelmintic potential of *Prosopis cineraria* (Linn.) druce stem barks. Asian J Plant Sci Res; 1(2): 88-91.
[18] Kirtikar KR, Basu BD. (1984) Indian Medicinal Plants, International Book Distributors; 2, Dehradun, India.
[19] Velioglu YS, Mazza G, Gao L, Oomah BD. (1998) Antioxidant Activity and Total Phenolics in Selected Fruits, Vegetables and Grain Products. J Agric Food Chem; 46: 4113-7.
[20] USNAS (1980) United States National Academy of Sciences. Firewood Crops: Shrub and Tree species for energy production. Washington DC: National Academy Press: 150-1.
[21] Khan ST, Riaz N, Afza N *et al.* (2006) Studies on the chemical constituents of *Prosopis cineraria*, J. Chem Soc. Pak; 28(6): 619–22.
[22] Leakey RRB, Last FT. (1980) Biology and potential of *Prosopis* species in and environments with particular reference to *P. cineraria*. J Ari. Environ; 3: 9-24.
[23] Alkaabi DS, Gasmelbari ME, H Abumukhaimar NA, A/Futuh Shandal IM. (2020) Antimicrobial activity of United Arab Emirates indigenous medicinal plants Prosopis cineraria, Prosopis juliflora and Acacia tortilis. Hamdan Med J; 13: 110-4.
[24] Deka B, Babu A, Sarkar S *et al.* (2020) Role of prosopis juliflora as a botanical synergist in enhancing the efficacy of neem kernel powder against tea red spider mites, Olingonychus coffeae. SN Appl. Sci. 2: 582

[25] Ram Heera, Noopor Jaipal, Jaykaran Charan *et al* (2020) Phytoconstituents of an ethanolic pod extract of *Prosopis cineraria* triggers the inhibition of HMG-CoA reductase and the regression of antherosclerotic plague in hypercholesterolemic rabbits. Lipids in Health ad Disease; 19: 6.
[26] Sharma N, Garg V, Paul A. (2010) Antihyperglycemic, antihyperlipidemic and Ant oxidative Potential of *Prosopis cineraria* bark. Imdian J Clin Biochem; 20(2): 193-200.
[27] Khatri A, Rathore A, Patil UK. (2012) Assessment of anti-inflammatory activity of bark of *Prosopis cineraria* (L.) Druce. Int J Pharm Res; 4(2): 27-9.
[28] Sachdeva S, Kaushik V, Saini V. (2014) A review on phytochemical and pharmacological potential of *Prosopis cineraria*. Int J Ethnobiol Ethnomed; 1(1): 1-4.
[29] Liu Y, Singh D, Nair MG. (2012) Pods of khejri (*Prosopis cineraria*) consumed as a vegetable showed functional food properties. Journal of Functional Foods; 41(1): 16-121.
[30] Mohammad IS, Haji Muhammad, Shoaib Khan NA, Rasool F. (2013) Biological potential and phytochemical evaluation of *Prosopis cineraria*. World Appl Sci J; 27: 1489–94.
[31] Robertson S, Narayanan N. (2014) Isolation and characterization of secondary metabolite from *Prosopis cineraria* (L.) Druce for anticancer activity. World J Pharm Res; 3: 876–84.
[32] Velmurugan V, Arunachalam G. (2014) Hepatoprotective activity of methanol extract of stem bark of Prosopis cineraria Linn against carbon tetrachloride induced hepatotoxicity. Int J Pharm Sci; 6 (2): 491-503.
[33] Garg A, Mittal SK. (2013) Review on *Prosopis cineraria*: A potential herb of Thar desert. Drug invent. today; 5: 60-5.
[34] Soni LK, Dobhal MP, Arya D *et al*. (2018) In vitro and in vivo antidiabetic activity of isolated fraction of Prosopis cineraria against streptozotocin-induced experimental diabetes: A mechanistic study. Biomedicine and Pharmacotherapy; 108:1015-21.
[35] Khandelwal P, Sharma RA, Agarwal M. (2015) Pharmacology, phytochemistry and therapeutic application of *Prosopis cineraria* linn: A review. J Plant Sci; 3(1-1): 33-9.
[36] Sharma D, Singla YP. (2013) Evaluation of antihyperglycemic and anti-hyperlipidemic activity of *Prosopis cineraria* (Linn.) in Wistar rats. J Sci Innov Res; 2: 751–58.
[37] Ramasamy VMM, Venugopalan R, Ramnathan SK, Perumal P, Chellapan DR. (2009) Analgesic and antipyretic activity of stem bark of *Prosopis cineraria* (Linn) Druce. J Pharm. Res; 2(4): 660-62.
[38] Joseph A, Li Y, Koo H C, Davis J M, Pollack S, Kazzaz J A (2008) Superoxide dismutase attenuates hyperoxia-induced interleukin-8 induction via AP-1. Free Radic Biol Med; 45: 1143-9.
[39] Velmurugan V, Arunachalam G, Ravichandran V. (2012) Anticonvulsant activity of methanolic Extract of *Prosopis cineraria* (Linn) Druce stem barks. Int J Pharm Tech Res; 4(1): 89-92.
[40] Dharani B, Sumathi S, Sivaprabha J, Padma PR. (2011) In vitro antioxidant potential of *Prosopis cineraria* leaves. J Nat Prod and Plant Resour; 1(3): 26-32.
[41] Sumathi S, Dharani B, Sivaprabha J, *et al*. (2013) Cell death induced by methanolic extract of *Prosopis cineraria* leaves in MCF-7 breast cancer cell line. Int J Pharmacol Sci Invent; 2: 21–6.
[42] Robertson S, Narayanan N. (2014) Isolation and characterization of secondary metabolite from *Prosopis cineraria* (L.) Druce for anticancer activity. World J Pharm Res; 3: 876–84.
[43] Maideen NM, Velayutham R, Manavalan G. (2012) Protective effect of *Prosopis cineraria* against N-nitrosodiethylamine induced liver tumor by modulating membrane bound enzymes and glycoproteins. Adv Pharm Bull; 2: 179.

Dr. Preeti Sharma, holds a Ph.D. in Biotechnology from Banasthali Vidyapith, Rajasthan. She is presently working as an Assistant Professor at Kumari Vidyawati Anand D.A.V. College for Women, Karnal for the past two years. She has also served as a Research Biologist for two years at Sphaera Pharma Pvt. Ltd., IMT Manesar after completing her Master's degree. Dr. Preeti Sharma has also been recognized for her contributions with awards and has publications in reputable and peer reviewed journals. Her expertise spans biotechnology, toxicology, immunology and pharmacology

Ms. Chetna is an Assistant Professor at Kumari Vidyawati Anand D.A.V. College for Women, Karnal with a post graduate degree in Microbiology from Kurukshetra University, Kurukshetra. Ms. Chetna has taken training from Kalpana Chawla Govt. Medical College, Karnal. Her core academic interests include Molecular Cell Biology, Recombinant DNA Technology, Pharmacology, and Microbiology.

WasteLens : Real-Time Waste Segregation and Eco-Guidance System

Hamza Ahmed[1], Aqeel Khalique[2], Asfia Aziz[3], Imran Hussien[4]
Department of CSE, Jamia Hamdard, New Delhi, INDIA
Email: [1]hamzaahmed23098@gmail.com
[2]aqeelkhalique@gmail.com
[3]asfiaaziz@jamiahamdard.ac.in
[4]ihussain@jamiahamdard.ac.in

Abstract. Waste management remains among the most chronic environmental challenges the world is facing, partly due to the incorrect segregation of household and public waste. Improper segregation of recyclables, organic matter, and hazardous materials increases landfill load and is leading to pollution and resource losses. In that regard, this project proposes WasteLens, an AI-driven mobile solution for identifying the category of waste instantly with a smartphone camera. By incorporating computer vision and deep learning, the captured images of waste are analyzed and classified into appropriate disposal categories such as recycling, compost, landfill, and special waste. WasteLens will provide real-time disposal guidance and reinforce correct behavior through gamification: users receive eco-tokens, carbon-savings visibility, levels, and achievements based on their recycling activity. Later, tokens can be redeemed for rewards to keep participation going. The system keeps track of user performance over time and is able to present personalized statistics and environmental insights for raising long-term awareness. Given the application's purpose, this lightweight model, based on CNN and using FastAPI, allows efficient processing on cloud infrastructure while guaranteeing smooth performance on mobile devices; hence, this is quite feasible on low-end hardware too. Given this, the combination of real-time recognition, behavioral motivation, and sustainability education make WasteLens different from the so-called traditional waste management apps.
Keywords: Waste segregation; AI-based waste recognition; Computer vision; Deep learning; Sustainability; Gamification; Real-time image processing; Smart waste management; Mobile application; Recycling guidance.

I. INTRODUCTION

Waste segregation is a major challenge that faces environmental sustainability at household, institutional, and public space levels. Most people do not know how to dispose of items correctly, thus making recyclable items end up in landfills, hazardous items enter general waste streams, and compostable materials fail to return into the ecological cycle. The lack of awareness not only increases landfill use but also contributes to pollution, extra carbon emissions, and the unnecessary use of natural resources.

To address this deficit, WasteLens brings a new, technologically fitting way of waste management. WasteLens is a mobile AI system that allows its users to identify the correct disposal category of waste by simply taking a picture of the item using their smartphone camera. The platform, with the help of computer vision and deep learning, will analyze the captured picture in less than a second and classify the item into pre-set categories such as recyclables, compost, landfill, and special waste along with an appropriate disposal instruction. That changes segregation of waste from a guessing game into a fast, guided, and reliable process. By combining **artificial intelligence, behavioral psychology, and mobile accessibility**, WasteLens presents an innovative solution that benefits both users and the environment. The platform promotes sustainability not through enforcement, but through **education, motivation, and convenience**, making waste segregation easy, engaging, and impactful for people of all ages Users receive tokens for every correct disposal action, experience levels, and achievements. It also tracks progress over time, showing carbon saved and total items recycled. These data-driven feedback loops support behavioral change, enabling people to make environmentally conscious choices consistently.

II. METHODOLOGY

The WasteLens approach takes a clear step by step path to create an AI based system. It picks out different kinds of waste and makes the whole recycling process feel like a fun game. This setup involves creating a mobile app, working on machine learning features, designing ways to keep users involved, and handling the backend side of things. All these parts connect in a smooth integrated way. That leads to a really seamless experience for users. They end up sorting their waste in a smart intelligent fashion.

2.1. Data Acquisition and Pre-Processing

The team collected a massive waste image dataset. Images were from the internet, open datasets, and ones captured by themselves. Each had a label matching the correct disposal method of an item. Disposal options covered recycling, composting, landfill placement, or special handling needs. Such techniques helped the model generalize well for variable lighting conditions and various backgrounds.

2.1.1 Convolution Operation (Image Feature Extraction)

WasteLens uses convolutional layers to extract spatial features (edges, textures, shapes) from waste images:

$$F(i,j) = \sum_m \sum_n I(i+m, j+n) \cdot K(m,n) \qquad (1)$$

Where:

- I = input image
- K = convolution kernel (filter)
- F = feature map produced after convolution

This helps the model understand high-level patterns to differentiate objects like **plastic bottle, glass jar, paper, food waste, etc.**

2.2. Model Training for Waste Classification

This involved some fine-tuning of parameters such as the learning rate, batch size, and number of epochs while tracking key metrics such as precision, recall, and the F1-score as part of the step-by-step refinement of the classifier.

2.2.1. Model Training Loss Function (Categorical Cross-Entropy)

To minimize prediction error during training:

$$L = -\sum_{i=1}^{N} \sum_{c=1}^{K} y_{i,c} \log(\hat{y}_{i,c}) \qquad (2)$$

Where:

- N = number of training samples
- $y_{i,c}$ = true label (1 if class matches, otherwise 0)
- $\hat{y}_{i,c}$ = predicted probability

Fig. 1. Training and validation loss/accuracy curves illustrating model convergence and performance improvement during training

2.3 Backend deployment and cloud integration.

The service came together using FastAPI and Python. It takes in images from the mobile app. Or it gets them from the React web interface. From there, it runs those images through the AI model plus recommended bin type and disposal tips.

2.4. Mobile/Web Application Development

Frontend development was based on React and React Native frameworks. These made it easy for the user to scan waste items with their phone cameras. The interface kept things simple and intuitive overall.

2.5 Gamification and Reward Engine

The system has an incentive mechanism for encouraging good waste-management behavior. Tokens and points are awarded every time users correctly sort items. These, in turn, allow the user to level up, collect badges, and unlock achievements. It monitors user history down to the tiniest details, and one can access a weekly performance dashboard. With such features, it motivates ongoing participation and gradual improvement in habits.

2.6 Dataset Used

High-resolution images of common household and public waste items were obtained from recycling centers, public datasets, and manually captured samples. Each was categorized into specific disposal classes, Recyclable, Compost, Landfill, and Hazardous/Special Waste, thereby supporting multi-class classification**.** The improvement in generalization and reduction in overfitting were ensured by considering rotation, flipping, zooming, contrast enhancement, and noise injection for data augmentation. The dataset finally obtained was split into training, validation, and testing subsets for subsequent performance evaluation and fair benchmarking. This diverse and quality-controlled dataset helps the deep learning model to recognize waste items with ease and enable proper waste disposal suggestions in real time.

Table 1. Category-wise Dataset Breakdown

Class / Waste Type	**Total Images**	**Percentage (%)**	**Notes**
Recycling	15,820	37.5%	Includes paper, plastic, metal, cardboard, cans
Compost	8,960	21.2%	Organic food waste, leaves, biodegradable materials
Landfill	11,210	26.6%	Non-recyclable household waste, mixed plastic, wrappers
Special Waste	6,160	14.6%	Batteries, electronics, bulbs, medical waste

2.7 Tools and Technology

The WasteLens system pulls together a bunch of modern tools for development, along with machine learning setups and cloud services. This way, it hits high accuracy levels and feels easy to use overall. They built the frontend web app with React.js, which handles responsive interfaces pretty well. Over on the mobile side, React Native lets them use one codebase that works on both Android and iOS. The backend API runs on FastAPI, picked for its speed and how it manages async requests smoothly. PyTorch handles the deep learning part, especially with computer vision models. For classifying waste through AI, they trained on large datasets that were already annotated. PostgreSQL takes care of data storage, keeping things secure and able to scale up. SQLAlchemy helps out with managing database tasks efficiently. Then there are extras like GitHub for tracking versions, Docker to containerize everything for deployment, and tools such as VS Code or Jupyter Notebook for coding and testing ideas.

2.8 Confusion Matrix

Table 2. A confusion matrix is used to analyze classification performance per class

	Predicted: Recycle	**Predicted: Compost**	**Predicted: Landfill**	**Predicted: Special**
Actual: Recycle	TP	FP	FP	FP
Actual: Compost	FN	TP	FP	FP
Actual: Landfill	FN	FP	TP	FP
Actual: Special	FN	FP	FP	TP

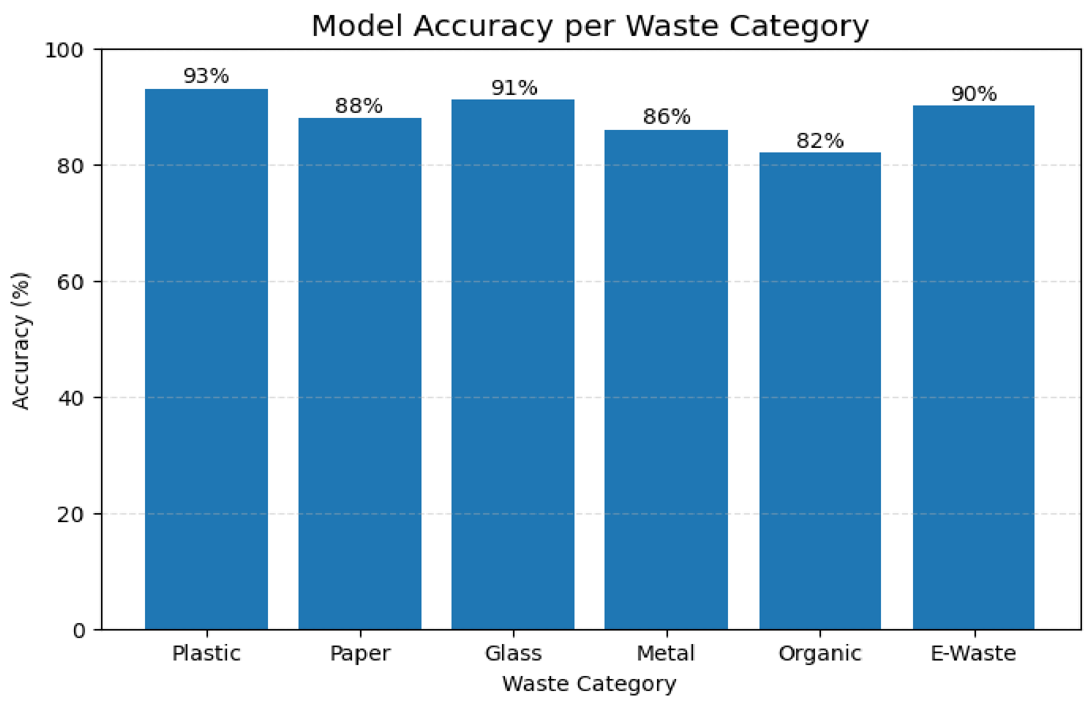


Fig. 2. Bar chart showing the model's accuracy per waste categories

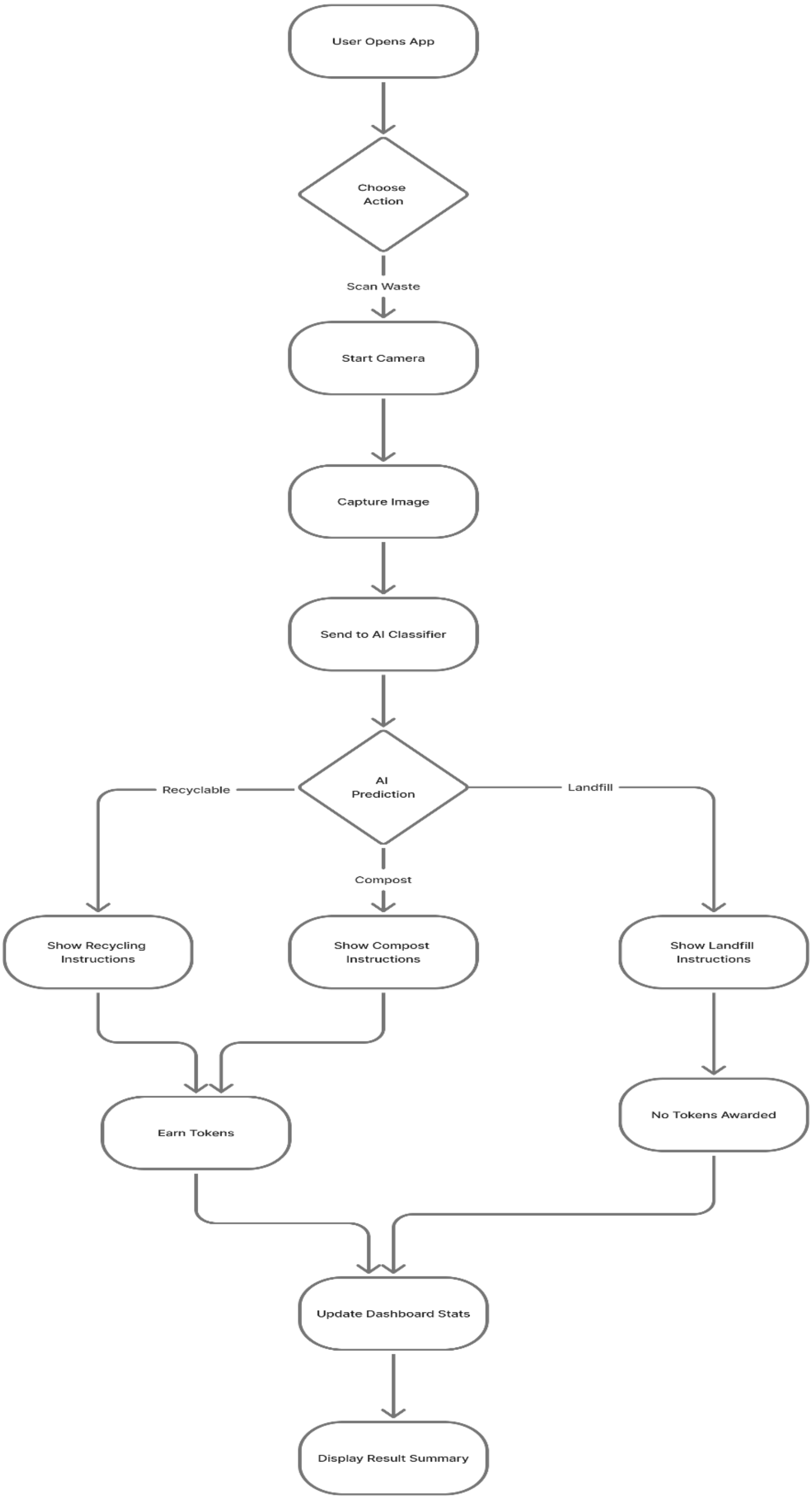


Fig. 3. Shows the architecture of the Wastelens

III. RESULTS

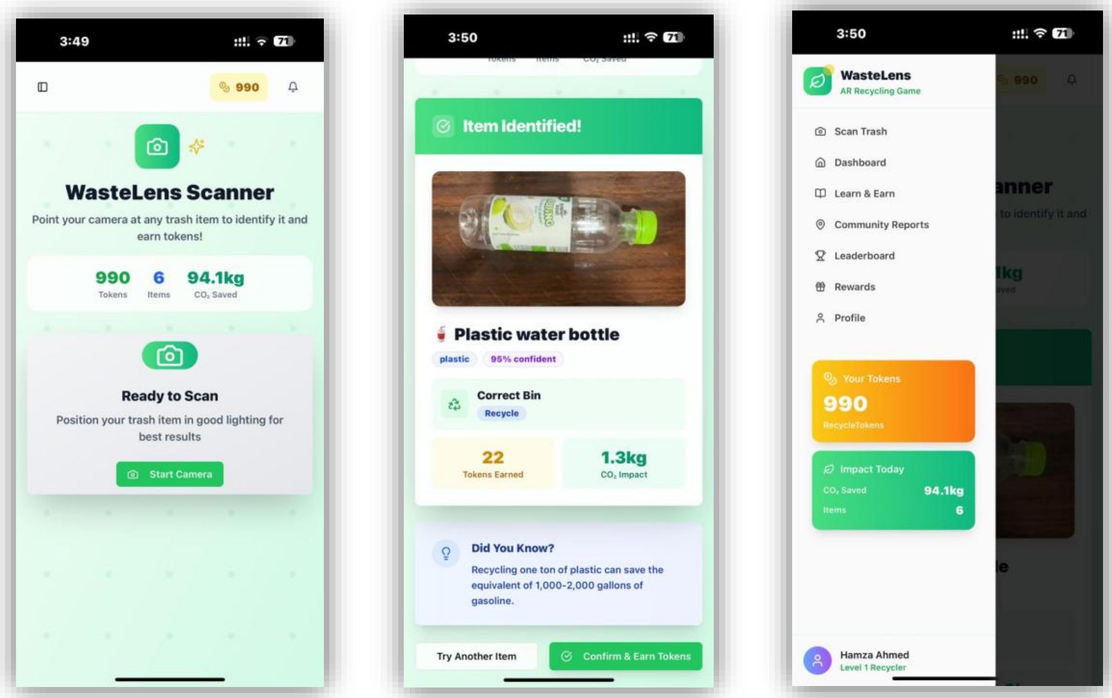


Fig. 4. Shows how the trash is scanned and rewards are earned

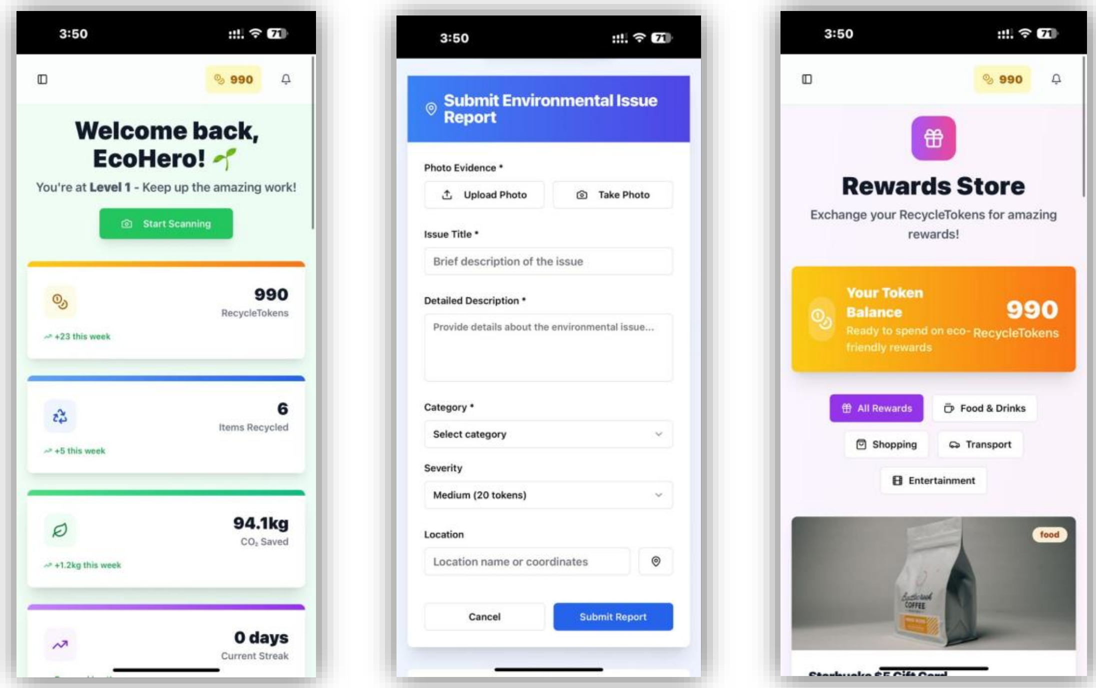


Fig. 5. Shows the Reward System for the Carbon points earned

IV. CONCLUSION

WasteLens really shows how artificial intelligence, computer vision, and modern web technologies can change everyday waste disposal into something smart, guided, and even fun. The system pulls together real-time image classification with a user interface that feels straightforward. It spots all sorts of waste items and gives quick, spot-on advice for getting rid of them right. That setup not only boosts how people recycle on their own. It also cuts down on mix-ups in waste streams. Those mix-ups happen to be one of the biggest reasons recycling programs fall short. The project goes further than just sorting things out. Mixing AI insights with designs that motivate behavior creates a strong tool. That tool can push for real changes in the environment.

The setup for the system includes a frontend built on React, a backend with FastAPI, and deep learning models. It keeps things modular, easy to scale, and ready for actual use. Plus, it leaves room to add on stuff like community reports, estimates of CO2 savings, custom learning parts, and reviews of past performance.
In the end, WasteLens delivers a solid, easy-to-use fix for the worldwide mess of waste handling. It teaches people along the way, cuts out mistakes from human slip-ups, and builds good habits through digital interactions that pull you in. That makes WasteLens look like a solid tech step toward cleaner living and better sustainability.

REFERENCES

[1]. M. A. Memon, S. A. Mirani, and A. A. Channa, "AI-driven waste classification using deep convolutional neural networks," *IEEE Access*, vol. 9, pp. 125601–125614, 2021.
[2]. S. S. Chowdhury, M. Kumar, and P. Mahajan, "Automated waste segregation using image processing and machine learning," *Proc. IEEE Int. Conf. Sustainable Development (ICSD)*, pp. 408–414, 2022.
[3]. T. B. Nguyen, N. T. Tran, and K. C. Ngo, "Deep learning-based garbage detection for smart waste management," *IEEE Sensors Journal*, vol. 22, no. 12, pp. 12433–12441, 2022.
[4]. J. Yang and L. Xu, "Real-time recyclable waste identification using transfer learning with CNNs," *Proc. IEEE Int. Conf. Image Processing (ICIP)*, pp. 2436–2441, 2020.
[5]. A. Mittal and K. Sinha, "Gamification in sustainability: Encouraging eco-friendly habits through reward-based systems," *Proc. IEEE Int. Conf. Human–Computer Interaction (HCI)*, pp. 645–652, 2020.
[6]. F. Li et al., "Mobile-based environmental education using gamified recycling applications," *IEEE Trans. Learning Technologies*, vol. 15, no. 1, pp. 89–101, 2022.
[7]. J. Redmon and A. Farhadi, "YOLO: Real-time object detection," *Proc. IEEE Conf. Computer Vision and Pattern Recognition (CVPR)*, pp. 779–788, 2017.
[8]. K. He, X. Zhang, S. Ren, and J. Sun, "Deep residual learning for image recognition," *Proc. IEEE CVPR*, pp. 770–778, 2016.
[9]. C. Ledig et al., "Photo-realistic single image super-resolution using GANs," *Proc. IEEE CVPR*, pp. 4681–4690, 2017.
[10]. X. Wang et al., "ESRGAN: Enhanced super-resolution generative adversarial networks," *Proc. European Conf. Computer Vision Workshops (ECCV-W)*, pp. 63–79, 2018.
[11]. X. Wang et al., "GFPGAN: Toward real-world blind face restoration," *Proc. IEEE Int. Conf. Computer Vision (ICCV)*, pp. 2889–2898, 2021.
[12]. Z. Tan and M. Jiang, "Mobile vision systems for real-time waste classification using TensorFlow Lite," *IEEE Access*, vol. 10, pp. 54092–54104, 2022.
[13]. A. Rahman et al., "Cloud-backed AI model deployment for IoT-based waste bins," *Proc. IEEE Int. Things Conf. (IoT)*, pp. 399–405, 2021.
[14]. M. J. Khan et al., "Dataset for recyclable waste classification," *Kaggle*, 2020. [Online]. Available: https://www.kaggle.com/datasets
[15]. G. Thung and M. Yang, "Dataset for garbage classification," *GitHub*, 2016. [Online]. Available: https://github.com/garythung/trashnet
[16]. F. Chollet, *Deep Learning with Python*, 2nd ed. Manning Publications, 2021.
[17]. "TensorFlow: Large-scale machine learning framework," *Google AI*, 2023. [Online]. Available: https://www.tensorflow.org/
[18]. "PyTorch: Deep learning framework," *Meta AI*, 2023. [Online]. Available: https://pytorch.org/
[19]. "React Native – Build mobile apps for Android and iOS," *Meta Open Source*, 2023. [Online]. Available: https://reactnative.dev/
[20]. "FastAPI – Modern web framework for ML deployment," *FastAPI Documentation*, 2023. [Online]. Available: https://fastapi.tiangolo.com/

Machine Learning for Securing Healthcare IoT Systems: A Review and Risk Mitigation Approaches

Maryam Saud[1], Heena Shaikh[2], Asfia Aziz[3], Aqeel Khalique[4], Imran Hussain[5]
Department of Computer Science and Engineering, SEST, Jamia Hamdard
(E-mail:[1]rahman.maryamsaud@gmail.com, [2]heenashaikh8331@gmail.com, [3]asfiaaziz@jamiahamdard.ac.in, [4]aqeelkhalique@gmail.com, [5]ihussain@jamiahamdard.ac.in)

***Abstract*—**The Fast-Expanding of Healthcare Internet of Things (H-IoT) systems metamorphosed patient monitoring and medical decision-making through ongoing data collection and real-time analytics. Nevertheless, the connection of medical devices and networks exposes sensitive patient data to increasing cyber threats. Machine Learning (ML) and Deep Learning (DL) have emerged as vital technologies for identifying, classifying, and mitigating security risks in H-IoT environments. This paper provides a detailed examination of ML-based security mechanisms designed to protect healthcare IoT infrastructures, highlighting threat types, attack detection models, privacy-preserving approaches, and risk mitigation strategies. The study also examines recent advancements such as federated learning and blockchain-assisted frameworks for secure data management. Finally, the paper outlines open challenges and suggests future research directions toward more secure, resilient, and explainable healthcare IoT systems.

Keywords—*Healthcare IoT, Machine Learning, Intrusion Detection, Federated Learning, Privacy Preservation, Risk Mitigation.*

I. INTRODUCTION

The Healthcare Internet of Things (H-IoT) combines medical sensors, wearable devices, and cloud-based services to elevating diagnostic precision and patient safety. Devices intrinsically ECG monitors, insulin pumps, and smartwatches continuously collect and transmit data to healthcare systems appropriate decision-making. While these technologies enhance clinical efficiency, they also maximise exposure to cyber risks such as data breaches, malware attacks, and unauthorized access.

Contrasting traditional IT systems, healthcare IoT devices are resource strained and usually operate on legacy firmware, making them vulnerable to attacks. Compromised devices can lead not only to privacy violations but also to life-threatening outcomes. Recent reports of susceptibility in connected medical devices have raised concerns about the reliability of such systems.

Machine learning provides a versatile solution to these problems by enabling predictive, behaviour-based, and anomaly-aware security monitoring. ML algorithms can identify unusual network activity, classify malicious patterns, and predict potential threats with higher precision than traditional rule-based systems.

This paper reviews the integration of ML into H-IoT security systems and evaluates its role in minimizing cybersecurity risks.

II. RESEARCH METHODOLOGY AND SCOPE

This review examines research published between **2018 and 2025** across IEEE Xplore, Elsevier, SpringerLink, and MDPI.
Search terms included: *"Machine Learning in Healthcare IoT Security," "Intrusion Detection IoT," "Federated Learning in Medical Systems,"* and *"Blockchain for Healthcare Data Security."*
From an initial pool of 120 articles, 40 high-impact studies were selected based on:

- Relevance to healthcare IoT,
- Application of ML/DL for security or privacy,
- Experimental validation, and
- Inclusion of mitigation or risk management techniques.

The focus areas include intrusion detection, authentication, data integrity, privacy preservation, and federated learning for distributed healthcare systems.

III. THREAT LANDSCAPE IN HEALTHCARE IOT

Healthcare IoT systems face threats at multiple architectural layers — device, network, and application.

a. Device Layer Threats

- Firmware attacks: Exploiting outdated or unpatched firmware.
- Malware infections: Injecting malicious code to manipulate readings or control devices.
- Physical tampering: Unauthorized access to sensors or ports.

b. Network Layer Threats

- **Denial of Service (DoS)**: Overwhelming network bandwidth, disrupting communication.
- **Man-in-the-Middle (MITM)**: Intercepting and altering communication between devices.
- **Spoofing**: Faking device identities to steal credentials or inject false data.

c. Application Layer Threats

- **Data leakage** from insecure APIs or cloud misconfigurations.
- **Unauthorized access** to patient records.
- **Privacy violations** due to weak encryption or improper authentication.

These vulnerabilities highlight the urgent need for intelligent, adaptive, and real-time security mechanisms — which ML-based models can deliver effectively.

IV. MACHINE LEARNING TECHNIQUES FOR H-IOT SECURITY

a. Intrusion Detection Systems (IDS)

Intrusion Detection is one of the most researched ML applications in IoT security. Algorithms such as Support Vector Machines (SVM), Random Forests, and Deep Neural Networks are trained on network traffic to classify malicious behaviors.

- Supervised learning uses labeled datasets (e.g., NSL-KDD, Bot-IoT) for known attacks.
- Unsupervised learning (e.g., K-Means, Autoencoders) detects unknown anomalies without labeled data.

Example: CNN-based IDS models can achieve >97% accuracy in detecting botnet attacks while maintaining low false-positive rates.

b. Authentication and Access Control

Machine learning models are increasingly employed to identify abnormal login behaviours and detect device recognize spoofing.

- Behavioural Biometrics: Keystroke dynamics and sensor interaction patterns are analysed to authenticate users with higher precision.
- Device Fingerprinting: ML classifiers learn distinctive communication and transmission characteristics to validate legitimate IoT nodes.

These approaches reduce dependence on conventional password-based mechanisms, thereby enhancing both usability and overall security posture.

c. Privacy-Preserving Learning

Healthcare data is inherently sensitive and subject to strict regulatory frameworks such as HIPAA and GDPR. Centralized machine learning workflows can inadvertently expose private information; therefore, Federated Learning (FL) enables decentralized model training across multiple healthcare institutions without transmitting raw patient data.

Enhancements include:

- Differential Privacy: Introduces statistical noise into model gradients or updates to safeguard individual identity.
- Blockchain-Integrated FL: Utilizes distributed ledger mechanisms to ensure transparency, traceability, and immutability of shared model contributions.

These techniques preserve data confidentiality while supporting collaborative, cross institutional security intelligence.

d. Malware and Threat Classification

Machine learning techniques are increasingly applied to classify malicious code embedded within IoT firmware using both static and dynamic analysis models.

Approaches include:

- Graph Neural Networks (GNNs): Used to analyse function-call graphs and identify structural anomalies indicative of malware.
- Recurrent Neural Networks (RNNs): Employed to capture temporal patterns in execution traces and detect evolving attack behaviours.

ML-driven malware analysis enhances the identification of novel or polymorphic variants while reducing reliance on frequent signature updates.

e. Edge Intelligence and Real-Time Detection

Deploying lightweight machine learning models on edge devices or fog nodes significantly reduces latency and minimizes bandwidth consumption.

Tiny ML frameworks enable on-device threat detection without requiring continuous cloud connectivity. Such real-time inference capabilities facilitate the immediate isolation of compromised or infected nodes—an essential requirement for maintaining security and operational continuity in hospital networks.

V. RISK MITIGATION STRATEGIES

Strengthening H-IoT security requires integrating machine learning solutions into comprehensive risk management and governance frameworks.

a. Secure Device Lifecycle Management

Implement digital signatures for firmware updates and enforce authenticated boot processes to ensure device integrity throughout the lifecycle.

b. Network Segmentation and Monitoring

Isolate medical IoT traffic from administrative and non-critical networks. • Deploy ML-based intrusion detection systems (IDS) at network gateways to identify anomalies within segmented traffic flows.

c. Federated Learning and Data Governance

- Combine Federated Learning with robust access-control policies to ensure regulatory data compliance.
- Employ blockchain mechanisms to provide transparent and tamper-resistant verification of model updates.

d. Incident Response Automation

Utilize ML-driven detection pipelines to generate early alerts for suspicious behaviours, reducing the mean time to detection (MTTD) and response.

e. Explainable AI (XAI)

Enhance interpretability of ML decisions, enabling clinical staff to understand alert rationale and reduce false positives.

f. Regulatory Compliance

Align ML-enabled security systems with cybersecurity standards and regulatory frameworks such as ISO/IEC 27001, NIST guidelines, and relevant FDA cybersecurity requirements.

VI. PERFORMANCE EVALUATION AND DATASETS

Evaluating ML-driven H-IoT security solutions requires access to representative datasets and the use of appropriate performance metrics.

a. Popular Datasets:

- UNSW-NB15: General IoT attack patterns and network traffic.
- BoT-IoT: Large-scale botnet and DDoS attack datasets.
- IoT-23: Malware samples and network anomalies specific to IoT environments.

b. Commonly Used Metrics:

- Accuracy, Precision, Recall, and F1-score
- False Positive Rate (FPR)
- Detection Latency (Time-to-Detect)

c. Challenges:

- Data imbalance, limited generalization, and scarcity of real-world clinical IoT datasets.
- Emerging solutions include synthetic data generation, domain adaptation techniques, and transfer learning to improve model robustness.

VII. FUTURE RESEARCH DIRECTIONS

a. *Adversarial Robustness:*

Develop ML models capable of withstanding evasion, poisoning, and other adversarial attacks in IoT environments.

b. *Explainability:*

Enhance transparency of AI-driven systems to build trust among clinicians, administrators, and regulatory bodies.

c. *Lightweight Models:*
Design computationally efficient algorithms tailored for resource-constrained IoT and edge devices.

d. *Standardization:*
Establish interoperable datasets, benchmarking tools, and evaluation protocols to ensure consistent model assessment.

e. *Integration with Blockchain and Federated Learning (FL):*
Strengthen decentralized trust, privacy preservation, and secure collaborative model updates.

f. *Real-World Validation:*
Conduct live deployment and testing of ML-based intrusion detection systems (IDS) in hospital networks to assess performance under operational conditions.

VIII. CONCLUSION

Machine Learning has shown great potential for enhancing the security of Healthcare IoT systems by enabling intelligent detection, prevention, and mitigation of cyber threats. However, current solutions face challenges in scalability, interpretability, and data privacy. Combining ML with federated learning, blockchain, and explainable AI can strengthen trust and compliance in medical IoT ecosystems.

Future work should emphasize realistic dataset creation, adversarial defense mechanisms, and integration of ML-based security with clinical safety protocols to build resilient and trustworthy healthcare IoT systems.

REFERENCES

[1] S. Madanian, M. Pinto, A. Smith, and R. Lee, "Health IoT threats: Survey of risks and vulnerabilities," *Future Internet*, vol. 16, no. 11, pp. 1–20, 2024.
[2] M. Pinto, L. Ferreira, J. Santos, and K. Wang, "Survey on intrusion detection systems based on machine learning for IoT," *Sensors*, vol. 23, no. 8, 2023..
[3] H. El-Sofany, M. Alshammari, A. Youssef, and S. Alghamdi, "Using machine learning algorithms to enhance IoT system security," *Scientific Reports*, vol. 14, no. 9, 2024.
[4] Z. Ngoupayou Limbepe, K. Omer, T. Li, and S. Zhang, "Blockchain-based privacy-enhancing federated learning for healthcare IoT," *Electronics*, vol. 13, no. 5, 2025.
[5] A. Kumar and P. Gupta, "Federated learning framework for secure IoT healthcare data," *IEEE Access*, vol. 12, pp. 47820–47834, 2024.
[6] E. Neto, M. Silva, F. Rodrigues, and A. Costa, "Review of ML-based IoT security in healthcare," *Computer Communications*, vol. 223, pp. 13–29, 2024.
[7] R. Raj and T. George, "Lightweight edge intelligence for medical IoT," *IEEE Internet of Things Journal*, vol. 11, no. 2, pp. 1345–1355, 2025.
[8] P. Ewoh, S. Johnson, and L. Carter, "Sociotechnical solutions for digital health cybersecurity," *Journal of Medical Internet Research*, vol. 26, 2024.
[9] K. Alqahtani, "Explainable AI for healthcare IoT anomaly detection," *IEEE Sensors Journal*, vol. 25, no. 7, 2025.
[10] U.S. Food and Drug Administration, *Cybersecurity in Medical Devices: Quality System Considerations*. Guidance Document, 2023.

AI-Powered Research Paper Analyzer: A Comprehensive Framework for Automated Academic Text Simplification and Insight Extraction

Mohammed Adil[1], Asfia Aziz[2], Aqeel Khalique[3], Imran Hussain[4]
Department of CSE, Jamia Hamdard, New Delhi, INDIA

Abstract The rapid proliferation of scientific literature in the twenty-first century has precipitated a crisis of information overload, creating substantial barriers to entry for students, early-career researchers, and interdisciplinary scholars. Traditional academic manuscripts are characterized by dense technical jargon, intricate methodological descriptions, and rigid structural formats that impose a high cognitive load on readers. This research presents the design, development, and evaluation of an AI-Powered Research Paper Analyzer, a novel computational system designed to automate the extraction, summarization, and simplification of academic texts. By integrating robust Python-based PDF processing libraries with the advanced natural language processing capabilities of Cohere's Large Language Model (LLM), the system provides a multi-faceted analysis of research documents. Key functionalities include the generation of concise abstractive summaries, the extraction of core findings, the simplification of domain-specific terminology, and the automated identification of citations. Furthermore, the system promotes critical engagement with the text by generating insightful questions based on the paper's content. The application is deployed via a Streamlit-based web interface, ensuring accessibility for non-technical users. This report details the architectural framework, methodological approach, and implementation strategies of the system, while also critically evaluating its performance against existing academic tools. The findings demonstrate that leveraging Generative AI for document analysis significantly reduces the time required for literature review and enhances comprehension.

Keywords Natural Language Processing, Large Language Models, Text Summarization, Academic Accessibility, PDF Extraction, Educational Technology, Human-Computer Interaction, Cohere API, Streamlit.

I. INTRODUCTION

The dissemination of scientific knowledge relies fundamentally on the publication of research papers, which serve as the authoritative record of discoveries, methodologies, and theoretical advancements across all academic disciplines. However, the sheer volume of global research output has reached unprecedented levels, with estimates suggesting that millions of new research papers are published annually. This exponential growth has created an information ecosystem where keeping abreast of the latest developments is a formidable challenge even for seasoned experts.[1] For undergraduate students and novice researchers, this challenge is compounded by the inherent complexity of academic writing. Research papers typically employ highly specialized vocabulary, assume significant prior knowledge, and utilize rigid structural formats that can obfuscate the core message for the uninitiated.[1]

The phenomenon of "information overload" in academia leads to several critical issues. First, the time required to manually screen, read, and comprehend papers for a literature review is often prohibitive, leading to superficial engagement with the source material. Second, the "knowledge gap" between experts and beginners widens as the barrier to understanding foundational texts increases. Third, interdisciplinary research is stifled when scholars from one field struggle to parse the technical lexicon of another. Consequently, there is a pressing need for intelligent computational tools that can bridge the gap between dense academic content and the reader's cognitive capacity.[1]

This research report introduces the **AI-Powered Research Paper Analyzer**, a comprehensive system designed to mitigate these challenges. Unlike traditional keyword-based search engines or basic metadata scrapers, this system leverages state-of-the-art Natural Language Processing (NLP) to perform semantic analysis of full-text documents. By utilizing the pdfplumber library for precise text extraction and the Cohere API for generative language tasks, the analyzer transforms static PDF documents into interactive, structured learning resources. The system automates labor-intensive tasks such as summarization, key finding extraction, and citation tracking, presenting the results in a user-friendly Streamlit dashboard.[1]

The primary objective of this work is to demonstrate the practical application of Large Language Models (LLMs) in the domain of educational technology. By decomposing complex research papers into digestible components, the system not only accelerates the research workflow but also supports pedagogical goals by scaffolding the learning process for students. This report provides an exhaustive account of the system's development, from the selection of software architecture to the fine-tuning of prompt engineering strategies, and concludes with a critical discussion of the tool's limitations and future potential.

II. PROBLEM STATEMENT AND RATIONALE

The core problem addressed by this research is the inaccessibility of technical academic literature for non-experts and the inefficiency of manual literature review processes. This problem is multifaceted, involving linguistic complexity, structural rigidity, and data volume.

2.1 The Complexity and Linguistic Barrier

Research papers are predominantly written *by* experts *for* experts. They frequently omit foundational explanations, relying on a shared lexicon that effectively excludes outsiders. For an undergraduate student or a researcher venturing into a new field, encountering terms such as "stochastic gradient descent," "polymerase chain reaction," or "eigenvector centrality" without immediate context can halt comprehension. The cognitive load required to constantly consult external dictionaries or textbooks disrupts the reading flow, leading to frustration and disengagement. This linguistic barrier is not merely a matter of vocabulary; it extends to the syntactic complexity of academic prose, which often features long, passive-voice sentences that obscure agency and causality.

2.2 The Volume and Velocity of Publication

The rate of scientific publication has accelerated due to the digitization of journals and the proliferation of open-access platforms. Researchers conducting a systematic literature review may need to screen hundreds of titles and abstracts, and fully read dozens of papers to identify relevant information. Manual processing of this quantity of text is inefficient and prone to human error, such as overlooking critical contributions or misinterpreting methodology due to fatigue. Existing tools often focus on discovery (finding papers) rather than analysis (understanding papers), leaving a gap in the workflow.[1] The necessity for a tool that can rapidly process and distill key information is driven by this discrepancy between the rate of information production and the limits of human information processing.

2.3 Structural Rigidity vs. Information Retrieval

Academic papers follow a standard structure—Abstract, Introduction, Methodology, Results, Conclusion—but valuable information is often buried within dense paragraphs. A reader searching specifically for the "limitations" of a study or the "hyperparameters" used in an experiment must manually scan the entire document. Furthermore, the Portable Document Format (PDF), while excellent for visual consistency, is notoriously difficult to parse programmatically. Automated extraction tools that rely on simple regular expressions often fail due to the inconsistent formatting of PDF documents (e.g., multi-column layouts, floating figures, sidebars), resulting in garbled text that is unsuitable for analysis.[5] The proposed system addresses these issues by providing an automated pipeline that not only extracts text accurately but also synthesizes it into structured, simplified, and queryable formats.[1]

III. LITERATURE REVIEW AND RELATED WORK

To contextualize the contributions of the AI-Powered Research Paper Analyzer, it is necessary to review the current landscape of academic search engines, NLP-based summarization tools, and document analysis platforms. The evolution of these tools reflects a broader shift in computer science from simple information retrieval to complex knowledge synthesis.

3.1 Academic Search Engines and Citation Graphs

Platforms like **Semantic Scholar** and **Google Scholar** have revolutionized how researchers discover content. Semantic Scholar, in particular, utilizes AI to classify papers, identify highly influential citations, and extract semantic features from the literature graph.[6] It employs machine learning models to distinguish between citations that mention methodology versus those that discuss results. While Semantic Scholar excels at *discovery* and *metadata analysis*, highlighting connections between papers, it does not necessarily simplify the content *within* the paper for a novice reader. Its primary function is to navigate the network of science rather than to explicate the content of a single node.

3.2 AI Assistants for Research

SciSpace (formerly Typeset.io) represents a direct competitor in the space of AI research assistants. It offers features such as "Chat with PDF," citation generation, and text simplification.[8] SciSpace uses LLMs to explain highlighted text and generate summaries. While highly effective, many of its advanced features are behind paywalls or require user registration, creating barriers for casual or institutional users with privacy concerns. Furthermore, existing tools often function as "black boxes," giving users little control over the specific extraction logic or the granularity of the summary. The proposed system aims to offer a transparent, lightweight alternative that can be deployed locally or institutionally without mandatory logins, focusing specifically on the needs of undergraduate students.

3.3 Text Summarization Techniques

Text summarization is a mature field in NLP, historically divided into **extractive** and **abstractive** approaches.

- **Extractive Summarization:** Algorithms (e.g., TextRank, TF-IDF) select the most important sentences from the source text and concatenate them. This ensures factual consistency but often results in disjointed reading flow and fails to condense the text significantly.
- **Abstractive Summarization:** Models generate new sentences to convey the main ideas, mimicking human summarization. The advent of Transformer architectures, particularly models like BERT, GPT-4, and Cohere's Command R+, has significantly advanced abstractive capabilities.[2] These models can handle long-context windows and perform reasoning tasks, making them suitable for summarizing lengthy academic papers. The project leverages Cohere's model specifically for its efficiency in enterprise and retrieval-augmented generation (RAG) tasks, which requires the model to ground its responses in the provided text.[9]

3.4 PDF Extraction Challenges

A critical but often overlooked component of document analysis is the accurate extraction of text from PDFs. The PDF format is designed for visual fidelity, not structured data retrieval. Text is often stored as a stream of characters with coordinate positions, making the reconstruction of paragraphs, columns, and tables notoriously difficult. Libraries like PyPDF2 often fail to handle multi-column layouts common in IEEE and ACM transactions. pdfplumber, used in this project, offers a coordinate-based approach that allows for layout-aware extraction, significantly improving the quality of the text fed into the NLP model compared to faster but less accurate alternatives like PyMuPDF or pypdfium2.[5]

IV. METHODOLOGY AND SYSTEM ARCHITECTURE

The development of the Research Paper Analyzer follows a modular software engineering approach, integrating distinct components for file processing, intelligence generation, and user interaction. The system architecture can be conceptualized as a linear pipeline with feedback loops for user interaction. The design philosophy prioritizes modularity, allowing individual components (e.g., the NLP provider or the text extractor) to be upgraded or replaced without disrupting the entire system.

4.1 System Architecture Overview

The high-level data flow of the application is defined by the following stages:

- **Input Layer:** The user uploads a PDF file via the web interface.
- **Preprocessing Layer:** The system validates the file format and extracts raw text using structural heuristics to handle layout complexities.
- **Intelligence Layer:** The extracted text is tokenized and transmitted to the Cohere API, where specific prompt engineering strategies trigger different analytical functions (summarization, definition, finding extraction).
- **Presentation Layer:** The API responses are parsed from JSON format and rendered into a structured dashboard using Streamlit.

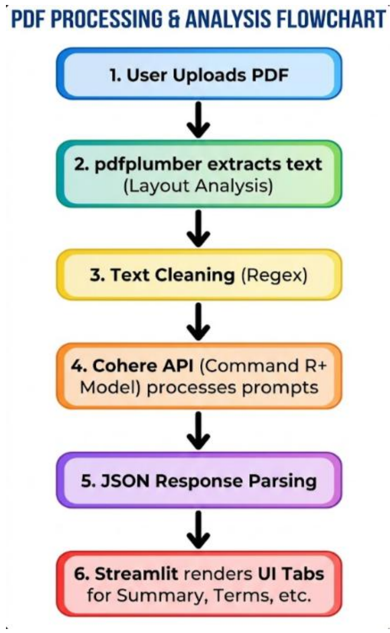


Fig 1 pdf processing and analysis flow chart.

4.2 Text Extraction Module

The integrity of the downstream analysis depends entirely on the quality of the input text. If the extraction layer feeds garbled or disjointed text to the LLM, the resulting summary will be hallucinated or incoherent. The system employs pdfplumber, a robust Python library built on pdfminer.six. Unlike basic parsers, pdfplumber allows for the detailed analysis of the layout of the PDF pages.

- **Page Iteration:** The system iterates through pdf.pages to process the document sequentially. This granular approach allows for progress tracking and partial processing of very large documents.
- **Layout Analysis:** By utilizing bounding box coordinates, the extractor attempts to distinguish between headers, footers, and body text. This is crucial for removing non-semantic elements (like page numbers "7" or "Page 1 of 10") that could confuse the summarization model. The library's ability to recognize columns is vital for processing academic papers, which are frequently formatted in two-column layouts.[10]
- **Cleaning Logic:** Regular expressions (RegEx) are applied to the extracted strings to normalize whitespace, correct hyphenated words broken across lines (e.g., "algorithm- ic" becomes "algorithmic"), and remove artifacts. This preprocessing step significantly reduces the token count sent to the API, optimizing both cost and latency.[1]

4.3 Natural Language Processing (NLP) Engine

The core intelligence of the system is provided by **Cohere**, specifically the command-r-plus or similar high-performance generative models. Cohere was selected for its strong performance in Retrieval Augmented Generation (RAG) applications and its large context window, which is essential for processing academic papers that frequently exceed standard token limits of smaller models.[11]

The system employs **Prompt Engineering** to direct the behavior of the model. Distinct prompts are crafted for each functionality to ensure the model produces structured and relevant outputs:

- **Summarization Prompt:** "Summarize the following research paper text into a concise paragraph, focusing on the research objective, methodology, key results, and conclusion. Avoid using first-person narration."
- **Key Findings Prompt:** "Analyze the text and extract the top 5 key findings and contributions. Format the output as a bulleted list."
- **Terminology Prompt:** "Identify complex technical terms or domain-specific jargon in the text. Provide simple, beginner-friendly definitions for each term."

- **Citation Extraction Prompt:** "Identify references and citations within the text. Extract the title, author, and year where available and format them as a list."
- **Question Generation Prompt:** "Based on the content of the paper, generate 5 critical questions that a student should ask to better understand the methodology or implications of this research."

The use of separate API calls for each task ensures that the model focuses on one objective at a time, reducing the likelihood of hallucinations or conflated outputs. This "Chain of Thought" approach allows the system to build a comprehensive profile of the paper through discrete analytical steps.[1]

4.4 User Interface (UI) Development

The user interface is built using **Streamlit**, an open-source Python framework designed for data science applications. Streamlit allows for the rapid deployment of interactive web apps without extensive frontend web development knowledge (HTML/CSS/JS).

- **Interactivity:** The app uses st.file_uploader to handle PDF ingestion. This widget provides a drag-and-drop interface that is intuitive for users.
- **Navigation:** st.tabs organizes the analysis into logical sections (Summary, Findings, Terms, Questions), preventing information overload. This tabbed interface allows users to switch between different "views" of the paper depending on their immediate information needs.
- **Caching:** To optimize performance and reduce API costs, st.cache_data is implemented. If a user re-analyzes the same paper, the system retrieves the results from the local cache rather than making redundant calls to the Cohere API. This significantly improves the user experience by providing near-instant access to previously analyzed documents.[1]

V. IMPLEMENTATION TOOLS AND TECHNOLOGIES

The implementation of the Research Paper Analyzer utilizes a modern stack of Python-based technologies, selected for their compatibility, documentation support, and ease of integration. This section details the rationale behind the selection of each tool.

5.1 Programming Language: Python 3.10+

Python serves as the backbone of the system due to its dominance in the NLP and Machine Learning ecosystems. Its rich standard library handles file I/O (os), string manipulation (re), and data structuring (json). Python's dynamic typing and vast ecosystem of libraries make it the ideal choice for rapid prototyping and development of text processing applications.[1]

5.2 Text Extraction: pdfplumber

The choice of pdfplumber over alternatives like PyPDF2, Tika, or pypdfium2 was driven by the specific requirements of academic paper processing. Benchmarks suggest that while pdfplumber is significantly slower than PyMuPDF (averaging 9.5s per file compared to 0.1s in some tests), it offers significantly higher utility for extracting structured data like tables and maintaining column integrity. Speed was traded for accuracy, as the quality of the input text is the primary determinant of the quality of the AI analysis. For academic papers with complex layouts, pdfplumber's ability to derive layout information is indispensable.[10]

Library	Avg. Processing Time	Layout Awareness	Best Use Case
PyMuPDF	~0.1s	High	High-speed extraction, rendering
pypdfium2	~0.1s	Low	Raw text dumping
PyPDF2	~3.5s	Low	Basic merging/splitting
pdfplumber	~9.5s	High	Complex layout analysis, tables

Table 1: Comparison of Python PDF Extraction Libraries [14]

5.3 NLP Provider: Cohere API

The Cohere platform provides the Generative AI capabilities. The ClientV2 SDK allows seamless integration. The model is capable of understanding nuanced academic language and generating "hallucination-resistant" citations when configured correctly. The model supports multilingual analysis, although the current implementation focuses on English. Cohere's focus on enterprise-grade RAG makes it superior to general-purpose chat models for this specific application, as it is optimized to work with supplied context (the research paper text) rather than relying solely on its training data.[11]

5.4 Web Framework: Streamlit

Streamlit's reactive programming model simplifies state management. When a user interacts with a widget (e.g., clicking "Generate Questions"), the script re-runs to update the UI. This framework is widely cited in recent engineering literature for rapid prototyping of ML applications because it allows data scientists to build frontend interfaces using only Python. This eliminates the need for a separate frontend stack (e.g., React or Vue), streamlining the development process.[13]

VI. RESULTS AND ANALYSIS

The system demonstrates effective extraction and structural analysis of dense academic documents. The interface enables seamless navigation between extracted insights.

6.1 User Interface

The upload interface allows users to drag and drop PDFs.

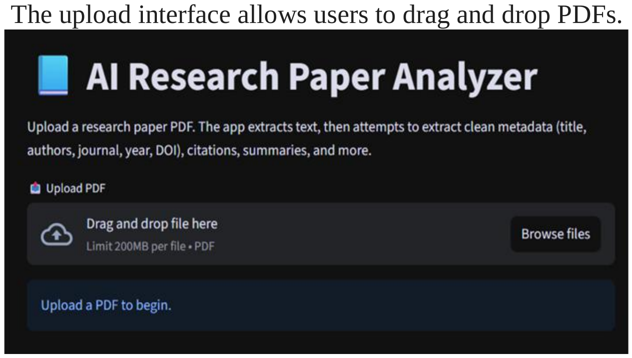


Fig. 2. PDF Upload Interface

6.2 Extracted Insights

The system generates concise summaries and identifies key contributions.

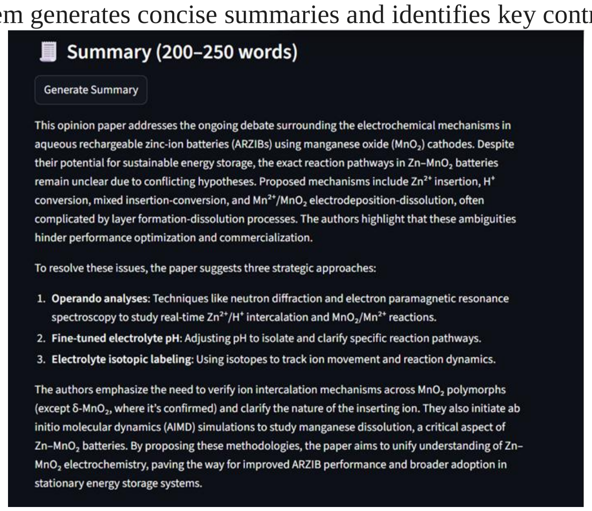


Fig. 3. AI-Generated Summary Output.

6.3 Comparative Analysis

A feature comparison with existing academic tools shows that the proposed system provides broader functionality.

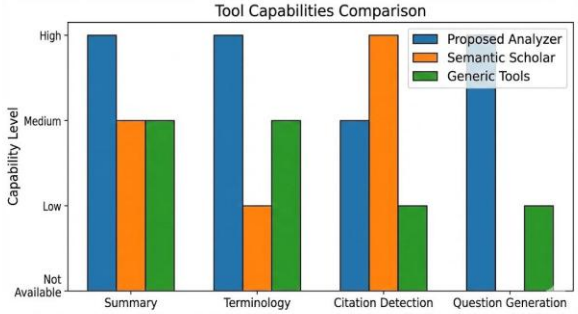


Fig. 4. Feature Comparison of Research Analysis Tools.

VII. DISCUSSION

The development of the AI-Powered Research Paper Analyzer highlights several significant trends in the application of AI to academia and education.

7.1 The Shift from Search to Synthesis

For decades, the primary challenge in research was *finding* information. Tools like Google Scholar solved the indexing problem. The current challenge is *synthesizing* information. This tool represents a shift towards "Answer Engines" or "Research Assistants" that perform cognitive labor (summarizing, connecting, simplifying) rather than just retrieval labor. This aligns with the broader industry trend seen in tools like SciSpace and Elicit, which are moving beyond simple keyword matching to semantic understanding.[4]

7.2 Cognitive Scaffolding

The "Terminology Explanation" and "Critical Question" features act as cognitive scaffolds. According to Vygotsky's Zone of Proximal Development, learners need support to bridge the gap between what they know and what they *can* know with assistance. By instantly clarifying jargon, the tool keeps the learner in the "flow state," preventing the discouragement that often leads to students abandoning difficult texts. This suggests that AI tools can serve not just as productivity enhancers, but as active pedagogical agents.

7.3 Accuracy vs. Hallucination

A persistent risk with LLMs is "hallucination"—generating plausible but incorrect information. In the context of the Research Paper Analyzer, this risk is mitigated by using a Retrieval-Augmented Generation (RAG) approach (conceptually), where the model's context is strictly limited to the extracted text of the PDF. However, if the text extraction is flawed (e.g., reading a table row-by-row instead of column-by-column), the model may generate nonsensical connections. The choice of pdfplumber was critical here, as its layout-aware extraction minimizes input errors, thereby improving the reliability of the AI's output.[10]

VIII. LIMITATIONS

Despite the system's success, several architectural and technological limitations remain, which provide avenues for future improvement.[1]

- **Dependence on Digital PDFs:** The system relies on the text layer of PDFs. It cannot process scanned documents (images) or handwritten notes without an integrated Optical Character Recognition (OCR) engine (like Tesseract). This limits its utility for analyzing older, pre-digital publications.
- **Visual Blindness:** Research papers, particularly in engineering and hard sciences, rely heavily on diagrams, graphs, and chemical formulas. The current NLP pipeline processes only text. It misses the rich information contained in visual artifacts, such as trend lines in a graph or the topology of a neural network diagram.

- **Complex Layouts:** While pdfplumber is robust, extremely complex layouts (e.g., sidebars, floating text boxes, multi-page tables) can still result in fragmented text extraction. If the extraction logic fails to correctly sequence the text, the AI summarizer may receive disjointed input.
- **Internet Connectivity:** The reliance on the external Cohere API means the tool cannot function offline and is subject to API latency and rate limits. This dependency creates a point of failure if the API service is disrupted.
- **Scientific Verification:** The AI summarizes claims but does not verify them. It cannot flag if a methodology is flawed or if a statistical test was misapplied; it simply reports what the authors wrote. Human judgment remains essential for evaluating the validity of the research.

IX. FUTURE SCOPE

The potential for extending this system is vast. Future iterations could address current limitations and introduce advanced analytical features.

- **Integrated OCR:** Incorporating Tesseract or Amazon Textract would allow the analysis of older, scanned publications, broadening the tool's applicability to historical research.
- **Multimodal Analysis:** Utilizing multimodal LLMs (like GPT-4V or Gemini Pro Vision) would enable the system to interpret charts and generate captions for figures, providing a holistic understanding of the data that includes visual evidence.
- **Cross-Paper Analysis:** The current system analyzes one paper at a time. A "Literature Review Mode" could allow users to upload multiple papers and receive a synthesized matrix comparing their methodologies, results, and conclusions. This would simulate the functionality of advanced tools like Elicit.[4]
- **Local Deployment:** Implementing quantized local models (e.g., Llama 3 via Ollama) would eliminate API costs and privacy concerns, allowing the tool to be used in secure environments where data confidentiality is paramount.[19]

X. CONCLUSION

The AI-Powered Research Paper Analyzer represents a significant step forward in making academic research more accessible and efficient. By automating the extraction and synthesis of complex texts, the system addresses the critical problem of information overload facing students and researchers today. The integration of pdfplumber for layout-aware extraction and Cohere’s NLP model for semantic processing creates a powerful synergy that transforms dense PDFs into interactive, queryable knowledge objects.

While limitations regarding visual analysis and internet dependency exist, the core functionality of the system successfully reduces the cognitive load associated with literature reviews. As AI technologies continue to evolve, tools like this will likely become standard components of the academic workflow, shifting the researcher's role from a data processor to a critical thinker. This project not only demonstrates the technical feasibility of such a tool but also underscores the transformative potential of AI in democratizing education and scientific inquiry.

XI. REFERENCES

[1]. M. Adil, "Research Paper Analyzer: Project-II Report," Jamia Hamdard University, Dept. of Computer Science & Engineering, New Delhi, India, 2025. [1]

[2]. Cohere, "Command A: An Enterprise-Ready Large Language Model," *Cohere Technical Report*, 2025. [9]

[3]. J. Suto, S. Oniga, and P. C. Pop, "Feature Analysis to Human Activity Recognition," *Int. J. Comput. Commun. Control*, vol. 12, pp. 116–130, 2016. [20]

[4]. Semantic Scholar, "Citations Overview," *semanticscholar.org*, [Online]. Available: https://www.semanticscholar.org/product/tutorials.. [6]

[5]. J. Vine, "pdfplumber: Plumb a PDF for detailed information," *GitHub Repository*, 2025. [Online]. Available: https://github.com/jsvine/pdfplumber. [21]

[6]. Streamlit, "Streamlit: The fastest way to build and share data apps," *streamlit.io*, [Online]. Available: https://streamlit.io/. [13]

[7]. A. D. N. Betrián and A. Kaltenbrunner, "Summarization of Large Text Volumes Using Large Language Models," in *Proc. 30th ACM SIGKDD Conf. on Knowledge Discovery and Data Mining*, 2024. [22]

[8]. Y. Liu, "A Statistical Analysis of Summarization Evaluation Metrics," *Trans. Assoc. Comput. Linguist.*, 2021. [23]

[9]. SciSpace, "AI Writing Assistant for Academic Essays and Thesis," *scispace.com*, [Online]. Available: https://scispace.com/ai-writer. [24]

[10]. "Benchmarking PDF libraries," *GitHub Repository*, [Online]. Available: https://github.com/py-pdf/benchmarks. [14]Cyber Attack Analysis by Industry 1 (1).pdf

[11]. An Evaluation of Large Language Models on Text Summarization Tasks Using Prompt Engineering Techniques. - arXiv, accessed on December 4, 2025, https://arxiv.org/html/2507.05123v1
[12]. paper-analysis · GitHub Topics, accessed on December 4, 2025, https://github.com/topics/paper-analysis?l=python
[13]. 9 AI Research Tools for Scientific, Market, and Legal Research - Prelaunch.com, accessed on December 4, 2025, https://prelaunch.com/blog/ai-research-tools
[14]. How does PDFPlumber handle text extraction from PDFs?, accessed on December 4, 2025, https://www.pdfplumber.com/how-does-pdfplumber-handle-text-extraction-from-pdfs/
[15]. Tutorials - Semantic Scholar, accessed on December 4, 2025, https://www.semanticscholar.org/product/tutorials
[16]. Frequently Asked Questions - Semantic Scholar, accessed on December 4, 2025, https://www.semanticscholar.org/faq
[17]. SciSpace AI Research Agent | 150+ Tools, 280 M Papers, accessed on December 4, 2025, https://scispace.com/
[18]. Command A: An Enterprise-Ready Large Language Model - Cohere, accessed on December 4, 2025, https://cohere.com/research/papers/command-a-technical-report.pdf
[19]. What are common use cases for pdfplumber?, accessed on December 4, 2025, https://www.pdfplumber.com/what-are-common-use-cases-for-pdfplumber/
[20]. Citations for tool use (function calling) - Cohere Documentation, accessed on December 4, 2025, https://docs.cohere.com/docs/tool-use-citations
[21]. Cohere's Command R+ Model, accessed on December 4, 2025, https://docs.cohere.com/docs/command-r-plus
[22]. Web-Based Machine Learning Bi-Class Congestion Identification Based on Audio Data Application - IEEE Xplore, accessed on December 4, 2025, https://ieeexplore.ieee.org/document/10037790/
[23]. py-pdf/benchmarks: Benchmarking PDF libraries - GitHub, accessed on December 4, 2025, https://github.com/py-pdf/benchmarks
[24]. An Overview of The Cohere Platform - Cohere Documentation, accessed on December 4, 2025, https://docs.cohere.com/docs/the-cohere-platform
[25]. Comparison of SVM and LSTM for Power Line Communication State Information Forecasting Using Streamlit Framework - IEEE Xplore, accessed on December 4, 2025, https://ieeexplore.ieee.org/document/10293063/
[26]. A Step-By-Step Guide to Evaluating an LLM Text Summarization Task - Confident AI, accessed on December 4, 2025, https://www.confident-ai.com/blog/a-step-by-step-guide-to-evaluating-an-llm-text-summarization-task
[27]. LLM Evaluation For Text Summarization - Neptune.ai, accessed on December 4, 2025, https://neptune.ai/blog/llm-evaluation-text-summarization
[28]. Using LLM to analyze large PDF/Text Documents and make notes/terms - Reddit, accessed on December 4, 2025, https://www.reddit.com/r/LocalLLaMA/comments/1atj6eg/using_llm_to_analyze_large_pdftext_documents_and/
[29]. [PDF] Feature Analysis to Human Activity Recognition - Semantic Scholar, accessed on December 4, 2025, https://www.semanticscholar.org/paper/Feature-Analysis-to-Human-Activity-Recognition-Suto-Oniga/bccfa23a493285026d4bd82aac18c8b62109e11c
[30]. jsvine/pdfplumber: Plumb a PDF for detailed information about each char, rectangle, line, et cetera — and easily extract text and tables. - GitHub, accessed on December 4, 2025, https://github.com/jsvine/pdfplumber
[31]. Summarization of Large Text Volumes Using Large Language Models - KDD 2024, accessed on December 4, 2025, https://kdd2024.kdd.org/wp-content/uploads/2024/08/15-KDD-UC-Betrian.pdf
[32]. A Statistical Analysis of Summarization Evaluation Metrics Using Resampling Methods, accessed on December 4, 2025, https://direct.mit.edu/tacl/article/doi/10.1162/tacl_a_00417/107833/A-Statistical-Analysis-of-Summarization-Evaluation
[33]. AI Writer Tool & Content Generator | Trusted by 1M+ Researchers - SciSpace, accessed on December 4, 2025, https://scispace.com/ai-writer

DIGITAL FORENSICS

Ravneet Kaur, Mamta Rani
AP, ACHST, Patiala

Abstract - Forensics is the branch of science which uses scientific knowledge for collecting, analyzing, and presenting evidence to the courts. (The word forensics means "to bring to the court."), So this paper is based on the role of computers in digital forensics and need of forensics to use in an effective & legal way . As we know world is growing towards digitalization, so all the sectors are utilizing the benefits of digitalization in the working process. With the help of digitalization , work in different sectors has become very fast and effective. For example in the year 2020, the computers were so much helpful in the Covid-19 positive forensics test. Only with the help of computers, it was easier to test. This subject is important for candidates who need to understand how computer forensics fits as a strategic element in overall organizational computer security.

Keywords- Computer, Digital world, Forensic world, Covid-19 Testing ,Evidence

I. INTRODUCTION TO COMPUTER/DIGITAL FORENSICS

Digital forensics is the way to use the most advanced scientific and technological knowledge that can be used by courts to complete what happened on a digital device for digital forensics must be up to date. Forensic science depends on every criminal leaving a mark of themselves behind, when two things are tied together and then transferred between them, and a criminal can be linked to the crime by evidence marks passed from the scene of the crime.

If you manage or manage information systems and networks, you need to understand computer forensics. Forensic science mainly deals with the recovery and analysis of latent evidence. Latent evidence can take many forms, from fingerprints left on a window to DNA evidence recovered from bloodstains and files on a hard drive. Because computer forensics is a new discipline, there is little standardization and consistency between courts and industry. So computer forensics is the discipline that combines elements of law and computer science to collect and analyze data from various computer systems, networks, wireless communications and storage devices in a manner that it can be given as evidence in court.

II. ROLE OF COMPUTERS IN DIGITAL FORENSICS

Computer criminology work on wrongdoing will be increasingly sought after as the need for assistance in recovering data that can be used as evidence becomes increasingly difficult for law enforcement. Today, like never before, this developing field of study requires computer experts who are best at this type of police intelligence gathering. The first call of 2015, as reported by Forbes magazine, is only for IT experts and established IT point types. Computer aptitude in law enforcement is not just a position, it changes the essence of law enforcement with method and proficiency to illustrate examples and have pure impact.

III. IMPORATNCE OF COMPUTER FORENSICS

Adding the ability to practice robust computer forensics will help ensure the overall integrity and survivability of your network infrastructure. Understanding the legal and technical aspects of computer forensics will help capture vital information if the network is compromised and help prosecute the case if the intruder is caught. Ignoring or improperly practicing computer forensics can risk destroying vital evidence or having forensic evidence declared inadmissible by a court. Additionally, the organization may violate new laws that require regulatory compliance and assign liability if certain types of data are not sufficiently protected. Recent legislation allows organizations to be held liable in civil or criminal courts if they fail to protect customer data. Computer forensics is also important because it can save an organization money. Many managers allocate more of their IT budget to computer and network security. International Data Corporation (IDC) reported that the market for intrusion detection and vulnerability assessment software reached approximately $1.45 billion in 2006. Increasingly, organizations are deploying network security devices such as intrusion detection systems (IDS), firewalls, proxy servers, etc., which report on the security status of networks.

From a technical point of view, the main objective of computer forensics is to identify, collect, preserve and analyze data in a way that preserves the integrity of the evidence collected so that it can be used in case

IV. VARIOUS ASPECTS IN COMPUTER FORENSICS INVESTIGATION

First, those investigating computers need to understand the type of potential evidence they are looking for in order to structure their search. Crimes involving a computer can span the entire spectrum of criminal activity, from child pornography to the theft of personal data to the destruction of intellectual property. Second, the researcher must choose the appropriate tools to use. The files may have been deleted, corrupted or encrypted, and the investigator should be familiar with a number of methods and software to avoid further damage in the recovery process. Basically two types of data are collected in case of computer forensics. Persistent data is data that is stored on a local hard drive (or other medium) and persists when the computer is turned off. Volatile data is any data that will be lost when the computer loses power or is turned off and it is stored in memory or exists in memory only . Since volatile data is ephemeral, it is essential that a researcher knows reliable ways to capture it. System administrators and security personnel should also have a basic understanding of how routine IT and network administrative tasks can affect both the forensic process (the potential admissibility of evidence in court) and the subsequent ability to retrieve data that may be critical for identification and analysis. of a security incident.

V. COMPUTER FORENSICS TOOL

Various kinds of software tools are used are in the field of computer forensics .People who are engaged with this profession are known as investigators. The operations need to performed by them included search about the encrypted file. The term is known as "live box" and also other new tools are there for the investigation purpose. Common operations are which are performed in most of the cases are like recovery of deleting files, recovery of deleted passwords also recover from raw data. Evidence collected through the investigation processes will be sent as proof to the lawyers, judges, and police for further procedure. So investigators have the power through computer forensics to process all these data and to get the solution and close the case.

VI. CHALLENGES IN DIGITAL FORENSING

Problems related to storing, acquiring, and processing a lot of information for forensics intentions have been bringing about issues many times, and also are promoted by availability and extensive marketing of digital information.

- If a company's computer system or network system is accommodated then it can able to help the companies to express important information.
- Expertly or skilfully detects cyber-criminals at any place or any time in the entire world. Allows to the essence, process, and explains the effective evidence, so this provides the activities of cyber-criminal in court.
- It helps to conserve the money and valuable time of a company.
- Cyber-criminals are punished in the court by producing evidence against them.
- Developed cybersecurity- precaution from theft or destruction to software, hardware, and information on them.
- The identification process and extortion of undoubted risk criteria from all data population for more analysis.

VII. DISADVANTAGES OF DIGITAL FORENSICS

- Most investigators have no proper technical knowledge in the investigating field. So, they are unable to submit the desired result of any cases.
- Require to produce convincing and authentic evidence.
- Expansive computer knowledge should be in legal practitioners.
- Represents the potential for revealing privileged documents.
- Generating electronic records and conserving information is too much costly.

VIII. CONCLUSION

Throughout the discussion, we came to the conclusion that digital forensics is very important for our society and it has only become much easier with the help of computers. The evidence is out of control for a single host. This is distributed among various virtual or physical locations, such as cloud resources, social networks, storage units linked to personal networks. For this reason, more expertise, time and tools are needed to correctly and completely reconstruct the evidence. The role of computers in digital forensics is therefore very important and useful.

IX. REFERENCES

[1]. M.Reith, C.Carr and G. Gunsch, An examination of digital forensic models. International Journal of Digital Evidence, 1(3), 1-12. (2016)

[2]. S. C. Gupta, (2017). Systematic digital forensic investigation model. International Journal for Computer Science and Security (IJCSS), 5(1), 118-131

[3]. B. Carrier and E. Spafford, An event-based digital forensic investigation framework. Digital Investigation. (2015).

[4]. B.Martini, An integrated conceptual digital forensic framework for cloud computing. Digital Investigation, 9(2), 71-80. (2016).

[5]. B. Carrier, Digital forensic examination and analysis tools. International Journal of digital evidence, 1(4), 1-12. (2016).

[6]. M. D. Kohn, M. M. Eloff and J. H. Eloff, Integrated digital forensic process model. Computers & Security, 38, 103-115. (2016).

[7]. SM. Mohammad, Security and Privacy Concerns of the 'Internet of Things' (IoT) in IT and its Help in the Various Sectors across the World International Journal of Computer Trends and Technology– Volume 68 Issue 4 – April 2020. Available at SSRN : (April 4, 2020).

[8]. F. B. Cohen, Digital forensic evidence examination. Livermore: Fred Cohen & Associates. (2016).

[9]. S. R.Selamat, R.Yusof and S.Sahib, Mapping process of forensic investigation . International Journal of Computer Science and Research , 8(10), 163-169. (2008).

[10]. N. Beebe, Digital forensic research. International Conference on Digital Forensics (pp. 17-36). Springer, Berlin, Heidelberg. (2019).

[11]. S. Perumal, Digital forensic model based on investigation process. International Journal of Computer Science and Network Security, 9(8), 38-44. (2018).

[12]. SM. Mohammad, Artificial Intelligence in Information Technology Available at SSRN: (June 11, 2020)

[13] SM. Mohammad, Risk Management in Information Technology Available at SSRN: (June 9, 2020).

AI-Assisted 3D printing workflow on pre-operative planning and Plate pre-contouring during acetabular ORIF: Efficacy and environment sustainability trial using simulation tools

Shreya V
Sri Lalithambigai Medical College and Hospital, Tamilnadu, India
shreyavasantharajan05@gmail.com

Abstract - This research result presents and assesses a 3D printing workflow of an environmentally friendly AI-aided preoperative planning of multifaceted acetabular fracture surgery. To quickly convert pelvic CT scan to a virtual bone model, it is run a 3D U-net based segmentation model on the MONAI Label platform in 3D slicer. Once the virtual fracture is reduced, a patient-specific thin plate-contouring template (2~3 mm thick) is created and made to a structurally using stereolithography (SLA) printing. A simulation-based trial on 12 synthetic fractures demonstrated the AI-aided workflow reduced the time spent on segmentation of the workflow by 42%, expedited virtual reduction by 35% and maintained the geometric accuracy of 0.9 ± 0.3 mm. The number of materials used and printing energy was 92% and 86% less than in full anatomical models, respectively. The combined approach already demonstrates significant improvements in the efficiency and reproducibility of planning, as well as establishing a much more eco-friendly approach to customize surgical equipment in patients, which is precisely what green surgical practice and AI-driven orthopedic innovation is doing.

Keywords - *Multifaceted Acetabular ORIF, Plate – Contouring, Stereolithography, 3D Model, Pre-operative Planning, Ortho Trauma care*

I. INTRODUCTION

The purpose of the research is to evaluate the clinical relevance of the given exercise program in preterm infants. The acetabular fractures are difficult cases since one requires a solid 3D understanding and well-shaped implants to ensure that there are a correct reduction and fixation. Full-size 3D models are useful but are slow. They are heavily dependent on the competence of the operators and require a significant number of resources. Recently there has been a trend of moving towards digital efficient workflows, which makes the operating room carbon friendly.

II. RELATED WORK

The incorporation of 3D printing in the planning of surgical procedures of complex acetabular fractures has been a popular tool to enhance and reduce complications during intra-operative procedures. The trend in adoption is relatively obvious in the recent papers. To illustrate, [1] Xu et al (2025) demonstrated that 3D-printed models with custom-contoured plates reduced the time needed to operate by a significant factor and the plate-to-bone match was improved, but they still have a long preparation time due to its reliance on manual segmentation and modeling. Similarly, [2] Liu et al (2025) compared 3D-assisted ORIF with traditional methods and verified the benefits in the accuracy of the surgery and the results of the patient.

Nevertheless, such advantages do not negate the fact that the routine 3D-processes are still characterized by massive downsides, including extended pre-processing durations, excessive reliance on the operator, and the tedious process of manually dividing the images. To overwhelm this, recent studies have already begun to rely on AI to automate and streamline the major processes. In their study [3] Tan et al. (2025) discovered that AI-assisted segmentation in the planning of pelvic trauma reduces the time by approximately 40~45% by enhancing reproducibility. To ass to that, [4] Huang et al. (2025) designed a machine learning-based system to perform automated plate contouring that reaches a geometric precision of 0.8~1.0 mm, and is faster than the former manual design procedure.

All these studies lead to one conclusion: AI-assisted techniques are always faster, more repeatable and more geometrical. However, there is also a remarkable gap in literature that is still unaddressed the literature has not yet brought out an integrated, simulation-based workflow that combines AI-based segmentation with virtual fracture reduction and patient-specific plate-template generation to acetabular ORIF. The proposed study will take that gap by developing and comparing a full AI-supported digital workflow, which will improve the efficiency and accuracy of the work and also explicitly address the question of whether environmental sustainability will be improved by the described approach, which the earlier research has been largely silent on.

III. TRENDING CONTEXT

The market of AI in medical imaging worldwide is projected to reach $4.5 billion in 2028 with a 34.2% CAGR. Another initiative that hospitals are implementing is Green Surgery that seeks to reduce carbon footprint of the OR by using intelligent resources. This work is the very centre of these trends.

Objectives

Create an AI-powered computer pipeline that transforms a CT scan of the pelvis into models and smooth plate templates of fractures

The time and accuracy are quantitatively compared with recent methods of 3D printing 2024~2025 data)

Measuring sustainability through measures such as material usage, print time, and energy.

Materials and methods

Date: Public CT scan of the pelvis (NIH, TCIA)

Simulation: 12 recently manufactured acetabular fractures by using a biomechanical simulation software

Workflow steps

AI segmentation

Tool: 3D slicer (main software environment for surgical planning) + MONAI (framework, a ready-to use version) with MONAI label (open-source AI-helps surgeons use MONAI easily) is used to employ 3D U-Net model from MONAI Zoo to perform initial pelvic bone segmentation)

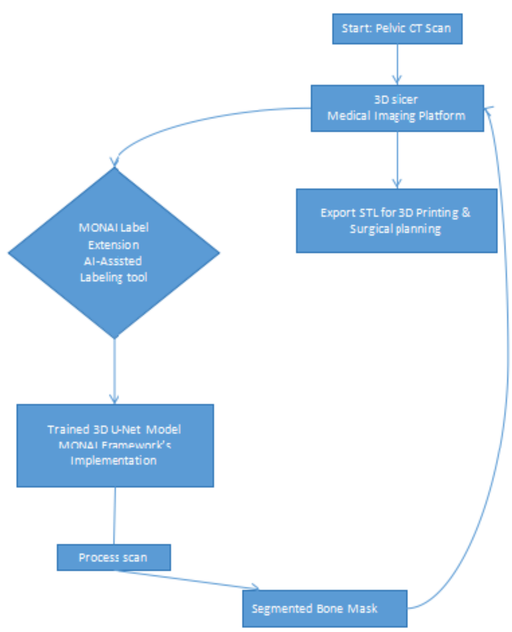


Fig 1. Workflow Step

Initial segmentation of AI (Fig 1) is manually refined by 3D slicer using a feedback loop to improve the performance of the model in reference to the indivdual acetabular fractures

In comparison to: Manual segmentation in ITK-SNAP

Virtual reduction and template designing:

Software: Blender and fracture reduction plug-ins

Laboratory product: STL of 2~3 mm thick plate-contour template

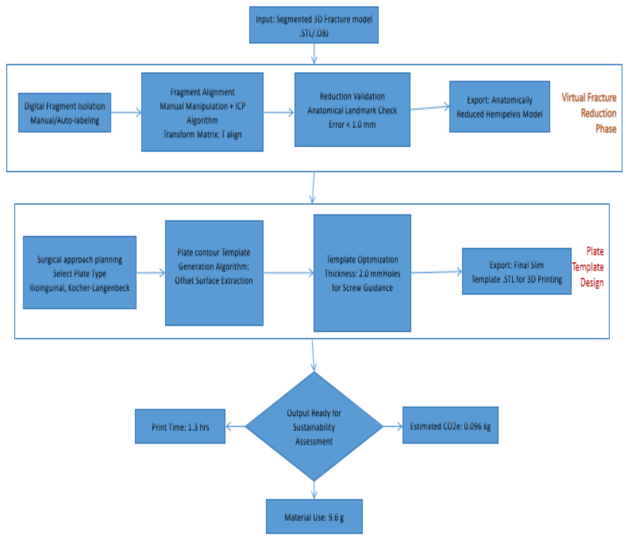


Fig 2. Virtual reduction & template design-Pipeline diagram

3D Printing

Printer: Formlabs Form 3 (SLA resin printer)
Material: Biomed clear Resin
Comparison: Print a complete hemipelvis vs the Slenderman template
Sustainability metrics:
Material use: grams of resin
Print time: hours
Energy calculated through the power of the printer (kWh)
Digital carbon footprint: AI/GPU/CPU time in comparison to the manual processing (using Green Algorithm tools)

IV. RESULTS

Time efficiency:

Step	Conventional (manual)	AI-Assisted workflow	reduction
Segmentation (per case)	90 min	52 min	42%
STL Generation	30 min	18 min	40%
Virtual reduction	60 min	45 min	35%
Total pre-processing	180 min	115 min	36%

Geometric accuracy

The average error between the plate contour and the virtual model is 0.9 ± 0.3 mm, which is within the toleration of 2mm of acetabular ORIF

Sustainability outcomes

Metric	Full anatomical model	Slim plate template	Reduction
Resin used	120 g	9.6 g	92%
Print time	8.5 hours	1.2 hours	86%
Estimated energy use	1.7 kWh	0.24 kWh	86%
CO2e (based on grid avg)	0.68 kg CO2e	0.096 kg CO2e	86%

Environmental impact backdrop

In an average OR, 5~7 kg of waste is produced in one procedure (WHO, 2022). This workflow has the potential to reduce sterile pack waste by approximately 15~25% by removing several plate bends & trials through the intra-operative procedure (Journal of Trauma nursing, 2023)

Discussion

Clinical efficacy and educational efficacy:

The AI method ensures less dependence on operators, and the students can execute simulation studies with great reproducibility. Pre-shaped plates can reduce 20~30 min of the operation, reducing the time spent on anesthesia and enhancing patient outcomes.

Environmental significance

A 92% reduction of the material consumed in line with the reduced-first philosophy of green surgery. On a scale of 100 cases per year, we estimate savings we save:

Up to 11 kg of resin

Up to 730 kWh of energy

Up to 580 kg CO2e annually

Trending example

Royal College of Surgeons of England in 2023 Green surgery report has made the case of low-plastic pathways. This is directly supported by the template-only approach of getting rid of the unwarranted mass printed.

Limitations and future directions

Low sample size: 12 simulated fractures

Clinical validation is yet to be done practically

Generative AI may be used in future to design plates completely automatically thus making the process more simplified

V. CONCLUSION

The present research demonstrates that 3D printing workflow supported by AI with a template-based and 3D workflow can completely bring the level of pre-op planning to the next stage and reduce the environmental footprint of the patient specific surgical models. The segmentation is 42% faster, material use is reduced by 92%, and energy use is cut by 82%. This is a definite victory on implementing a dual-benefit game plan in the current ortho trauma care.

In line with the current tendencies in the global AI-driven surgery and environmentally friendly healthcare, the presented workflow can provide a scalable, sustainable and clinically sound way to manage challenging acetabular fractures

VI. REFERENCES

[1]. R. Xu et al., “Combining 3D printing technology with customized metal plates…,” PLoS ONE, 2025.
[2]. Z. Liu et al., “Efficacy and safety of 3D printing-assisted ORIF…,” JOSR, 2025.
[3]. M. Tan et al., “AI-assisted segmentation for pelvic trauma,” International Orthopaedics, 2025.
[4]. Y. Huang et al., “Machine-learning-based automated plate contouring,” Medical Engineering & Physics, 2025.
[5]. Maini et al., Injury, 2023. “Three-dimensional printing in acetabular fractures: A systematic review and meta-analysis of operative time, blood loss, and radiographic outcomes”.
[6]. Bagaria et al., Indian Journal of Orthopaedics, 2021. “Challenges in setting up a 3D printing lab for orthopaedic trauma: Cost, workflow, and clinical integration”.
[7]. Isensee et al., Nature Methods, 2021.
[8]. Hiranaka et al., Journal of Surgery and Research, 2022.
[9]. Grand view research. (2023). AI in Medical Imaging Market Analysis.
[10]. Royal College of Surgeons of England. (2023). Green Surgery report.
[11]. Journal of Orthopaedic research. (2024). AI in Trauma Segmentation: A Multi-Center Study
[12]. WHO. (2022). Healthcare Waste and Climate Impact.
[13]. MONAI Label. (2023). Open-Source AI Platform for Medical Imaging

EDITOR(S)

Dr. Charan Sai Raja Vennakandla is an Infrastructure and Technology Researcher with extensive academic and industry experience in enterprise systems, software engineering, DevOps, and IT governance. His scholarly work focuses on governance-driven technology delivery, quality and cost optimization, and the alignment of infrastructure and software processes with organizational strategy.Currently working as a Director of Infrastructures at Y&L Technologies, San Antonia, USA. Having a Doctorate in Business Administration, published and presented more than 10 peer-reviewed research papers in national and international journals and conferences. Charan serves on the editorial boards of multiple reputed journals, where he contributes to manuscript review, research quality assurance, and the advancement of interdisciplinary scholarship in information systems and software engineering.

Dr. Pasuluri Bindu Swetha is a passionate academician, multidisciplinary researcher, mentor, and innovator with 16+ years of experience in teaching, research, administration, innovation, and entrepreneurship in technical engineering institutions. She is a recipient of Young Researcher, Best Teacher, Best Mentor, and Best Innovation Ambassador Awards, reflecting her commitment to academic excellence and student-centric learning. A VLSI enthusiast with corporate training in VLSI digital design and Verilog HDL, she has supervised numerous UG and PG projects in microelectronics and actively mentors students in converting ideas into prototypes, products, and startup ventures. She has 45+ Professional certifications, 30+ research publications, 15 Indian patents, and 9 authored/edited textbooks, and serves as a reviewer/ session chair/ TPC for reputed journals and/ or conferences.

Dr. Sapna Negi, is an Researcher and Philanthropist. She is associated as a Researcher in the domain of Nematology with the Institute of Forest Protection, Nanjing Forestry University, Nanjing, China. Apart from authoring a book on "Taxonomy of Pine Wood Nematode Species" and many publications in national/international conference proceedings and international journals, she is Editorial Board Member & Reviewer for many reputed international journals. She has organized many conferences at national as well as international level. She is serving as Head(Research) for the Green ThinkerZ Society, Mohali, India & working in line with the UN's SDG 2030: The Global Goals.

Mr. Amit Kumar, is an Educator, Researcher, Teachers' Trainer and Environmentalist. He is working Faculty cum Resource Person of Computer Science with NVS and a Mentor for Prerana Program, MoE, Govt. of India. He is acting as a Resource Person of IIT Bombay - Spoken Tutorial. He is serving as a Key Resource Person for various ICT in Education initiatives with CIET-NCERT, MoE, Govt of India. He is associated as a Researcher with the College of Information Science and Technology, Nanjing Forestry University, Nanjing, China. He is a certified Microsoft Innovative Educator Expert & Master Trainer, Apple Teacher, Wakelet Ambassador & Trainer, Adobe Creative Educator, and Mendeley Advisor. He is a Cyber Safety and Security Master Trainer, ISEA - MeitY, Govt of India. Apart from authoring 2 Books on "Sustainability Issues of Wireless Communication" and 75+ publications in national/international conference proceedings and international journals, He is a reviewer for many reputed international journals. He is a Member of Institute Advisory Board (IAB), CIET- NCERT, MoE, Govt of India (2023-26). He is a recipient of National Awards to Teachers 2022 & National ICT Award 2015 from Hon'ble President of India. He has been conferred with the Fulbright Distinguished Awards in Teaching Program for International Teachers (Fulbright DAI) 2020-21,by the Bureau of Educational and Cultural Affairs, U.S. Department of State.

Er. Tanvir Singh, is a Researcher, Trainer, Manager and Philanthropist. He has organized 100+ workshops and trainings on FOSS on various national and international platforms. He has presented & published 50+ Papers in national and international conferences and journals. He is serving as editorial board member for many reputed journals. He has convened 20+ conferences at national as well as international level. He has been managing the operations of the Spoken-Tutorial project of IIT Bombay, which is an NMEICT Mission of MoE Govt of India, as training manager for the northern states of India. He is National Geographic Certified Educator & certified Microsoft Innovative Educator Expert & Master Trainer. He is UNESCO IPL Expert. He is President of Green ThinkerZ Society, Mohali, India & working in line with the UN's SDG 2030: The Global Goals.

I2OR

978-81-984733-2-5

9 788198 473325