4TH SLIIT INTERNATIONAL CONFERENCE ON ENGINEERING AND TECHNOLOGY (SICET) 2025

"NEXT GENERATION ENGINEERING FOR DIGITAL AND SUSTAINABLE SOLUTIONS"

INDUSTRY CONNECT PAPERS

The articles published in the proceedings are based on engineering research and some are of professional interest. All published papers have been refereed in anonymity by at least two subject specialists.

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Preface

It is my great pleasure to present the proceedings of the 4th SLIIT International Conference on Engineering & Technology (SICET 2025). SICET continues to grow as a platform where rigorous scholarship meets practical impact—bringing together researchers, students, industry practitioners, and policymakers to co-create solutions for the public good.

This year's programme reflects both scale, international and quality. We received 176 submissions, from which 102 papers were selected through a double-blind review process. To broaden participation and practical skills, we ran 11 pre-conference workshops, 5 of which were international, featuring hands-on tutorials and emerging methods from global partners. Ensuring fairness and depth in evaluation, over 250 reviewers contributed to the double-blind process, with meta-review and TPC decisions taken per track to balance novelty, reproducibility, and societal impact.

SICET's intellectual breadth spans 11 technical tracks—from Next-Generation Communications & Networking, AI & Data-Driven Engineering, and Clean & Renewable Energy to Mechatronics & Robotics, Thermal & Fluid Engineering, Biomedical Engineering & Smart Health Systems, Sustainable Built Environment, Circular Economy, ICT for Societal Development, Next-Generation Transportation, and Construction Dynamics & Digitalisation. Our community is proudly international, with authors and institutions represented from Australia, Bangladesh, Canada, India, Japan, Kosovo, Maldives, Portugal, Russia, South Korea, the United Kingdom, and the United States, alongside Sri Lankan universities and research institutes.

The technical agenda is anchored by two distinguished Keynote Speakers—Prof. Sofiène Affes (INRS, Canada) and Prof. Andrey Koucheryavy (SPbSUT, Russia)—and complemented by two timely panel discussions: *"The Future of Research in Sri Lanka: Vision for 2030"* and *"AI in Engineering: Our Perspective."* Reflecting our commitment to translation and impact.

Our publication pathway ensures visibility and archival value. Proceedings are planned via the ACM International Conference Proceedings Series (ICPS), with selected papers invited to partner journals, including Advances in Science & Technology (AST), Key Engineering Materials (KEM), ARIS² etc.

I am deeply grateful to the Vice Chanceller and the University management, Dean of Engineering, Technical Programme Committee, Publication Committee, Track Chairs, over 250 reviewers, Workshop chairs and Logistics Committee, the Organising Committee, and our many volunteers for their exemplary service from Faculty of Engineering of SLIIT; to our authors for entrusting us with their best work; and to our partners and supporters for enabling this community to thrive. I must thank all our Sponsers who made this event a success. I invite all participants to engage with these proceedings—build on the ideas presented here, challenge assumptions, and collaborate across disciplines and borders to advance knowledge and deliver meaningful impact.

Prof. Dush N. K. Jayakody
General Chair, SICET 2025

Message from the Chancellor

It is with great pleasure that I extend my warmest congratulations to the organizers of the 4th SLIIT International Conference on Engineering & Technology (SICET 2025) and to all the authors whose work is featured in these proceedings. SICET continues to serve as a reputable, multidisciplinary forum that unites researchers, practitioners, and students to exchange ideas that advance engineering and technology for the benefit of society.

This year, the conference received 176 submissions from around the globe, including contributions from the UK, Australia, Canada, Europe (notably Portugal and Cyprus), China, Pakistan, and many others. Additionally, we welcomed representation from nearly all universities and research institutes in Sri Lanka. Following a rigorous peer-review process conducted by multiple independent reviewers, 102 papers were accepted for presentation across various technical tracks, demonstrating our community's commitment to quality and relevance. Selected papers will be published in the conference proceedings and featured in select journals, ensuring global visibility and lasting accessibility for the research presented.

SICET 2025 encompasses eleven technical tracks that cover both core and emerging areas of engineering. I am particularly pleased to highlight the introduction of an Industry Track this year, an initiative aimed at strengthening collaboration between industry and academia, fostering technology transfer, and inspiring solutions with real-world impact. This vital connection between research and practice is crucial for Sri Lanka's innovation ecosystem and for the professional growth of our graduates.

I would like to express my sincere gratitude to the Technical Program Committee, Track Chairs, Reviewers, Publication Partners, Sponsors, and the many dedicated staff and student volunteers whose efforts made this conference possible. To all authors and participants, I wish you fruitful discussions, the establishment of meaningful new partnerships, and continued success in your research endeavors.

With best wishes for a productive and memorable SICET 2025.

Prof. Lakshman L. Ratnayake
Chancellor - SLIIT

Message from the Vice Chancellor

It is with great pleasure that I welcome you to the 5th International Conference on Engineering and Technology (SICET 2025), organised by the Faculty of Engineering at SLIIT. SICET has established itself as a respected forum where research, practice, and education come together to address important challenges in engineering and technology. This year, the conference brings together participants from around the world, along with a strong representation from Sri Lanka's universities and research institutes. This demonstrates both the diversity of our scholarly networking and the importance of international collaboration in today's world.

As Sri Lanka moves forward in a knowledge-based economy, producing highly capable researchers and graduates is essential. SLIIT is committed to supporting this effort through various research funding opportunities, industry partnerships, and international engagements. I am confident that the discussions at this conference will focus on real challenges and practical solutions that can contribute to a sustainable and progressive future. This year's conference has received more than 170 submissions from international scholars and various universities and research institutes in Sri Lanka. Such participation reflects the confidence of the academic community in SICET as a valuable platform. The technical program that spans over a wide range of areas, from next-generation communications and artificial intelligence to clean energy, smart health systems, and sustainable cities, showcases that these themes closely align with SLIIT's research priorities and its commitment to addressing real needs in society. The inclusion of an Industry Track further reflects our culture of collaboration, where academic research is connected with practical applications to create a meaningful impact for communities and industry alike.

The publication opportunities offered by SICET through international partners and SLIIT's own journals ensure that the outcomes of this conference will reach beyond these sessions and support future research and development. We are also privileged to host keynote speakers Prof. Sofiène Affes from the Institut national de la recherche scientifique (INRS), Canada, and Prof. Andrey Koucheryavy from The Bonch-Bruevich Saint-Petersburg State University of Telecommunications (SPbSUT), Russia, whose insights will guide and inspire the discussions.

The success of this conference comes from the contributions of its participants, and their commitment gives SICET its true value. I would also convey my appreciation to the organising committee and the Faculty of Engineering for the effort and dedication that made this event possible. All participants are encouraged to engage actively, share knowledge, and build meaningful collaborations. I am confident that SICET 2025 will mark another important step in advancing engineering, technology, and related fields.

Prof. Lalith Gamage
Vice-Chancellor/CEO – SLIIT

Message from the Senior Deputy Vice-Chancellor & Provost

SICET 2025 is both a showcase of frontier research and a classroom without walls. This edition brings our community together in a hybrid format, welcoming participants on site and online. The spirit of SICET is collaborative and future-facing—uniting scholars, students, industry, and policymakers to translate ideas into solutions that benefit society.

The Technical Programme reflects academic rigor and translational relevance. From 176 submissions, 102 papers were selected through a double-blind review process—with 35 international paper submissions, sessions balanced for novelty, innovation, and societal impact.

The audience is proudly global, with participation from institutions in Sri Lanka, Australia, Bangladesh, Canada, India, Japan, Kosovo, the Maldives, Portugal, Russia, South Korea, the United Kingdom, and the United States—a testament to SICET's growing international reach. This diverse participation underscores the global impact of our work. Two distinguished Keynote Speakers anchor the agenda: Prof. Sofiène Affes (INRS, Canada) and Prof. Andrey Koucheryavy (SPbSUT, Russia). In addition, two timely panel discussions—*"The Future of Research in Sri Lanka: Vision for 2030"* and *"AI in Engineering: Our Perspective"*—bring together national leaders from the NSF, NRC, the Ministry of Science & Technology, senior academics, and advisors to examine policy, talent pipelines, and innovation pathways.

The conference features a unique Industry Connect stream that highlights deployable solutions and university–industry partnerships with tangible outcomes. These outcomes include pipelines for internships, joint R&D, and sponsored capstones, demonstrating the real-world impact of our work. The publication pathway underscores quality and visibility.

I extend my sincere appreciation to the authors, reviewers, Track Chairs, the Technical Programme Committee, the organizing team, sponsors, and the Faculty of Engineering of SLIIT. Their invaluable contributions have been instrumental in making SICET 2025 a resounding success. I encourage participants to mentor generously, ask bold questions, and convert the insights gained this week into sustained collaborations that yield global benefits.

Prof. Nimal Rajapakse
Senior Deputy Vice-Chancellor & Provost, SLIIT

Message from the Dean, Faculty of Engineering

It is a pleasure to extend my warmest greetings to all participants of SICET 2025 and to present this message on behalf of the Faculty of Engineering (FoE), SLIIT. SICET has become a signature achievement of our university—an arena where high-quality engineering research is shared, challenged, and transformed into solutions that benefit society.

This year's conference again reflects both breadth and rigour. The Technical Programme spans 11 tracks and a rich slate of 11 pre-conference workshops, 5 of which were delivered by international experts. Upholding academic integrity, the double-blind review was supported by over 250 reviewers, ensuring careful assessment and constructive feedback for every submission. The resulting programme showcases outstanding work across communications and networking, AI and data-driven engineering, energy and sustainability, mechatronics and robotics, biomedical systems, the built environment, and more.

On behalf of the Faculty of Engineering, I wish to record my sincere appreciation to our leadership for their continuous guidance and encouragement: the Chancellor, the Vice-Chancellor, and the Senior Deputy Vice-Chancellor & Provost. I also thank our General Chair, Prof. D. N. K. Jayakody and the Organising Committee, Track Chairs, the Technical Programme Committee, and the many reviewers, workshop leads, volunteers, and staff whose dedication has made SICET 2025 possible. We are grateful as well to our distinguished keynote speakers and to our partners from academia, industry, and government for their collaboration.

I trust that you will find the conference, its presentations, and these proceedings valuable to your current and future research and development work. I encourage you to use SICET to exchange ideas, build new collaborations, and strengthen the bridges between universities, research institutes, industry, and society.

Wishing you a stimulating and rewarding SICET experience.

Prof. Ayantha Gomes
Dean, Faculty of Engineering, SLIIT

Acknowledgement

We are pleased to host the 4th SLIIT International Conference on Engineering and Technology (SICET 2025) in Colombo and Malabe, Sri Lanka. This multidisciplinary forum provides a valuable platform for scholarly exchange, welcoming contributions across diverse research areas including Sustainable Built Environment, Sustainable Consumption and Production, ICT for Societal Development, Transportation Systems, Mechanics, Robotics and Intelligent Systems, Thermal and Fluid Engineering, Energy and Renewable Energy Systems, Hydraulics and Water Resources, Communication and Networking, Electrical Power Systems, Machine Dynamics and Design, Contract and Risk Management, and Industry Connect technical activities.

SICET aims to unite researchers, academics, industry professionals, and policymakers in a collaborative environment to share insights, disseminate findings, and explore the latest advances in engineering and technology. To maintain the highest standards of quality, all submissions have undergone a rigorous double-blind peer review process conducted by distinguished local and international experts. Only papers that exemplified originality, innovation, and scholarly excellence were accepted, thereby ensuring the conference's credibility and impact.

Further, we would like to express our heartfelt appreciation to all who played a vital role in the success of this event. We are grateful to the authors and presenters for their insightful contributions, the reviewers for their meticulous evaluations, the session chair and co-chair for their valuable contributions within the sessions, and the organizing committee for their unwavering commitment and hard work. We also give our fullest gratitude to the sponsors for their valuable contributions and support.

We are excited about the potential for further collaboration and knowledge creation stemming from the research presented here. We encourage your ongoing exploration in cutting-edge research areas, and we eagerly anticipate your continued engagement and contributions to advance engineering and technology through SICET 2026.

On behalf of the Organizing Committee,

Prof. Prasanna Gunawardane
Publication Chair, SICET 2025

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Pre-Conference Workshops

Workshop 1: Building Information Modelling (BIM) for Structural Detailing
Conducted by: Eng. Udara Perera (SLIIT) and Eng. Sudara Withana (SLIIT)
Date: 21st May 2025

Building Information Modeling (BIM) represents a significant shift in the construction sector. It provides numerous benefits across various Civil Engineering sub-domains, particularly for structural engineers, who can leverage this software for structural detailing, particularly in rebar modeling and layout preparation.
Eng. Udara Perera is a Lecturer in the Faculty of Engineering at the Sri Lanka Institute of Information Technology (SLIIT), specializing in Civil Engineering. He is recognized for his expertise in Building Information Modeling (BIM) and green building technologies.
Eng. Sudara Withana is a Lecturer in the Department of Civil Engineering at SLIIT since 2025. His background combines academic and hands-on engineering expertise in water supply and construction projects.

Workshop 2: Telco Softwarization: The Road to Cloud-Native, AI-Driven, and Autonomous Networks
Conducted by: Eng. Anuradha Udunuwara (Sri Lanka Telecom)
Date: 23rd May 2025

The telecommunications industry has evolved significantly over the past 170 years, navigating numerous technological and business transitions. Today, Telcos face increasing pressure to reduce operational costs and generate new revenue streams in a rapidly transforming, hyper-connected digital economy shaped by shifting customer demands and market dynamics. Telco Softwarization—originally encompassing SDN (Software Defined Networking), NFV (Network Functions Virtualization), and Cloud—emerged as a response to these challenges. With recent advancements in cloud-native technologies, AI, and automation, the concept has matured, offering new pathways for Telcos to become more agile, efficient, and future-ready. This workshop aims to introduce the concept of Telco Softwarization, examine how it addresses current industry challenges, and explore its role in enabling next-generation, autonomous networks.
Eng. Anuradha Udunuwara is a seasoned Telecom & Technology expert with over 20 years of industry experience, currently serving as a Senior Engineer specializing in Enterprise Business Solutions at Sri Lanka Telecom. He is recognized as a thought leader and trusted advisor in telecom strategy, digital transformation, and next-generation network technologies, including SDN, NFV, cloud computing, and AI-driven networking.

Workshop 3: Intelligent High Frequency Communications- The Foundation of 6G
Conducted by: Prof. Alexandros-Apostolos (Aristotle University of Thessaloniki)
Date: 06th June 2025

Prof. Alexandros-Apostolos is an academic with a Ph.D. degree in Electrical and Computer Engineering from Aristotle University of Thessaloniki. His doctoral research focused on interference mitigation techniques in modern wireless communication systems. His research interests include wireless telecommunications, high-frequency wireless systems, and next-generation communications such as 6G. He is an active member of IEEE and contributes to both teaching and research in wireless communication technologies.

Workshop 4: GIS for civil engineers
Conducted by: Eng. Rashini Weerasinghe
Date: 05th and 31st July 2025

This session introduces the fundamentals of Geographic Information Systems (GIS) with a focus on its practical applications in civil engineering. Participants will gain insights into how spatial data and analysis tools support decision-making in urban planning, transportation, water resources, surveying, and environmental management.
Eng. Rashini Weerasinghe holds a BSc (Hons) degree in Civil Engineering along with a Diploma in Geographic Information Systems (GIS). She is motivated to contribute positively in the field of civil engineering, focusing on applications of GIS in urban planning, transportation, water management, and environmental projects.

Workshop 5: All Roads Lead to TinyML: The Rome of Efficient Machine Learning in Engineering
Conducted by: Dr. Dinuka Sahabandu (SLIIT), Dr. Nushara Wedasingha (SLIIT), Ms. Madusha Weerasooriya (SLIIT), Mr. Asiri Gawesha (SLIIT) & Mr. Sanka Mohottala (SLIIT)
Date: 20th August 2025

TinyML represents the convergence point of multiple pathways to efficient machine learning—each grounded in the practical demands of engineering systems. This workshop explores how diverse forms of efficiency—parameter, computational, energy, data, task, and connectivity—collectively enable the deployment of intelligent models on resource-constrained platforms. These efficiency pathways directly address challenges in engineering fields such as energy, civil infrastructure, healthcare, transportation, and environmental monitoring, where AI must operate under tight constraints in terms of power, memory, and latency. By aligning theoretical techniques with real-world use cases, the workshop bridges the gap between advanced ML research and its practical deployment across the engineering spectrum.
Dr. Dinuka Sahabandu is an Assistant Teaching Professor in the Department of Computer Science at SLIIT. He has extensive expertise in machine learning, game theory, and cybersecurity. His research work includes developing advanced algorithms for the security of cyber-physical systems, and his PhD research has been recognized and commercialized internationally, including by the U.S. Naval Research Laboratory.
Dr. Nushara Wedasingha: Lecturer at SLIIT, involved in teaching and research activities. She contributes to academic programs likely related to computing and technology, fostering innovation in her field.
Ms. Madusha Weerasooriya: Assistant Lecturer at SLIIT supporting teaching and academic development, possibly assisting in research and student mentoring within the faculty.
Mr. Asiri Gawesha: Research Assistant at SLIIT, engaged in supporting research projects and academic initiatives, contributing to the advancement of knowledge in his area of expertise.
Mr. Sanka Mohottala: Academic Instructor at SLIIT, focused on instruction and training, particularly in emerging fields such as TinyML and efficient machine learning applications for engineering.

Workshop 6: Strengthening Power System Stability: Techniques and Strategies for High Renewable Penetration
Conducted by: Eng. Ravi Prematilaka (BC Hydro Generation Engineering)
Date: 29th August 2025

Power system stability is a broad subject spanning to different areas of interest. "Frequency Stability" is one of the fundamental areas of concern especially in the realm of increased penetration of inverter-based resources (IBRs), renewables such as solar and wind. Although the supplemental energy seems more attractive, the non-dispatchable and non-inertia nature of these IBRs challenges the power system stability with different set of problems.
The workshop mainly focuses on frequency stability in terms of electrical power generation side of the business. The presenter's expertise in electrical power transmission side of the business is limited but an attempt will be made to answer questions on voltage stability, transient stability, FACT devices etc. which are considered as out of scope items.
Eng. Ravi Prematilaka holds a BSc Engineering degree from the University of Moratuwa, Sri Lanka, an MSc from the University of Windsor, Canada, and a PhD from the University of British Columbia, Canada. He is an expert in power system stability, focusing on frequency stability, particularly in systems with high renewable energy penetration. He has academic and engineering expertise that bridges international education and industry practices.

Workshop 7: Driving Sustainability in the Building Sector – Use of Tools for Whole Building Life Cycle Assessment, Life Cycle Costing and Building Circularity Index
Conducted by: Prof. Shiromi Karunaratne (SLIIT), Eng. Madhavi Herath (SLIIT), Eng. Madhushika Senanayake (SLIIT) & Eng. Abiru Abayapala (SLIIT)
Date: 09th September 2025

This workshop is designed for engineers, architects, and quantity surveyors focused on integrating sustainability into building practice through advanced assessment methodologies. It will provide in-depth guidance on the application of Whole Building Life Cycle Assessment (WBLCA), Life Cycle Costing (LCC) and the Building Circularity Index (BCI) as decision-support tools in design, specification, and procurement. Participants will explore how to quantify environmental impacts and circularity performance across a building's life cycle, with hands-on demonstrations, case study analysis, and discussion on aligning these tools with regulatory frameworks and green certification systems.
Prof. Shiromi Karunaratne is a Professor in Civil Engineering at SLIIT with a PhD and extensive experience in sustainability assessment in the building sector. She focuses on developing methods and tools for assessing building sustainability based on life cycle thinking. Her work emphasizes whole building life cycle assessment, life cycle costing, and building circularity to promote sustainable construction practices.
Eng. Madhavi Herath is an Instructor in the Faculty of Engineering at SLIIT, specializing in Civil Engineering. She holds a BSc Engineering (Hons) and has research interests in building sustainability and environmental engineering.
Eng. Madhushika Senanayake is a civil engineer affiliated with SLIIT's Department of Civil Engineering, contributing to academic teaching and research efforts focused on sustainable construction and civil infrastructure (based on typical departmental roles and collaborations).
Eng. Abiru Abayapala is part of the Department of Civil Engineering at SLIIT, engaged in civil engineering education and research, aiding in development of sustainable building practices and engineering solutions.

Workshop 8: Steam Engineering Applications for the industry
Conducted by: Eng. Janith Ratnaweera (Thermax Ltd, Sri Lanka)
Date: 09th September 2025

Steam engineering plays a vital role in various industries, including manufacturing, food processing, textiles, and power generation. With the increase in energy costs, efficient steam systems are essential for process heating and energy generation, contributing to cost savings and sustainability. Optimizing steam distribution and condensate recovery enhances productivity, reduces operational costs, and supports Sri Lanka's transition towards greener industrial practices. Regular system audits and maintenance help prolong equipment life, improve reliability, and maintain consistent performance.
Eng. Janith Ratnaweera is a Senior Applications Engineer at Thermax Ltd in Sri Lanka. He holds an M.Sc. and a B.Sc. (Hons) in Mechanical Engineering from the University of Moratuwa. Janith has experience in engineering applications related to energy efficiency, steam systems, and thermal energy solutions, contributing to sustainable industrial practices in sectors like manufacturing and processing.

Workshop 9: Digital Innovation: From Fashion Design to Apparel Manufacturing
Conducted by: Dr. R. K. J. De Silva (Department of Textile and Apparel Engineering,University of Moratuwa)
Date: 09th September 2025

This workshop focused on the digital technologies utilized in the fashion and apparel industry, particularly in relation to the digital product creation process. This workshop will provide participants with both theoretical insights and practical perspectives, empowering them to innovate and contribute to the digital future of the apparel sector. The session is thoughtfully designed to bridge the gap between industry expertise and software development, facilitating the creation of next-generation fashion tools. Participants will have the opportunity to explore our team's VR and AR applications and engage in a discussion with an educational consultant from a leading 3D CAD software organization.
Dr. R. K. J. De Silva is a Senior Lecturer in the Department of Textile and Apparel Engineering at the University of Moratuwa, Sri Lanka. She specializes in new product development for the apparel industry, focusing on virtual prototyping, digital transformation, and the application of virtual and augmented reality technologies in apparel design and manufacturing. Her research contributes to advancing fit precision, sustainable apparel production, and digital innovation in the textile sector, supporting academic and industrial progress in garment technology.

Workshop 10: Smart and Sustainable Technologies for Next-Generation Cities
Conducted by: Prof. Ammar Muthanna (Saint Petersburg, Russia), Dr. Ahmed Mohamed Aziz Ismail, (School of Engineering, Central Asian University) & Dr Rakesh Vaid (Department of Electronics,the University of Jammu, India)
Date: 09th September 2025

This workshop brings together cutting-edge innovations that collectively advance the vision of smart, sustainable, and resilient urban environments. The session on AI for City Verse Services Optimization explores how holography, virtual and augmented reality, and AI-driven insights can transform city planning, service delivery, and citizen engagement in next-generation urban systems. The discussion on Compressive Sensing for IoT Applications addresses critical challenges in energy efficiency, data security, and network performance, presenting novel solutions to optimize IoT-enabled smart services. Meanwhile, the talk on Triboelectric Nanogenerators highlights emerging energy-harvesting technologies that convert ambient mechanical energy into clean electricity, supporting decentralized and eco-friendly power systems. Together, these sessions emphasize the integration of digital intelligence, sustainable energy solutions, and efficient data management as key enablers of future cities. The workshop outcomes point toward cross-disciplinary collaboration, offering pathways for smarter decision-making, reduced environmental impact, and enhanced quality of life in urban settings.
Prof. Ammar Muthanna is a professor based in Saint Petersburg, Russia, known for his research and academic contributions in smart and sustainable technologies, particularly in the context of next-generation cities.
Dr. Ahmed Mohamed Aziz Ismail is the Dean of the School of Engineering at Central Asian University. He holds advanced degrees including a PhD and DSc in Computer Science, specializing in Cybersecurity and Artificial Intelligence. Dr. Aziz has over 17 years of academic and leadership experience globally and is active in research on Smart Cities, AI, IoT, and network security.
Dr. Rakesh Vaid is a professor and former head of the Department of Electronics at the University of Jammu, India, with expertise in electronics and communications, contributing significantly to research and academic leadership in his field.

Workshop 11: Smart Procurement Strategies to Mitigate Supply Chain Risks in the Built Environment
Conducted by: Ch.QS Janitha Bogamuwa (National Highways, United Kingdom), Ch.QS Majith Kodithuwakku (International Construction Consortium (Pvt) Ltd.), & Dr. Thamasha Jayanetti (SLIIT)
Date: 09th September 2025

The construction industry supply chain in Sri Lanka faces significant challenges such as dependency on imports, small-scale suppliers, fragile policies, limited technological adoption, and quality control issues. These risks directly impact project cost, timelines, and overall quality. This workshop will explore how smart procurement strategies and digital integration can address these challenges, improve efficiency, and strengthen resilience. Drawing from both local experiences and international best practice, the session will provide actionable insights into innovative procurement methods, policy interventions, and capacity-building initiatives tailored for the Sri Lankan context.
Ch.QS Janitha Bogamuwa is the Lead Commercial Manager at National Highways, United Kingdom. He is a Chartered Quantity Surveyor with extensive experience in commercial management, contract administration, and project delivery within large infrastructure projects.
Ch.QS Majith Kodithuwakku is the General Manager of Estimates and Contracts at International Construction Consortium (Pvt) Ltd., with expertise in construction project cost management, contracts, and procurement strategies.
Dr. Thamasha Jayanetti is a Senior Lecturer at Sri Lanka Institute of Information Technology, Malabe. She specializes in construction management, supply chain integration, and digital innovation in the built environment.

Keynote 01: Optimization Methods in Computational Intelligence for Joint Wireless Channel Parameter Estimation over Advanced Radio Interface Technologies

Prof. Sofiene Affes
Wireless Communications Group
Institut national de la recherche scientifique (INRS), Canada

ABSTRACT

Advanced Radio Interface Technologies (RITs) combine broadband signalling—hence multi-carrier operation and richly multipath propagation—with multi-antenna transceivers. In these regimes, joint estimation of channel parameters (angles of arrival/departure, delays, Doppler/frequency offsets, gains/phases, etc.) becomes a central yet challenging inference problem. Objective or cost functions are often nonconvex, multimodal, and simulator-defined, with scarce gradients, tight pilot budgets, and low signal-to-noise ratios (SNRs). Therefore, among computational intelligence (CI) categories that encompass 1) neural networks and 2) fuzzy systems, the third or 3) population-based and bioinspired optimization (PBO/BO) methods – such as particle swarm optimization (PSO), differential evolution (DE), genetic algorithms (GA), grey wolf optimizer (GWO), and related swarms – have gained traction as global search engines that either directly minimize maximum-likelihood (ML) or mean-square error (MSE) criteria or act as robust initializers for hybrid pipelines. In this talk, first we integrate a disciplinary taxonomy relating artificial intelligence (AI), optimization, and Monte Carlo inference to place CI and PBO/BO within a broader computational context worth contemplating. Then we survey the current state of the art on CI optimization for wireless channel parameter estimation and analyze the strengths and weaknesses of each CI subcategory versus the others and against conventional estimation methods. We synthesize algorithmic patterns, objectives, accuracy, convergence/complexity trends, and empirical findings, etc., over advanced RITs, and we discuss most recent progress and open challenges.

BIOGRAPHY

Sofiene Affes received the Engineering Diploma in Telecommunications and the Ph.D. Degree (Hons.) in Signal Processing from Telecom Paris-Tech (ENST), Paris, France, in 1992 and 1995, respectively. He has been since with INRS, Montreal, QC, Canada, as a Research Associate until 1997, an Assistant Professor until 2000, an Associate Professor until 2009, and from then on as a Full Professor. From, 2013 till 2019, he was the Director of PERWADE, a unique 4M$ research-training program on wireless in Canada involving 27 academic and industrial partners from 8 universities and 10 industrial organizations. Dr. Affes has been twice the recipient of a Discovery Accelerator Supplement Award from NSERC, from 2008 to 2011 and from 2013 to 2016. From 2003 to 2013, he held a Canada Research Chair in Wireless Communications. And from 2017 to 2022, he was the recipient of a Cyrille-Duquet Research Chair in Telecommunications. In 2008 and 2015, he received the VTC and ICUWB Chair Recognition Award and Certificate from IEEE VTS and MTT-S, respectively, for exemplary contributions as General Co-Chair to the success of both conferences held at their Fall 2006 and 2015 editions in Montreal. In 2017, he served as General Chair of IEEE PIMRC also held in Montreal. His team received Best Paper Awards at IEEE Globecom, IEEE ICASSP, and IEEE VTC. He has been or is currently an Editorial Board Member for the IEEE Transactions on Communications, Signal Processing, and Wireless Communications, for the Wiley Journal on Wireless Communications & Mobile Computing, the MDPI Sensors and Sci Journals, and the Electronics and Signal Processing Journal.

Keynote 02: Triple Play: AI, MV, and HTC

Prof A. Koucheryavy
Chaired Professor, Telecommunication Network and Data Transmission Department
The Bonch-Bruevich Saint-Petersburg State University of Telecommunications, Russia

ABSTRACT

At the beginning of the 21st century, with the convergence of communication networks, the term Triple Play, which included voice, video, and data services, became a popular term for the provision of services by next-generation networks. At that time, this approach meant the unity of the convergent network and the universality of the services provided to the user.Now, about a quarter of a century after that time, the development of communication networks is taking place in the direction of creating various kinds of universes based on artificial intelligence technologies. Even urban universes have appeared as a development of smart cities. At the same time, the design Artificial Intelligence (AI) plus Metaverse (MV) was considered quite popular for some time. At the global standardization symposium in New Delhi in October 2024 during WTSA-24, it was proposed to supplement this dual with a holographic type of communications (HTC). This was necessary because there is a fairly widespread opinion that society will become holographic by 2030. This proposal was made by the ITU-T Focus Group Leader Richard Lee in 2018 at the first meeting of the focus group. Considering the great potential of holographic universes and the development of technologies in the field of providing holographic telepresence services, it seems useful to use the triune design of AI + MV + HTC at present.

The report further discusses the development of artificial intelligence in the field of communication networks, the transformation of metauniverses into holographic network universes (HolNetVerse), work in the field of creating various terminals for holographic interactions and implementing telepresence services, the creation of holographic universities, the creation of holographic cities using the example of St. Petersburg, the development of a telepresence suit with parametric feedback, the capabilities of such telepresence suits together with a network universe for remote rehabilitation of patients using the example of recovery for children with upper limb injuries. All these applications show how effective the use of the new Triple Play AI + MV + HTC can be.

BIOGRAPHY

After graduating from Leningrad University of Telecommunications in 1974, A. Koucheryavy joined Telecommunication Research Institute LONIIS, where he worked till October 2003 (from 1986 to 2003 as the First Deputy Director). Dr. A. Koucheryavy holds Professor position at the Bonch-Bruevich St. Petersburg State University of Telecommunications (SUT) since 1998. There, in 2011 he became a Chaired Professor in "Telecommunication Networks and data transmission" department. Dr. A.Koucheryavy was an advisor of the Central Science Research Telecommunication Institute (ZNIIS) from 2003 to 2010. Co-founder of the International Teletraffic Seminar (1993, 1995, 1998, 2002); founder of the model network for digital networks at LONIIS (1997); co-founder of the model network for packet networks at ZNIIS (2004); co-founder of the Internet of Things Laboratory (2012) and Quality of Experience and IPTV Laboratory (2014) at SUT. Chair of the Scientific school on teletraffic theory in LONIIS (1990 – 2003); Founder and scientific school chair "Internet of Things and self-organizing networks" in SUT (2010 up to now); Steering committee member of IEEE technically co-sponsored series of conferences ICACT, NEW2AN and ICFNDS, Chair of ICACT 2020 International Steering Committee. SG11 ITU-T vice-chairman 2005 – 2008, 2009 – 2012. WP3/WP4 SG11 chairman 2006 – 2012, WP4 SG11 vice-chairman 2015-2016, Chairman of SG11 from 2016 up to March 2022. Co-founder of International Testing Center for new telecommunications technologies at ZNIIS under ITU-D competence. Host and technical program committee member of the "Kaleidoscope 2014" at SUT. Founder of the model network for telepresence services in SUT (2021). Honorary member of Popov's society (2002).

Karate Kata Scoring and Performance Evaluation Using Video Analysis and Deep Learning

H.L.S.S. Liyanage*, H.M.S.D. Deshpriya, M.T.Kavindya, R.M.L.D.Ranasinghe, H.M.D.P.Herath, A.K.N.L.Aththanagoda
Department of Computing, Rajarata University of Sri Lanka, Mihintale, Sri Lanka

ABSTRACT

Karate kata, a fundamental element of traditional martial arts, consists of choreographed sequences of stances, strikes, and blocks performed against imaginary opponents, requiring precise posture, timing, and technique. However, self-practice often lacks objective feedback, leading to unnoticed errors and uneven skill development, and even competition scoring can be influenced by subjective judgment. To address this, we present a vision-based scoring system that evaluates kata from structured video recordings without wearable sensors, providing accurate, consistent scores to help practitioners track progress. The system processes videos through a multi-stage pipeline: frames are extracted at 10 frames per second using OpenCV and segmented with YOLOv8-seg to remove background clutter. Pose estimation is performed with MediaPipe, generating 99 normalized 3D keypoints, while hip-centered normalization and pelvic-width scaling ensure consistency across different body sizes. A modified ResNet50 classifies frames into nine fundamental stances with high accuracy and near real-time processing (~150 ms per frame at 1080p), and a custom Convolutional Neural Network evaluates the angular accuracy of 14 critical joints using trigonometric analysis against reference poses. Each kata is decomposed into 19 key positions, with a stance marked correct only if both classification and joint angles ($\leq \pm 2.5°$ deviation) meet the threshold, and final scores are calculated on a 5.0–10.0 scale to align with traditional judging. Experimental results show that ResNet50 achieves 95.97% accuracy, while the CNN reaches 96.11%, demonstrating that this approach offers a low-cost, accessible, and consistent scoring tool. It supports remote training, reduces judging bias, and provides practitioners with reliable feedback to improve their kata performance.

KEYWORDS: *Karate Pose Classification, 3D Keypoints, CNN, ResNet50, Pose Scoring, Sports Video Analysis*

BACKGROUND AND OBJECTIVE

Karate kata encodes both the technical precision and strategic flow of martial arts practice. In competitions and training, judges typically assess kata based on stance stability, joint alignment, and smooth transitions. However, human evaluation can be inconsistent, and remote learners cannot receive an immediate, measurable score. While computer vision techniques offer scalability and non-intrusive data collection, they often suffer from limitations such as joint occlusions, depth ambiguity in monocular setups, and sensitivity to environmental variations like dynamic lighting and background clutter[1], [2]. The iKarate system uses Kinect IR and F-DTW, achieving 91.07% accuracy with 830 ms inference time in a structured lab environment[3]. Yoga Assist, designed specifically for yoga, recognizes 3 poses using OpenPose with 95% accuracy, though inference time is not reported[4]. Our methodology addresses these technical constraints

by leveraging a fully vision-based pipeline that combines MediaPipe's 3D keypoint extraction with YOLOv8-powered semantic segmentation to isolate the athlete from background noise. The objective of this research is to create an AI-driven, vision-only kata scoring system that produces consistent results without wearable devices, improving fairness and accessibility, mainly focusing on reducing depth ambiguity and occlusion problems.

METHODOLOGY

Figure 1: We used a subset of the MADS dataset and custom-recorded 'Geisaki Dai Ichi' kata videos, extracting 3,600 frames (400 per class × 9 classes) at 10 FPS[5]. Backgrounds were removed using YOLOv8-seg, a deep learning segmentation model, and poses were tracked with MediaPipe, a real-time framework for detecting 2D/3D human keypoints. The client–server setup handles model inference on the server, with a mobile interface (Android Studio) supporting MP4 uploads up to 600 MB and secure authentication. Hip-centered coordinate normalization, scaled by a standard pelvic width, ensured size consistency, and data augmentation (flips, ±15° rotations) improved robustness. A fine-tuned ResNet50, a 50-layer image classification network, identified nine stance classes, while a custom Convolutional Neural Network (CNN) evaluated 14 joint angles using trigonometric analysis[6]. A stance was marked correct only if both classification and angular accuracy (≤ ±2.5°) met the threshold, with scores scaled to 5.0–10.0.

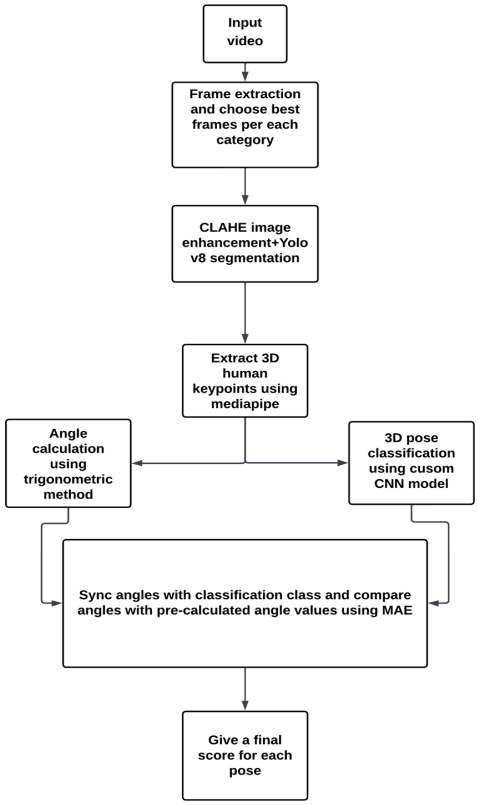


Figure 1 - Methodology high-level architecture - how models are integrated

RESULTS

Figure 2, the custom 11-layer CNN, trained on normalized 3D keypoints with regularization and preprocessing (CLAHE + YOLOv8-seg), achieved 98.16% training accuracy and 96.11% on unseen data, with a mean angular error of ±2.5°. Though it's ~578 milliseconds, inference time limits real-time use. Figure 3, the fine-tuned ResNet50, a 50-layer neural network that can classify images, trained on 3,600 frames, resized inputs (384×512), achieved 98.28% training and 95.97% validation accuracy, with ~150 ms inference per 1080p frame. Together, the models provide consistent kata scores across sessions, with hip-centered normalization and pelvic scaling reducing positional bias.

	precision	recall	f1-score	support
hachijiDachi_jodanYoko	0.90	0.99	0.94	70
sanchinDachi_ageUke	0.99	0.90	0.94	82
sanchinDachi_jodanTsuki	0.97	0.97	0.97	91
sanchinDachi_sotoUke	1.00	0.95	0.97	75
shikoDachi_gedanBarai	1.00	1.00	1.00	73
sotoUke_maeGeri	0.95	1.00	0.98	79
zenkutsuDachi_awaseTsuki	0.98	0.95	0.97	87
zenkutsuDachi_chudanTsuki	0.95	0.97	0.96	87
zenkutsuDachi_empiUke	0.99	1.00	0.99	76
accuracy			0.97	720
macro avg	0.97	0.97	0.97	720
weighted avg	0.97	0.97	0.97	720

Figure 2 - Classification report of the custom CNN used for 3D classification

Classification Report:

	precision	recall	f1-score	support
0	0.98	0.99	0.98	80
1	0.94	1.00	0.97	79
2	0.82	1.00	0.90	74
3	0.99	0.76	0.86	88
4	1.00	0.99	0.99	73
5	0.99	0.96	0.97	71
6	0.99	0.99	0.99	95
7	0.98	0.98	0.98	86
8	0.99	1.00	0.99	74
accuracy			0.96	720
macro avg	0.96	0.96	0.96	720
weighted avg	0.96	0.96	0.96	720

Figure 3 - Classification report of fine-tuned ResNet50

CONCLUSION

This research introduces a practical, vision-only kata scoring framework that bridges the gap between computer vision research and martial arts training. For academia, it contributes a reproducible pipeline that combines deep learning and biomechanical analysis in a novel application domain. Karate offers a standardized, objective scoring method that supports fairer judging, consistent athlete development, and broader access to performance evaluation tools. This work also presents a robust approach to karate pose classification and evaluation using 3D human pose detection, keypoint extraction, and CNN-based classification. By integrating MediaPipe for extracting body angles and using a comprehensive dataset, the

model achieves high accuracy in identifying and evaluating karate katas. The system facilitates feedback generation by comparing extracted angles with predefined pose standards, enabling learners to refine their techniques effectively. The inclusion of a gamified training environment enhances user engagement, making this tool valuable for martial arts training and assessment. The results demonstrate the system's potential to support athletes and instructors in achieving precision and consistency in karate practices. Future improvements will target faster on-device processing and expanded kata coverage.

REFERENCES

[1] M. Fernando, K. D. Sandaruwan, and A. M. K. B. Athapaththu, "Evaluation of Taekwondo Poomsae movements using skeleton points," *J Natl Sci Found*, vol. 52, no. 1, pp. 143–156, 2024, doi: 10.4038/jnsfsr.v52i1.11986.
[2] J. Echeverria and O. C. Santos, "Toward modeling psychomotor performance in karate combats using computer vision pose estimation," *Sensors*, vol. 21, no. 24, Dec. 2021, doi: 10.3390/s21248378.
[3] B. Emad *et al.*, "IKarate: Improving Karate Kata," in *Procedia Computer Science*, Elsevier B.V., 2020, pp. 466–473. doi: 10.1016/j.procs.2020.03.090.
[4] R. Huang, J. Wang, H. Lou, H. Lu, and B. Wang, "Miss Yoga: A Yoga Assistant Mobile Application Based on Keypoint Detection." [Online]. Available: https://github.com/gym-tutor/Miss-Yoga-App
[5] Zhang, W., Liu, Z., Zhou, L., Leung, H., & Chan, A. B. (2017). Martial arts, dancing and sports dataset: A challenging stereo and multi-view dataset for 3D human pose estimation. *Image and Vision Computing, 61*, 22–39. https://doi.org/10.1016/j.imavis.2017.02.002.
[6] J. Y. Choi, E. Ha, M. Son, J. H. Jeon, and J. W. Kim, "Human Joint Angle Estimation Using Deep Learning-Based Three-Dimensional Human Pose Estimation for Application in a Real Environment," *Sensors*, vol. 24, no. 12, Jun. 2024, doi: 10.3390/s24123823.

Design, Manufacturing and Operation of a Down draft Gasifier for Coconut Shell Charcoal Generation in Dankotuwa, Sri Lanka.

Ruwan Nagahawatta, Dilum Perera, Janith Ratnaweera, Pulina Nilanka

ABSTRACT

This study presents the design, fabrication, and operation of a downdraft gasifier specifically developed for coconut shell charcoal production in Dankotuwa, Sri Lanka. Traditional pit methods of charcoal production result in low yields, uncontrolled emissions, and limited process control. The proposed gasifier overcomes these issues by enabling batch feeding of green coconut shells from the top, continuous operation, and controlled partial oxidation to extract charcoal without reducing it to ash. The system incorporates a combustion cone with four strategically oriented air nozzles to ensure uniform material flow and high-temperature combustion, followed by a rotating grate in the reduction zone to regulate charcoal expulsion. Commissioning trials with a 1000 kg feedstock demonstrated a certain charcoal yield of at least 28% (w/w) while generating producer gas of sufficient calorific value to replace approximately three cubic yards of wood logs per 10-hour shift for industrial heating. The dual outputs of charcoal and producer gas provide both economic and environmental benefits, making the system a viable solution for small- to medium-scale enterprises seeking sustainable, low-cost energy.

KEYWORDS: *coconut shells, charcoal generation, down-draft gasifier, syngas, producer gas, industrial heating*

BACKGROUND

In Sri Lanka coconut shell charcoal production is primarily achieved by the traditional pit method. The pit method is basically partial combustion of coconut shells in a limited oxygen environment, using an open earth pit. Products are then quenched utilizing water. This traditional method comes with challenges such as air pollution due to uncontrolled emission of partially combusted gases, lesser yield, and constrained/unavailability of process parameters to control the carbonization process. With reference to the challenges faced in the traditional method, the requirement would arise for a mechanical device which can generate coconut shell charcoal by partial oxidization of the coconut shells(Rahman et al., 2021). As of 2017, there were 41 companies exporting charcoal, out of which main 8 companies proceeded to exporting activated carbon (*Export Market of Coconut Shell Charcoal and Coconut Shell Activated Carbon in Sri Lanka: Drivers and Bottlenecks*, n.d.). Systematic and continuous extraction of the producer gas can be utilized for heating or power generation application. The parameters related to the operation of the machine would provide the ability to control the carbonization rate.

Gasifiers can be seen to be commonly utilized as mechanical devices to generate producer gas and charcoal from biomass. The downdraft gasifier is a type of gasifier construct specifically used due to its lower tar generation rate characteristic. In downdraft gasifier fuel is loaded from the top. It mainly consists of drying, pyrolysis, combustion and reduction zone. In applications focusing only on the producer gas generation, ash will be output of the process. The reduction of the biomass inside the gasifier can be varied by design or operation to ensure extraction of charcoal as per the desired quality and quantity. The subject novel design discussed herein, is a downdraft type gasifier designed to extract coconut shell charcoal from green coconut shell, as the feedstock(Kelaiya et al., n.d.). The continuously extracted producer gas is of desired quality, which can be utilized for heating applications or power generation.

THEORY

Technical problem

Utilization of coconut shells as the feedstock for a downdraft gasifier operation poses multiple challenges. Operating for extraction of coconut shell charcoal can be further challenging. In existing

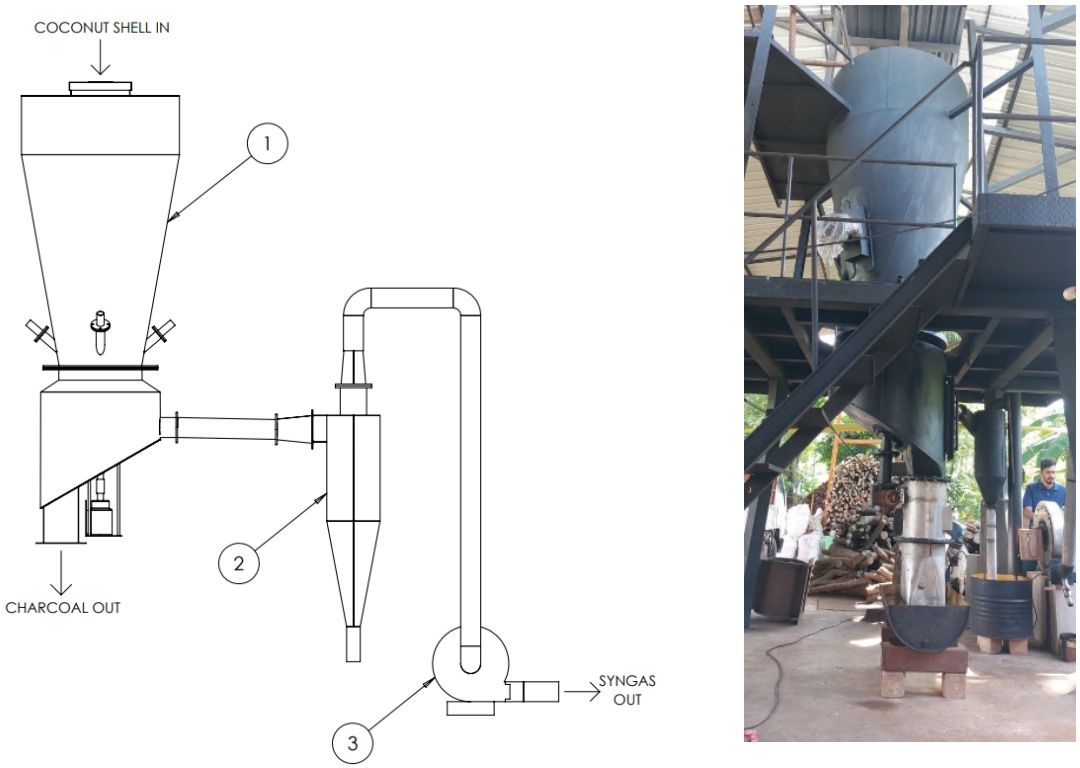
designs, the coconut shells would undergo the processes of drying, pyrolysis, combustion and reduction, which generates ash. The design discussed here is able to extract the feedstock as charcoal avoiding reduction of the same resulting in ash generation. The design ensures avoiding bridging of the coconut shells inside the gasifier which can disrupt the continuous operation of the machine.

Technical solution

The coconut shell charcoal is batch fed from the top where a healthy stock is maintained in the hopper. With the continuous operation of the unit, the shells will flow downwards. The material in the hopper will experience drying and pyrolysis processes in order (top to bottom), due to the heat transferred to the top from the combustion zone. After the hopper, material will flow through the throat area in the combustion cone. The throat in the combustion cone creates a restricted area where residence time (flowrate of the material) is controlled. Utilizing four nozzles, fresh air is supplied into this combustion cone creating a high temperature combustion zones. The nozzles are oriented in such a manner that the draft generated supports continuous downward flow of the material.

Below the combustion cone is the reduction bed, where its bottom will be a rotating grate. A bed of material is maintained on this rotating grate. The rotating speed of this grate will determine the charcoal expelling rate from the bed of material. The reduction bed is designed to ensure a generous amount of space for charcoal extraction from the bed. By controlling the grate speed, the extraction stage of the material was controlled, thus avoiding ash generation. The material will be extracted at the charcoal stage avoiding further reduction which will result in ash generation. The charcoal which falls off the edge of the rotor and reduction bed will be collected at the bottom of the outer cylinder. It will be then dry collected utilizing two air-locked sliding doors. This enables dry collection of charcoal without disrupting the continuous operation.

DESIGN AND FABRICATION



1(a) **1(b)**

Figure 4(a) & (b) – Design and fabrication of the charcoal generator

The design calculations and conceptualization were adhered to the guidelines made by the author's previous work. (Perera et al., 2024). The design and fabricated version of the charcoal generator are illustrated in Figure 1(a) & 1(b).

RESULTS

2(a) **2(b)** **2(c)**

Figure 5(a) – Green Coconut shell as the input; 2(b) - Charcoal as the main product; 2(c) - Producer gas as the byproduct.

A load of 1000kg was successfully processed in the system during the commissioning of the unit. In contrast to the traditional pit method, this design was able to obtain the yield of charcoal as well as producer gas. The owner of this charcoal gasifier was a coconut oil producer. With the help of a Air heat exchanger, the coconut kernels were dried utilizing the heat gained from the combustion of the producer gas.

Industrial applicability and Advantages

The gasifier was commissioned in 2023, and it was proven that the gasifier was to work as per the specified operating conditions of 800kg per 10-hour shift feed rate. The design was initiated in 2019. In spite of construction being scheduled to be 6 months, due to the status of the country of social economical unrests and corona virus, it took nearly 4 years to fabricate the design.

Batch feeding is done from the top while continuous operation can be carried out. The design is able to avoid common challenges related to downdraft gasifier operation on coconut shells, such as channeling and bridging of the fuel. The gasifier is able to extract (dry collection) the coconut shells at the charcoal stage without complete oxidation of the solids which will result in ash generation. The producer gas which is generated as a byproduct has a colorific value hence can be utilized as a gaseous fuel input for any heating application or power generation purpose.

In this particular installation, the gasifier was able to generate a charcoal yield not less than 28% (w/w basis) while also generating sufficient Producer Gas which catered for the previous woodlogs requirement for the heating application. Considering 10 hours shift per day, savings from fuel alone, accounted for the cost of approx. 3 cubic yards of wood logs. By selling the coconut shell charcoals, the plant user earned extra income which further justified the investment.

CONCLUSION

The development and successful commissioning of the downdraft gasifier for coconut shell charcoal generation in Dankotuwa, Sri Lanka, demonstrates a practical and sustainable alternative to the traditional pit method. The novel design effectively addresses the common challenges of fuel bridging, uncontrolled emissions, and ash formation, while enabling continuous operation with batch feeding of green coconut shells.

Trial runs provided a charcoal yield of at least 28% (w/w) along with simultaneous production of producer gas of adequate calorific value for industrial heating applications. This dual output not only reduces dependency on conventional firewood but also generates additional revenue through the sale of high-quality charcoal. Furthermore, the controlled operation of the system minimizes environmental impacts by reducing particulate and gaseous emissions compared to open-pit combustion.

This design is suitable for small and medium scale entrepreneurs who need sustainable energy requirements at lower cost.

ACKNOWLEDGEMENTS

Mr. Indika, the owner of coconut oil production facility at Dankotuwa, Sri Lanka is thankfully acknowledged.

REFERENCES

1. *Export Market of Coconut Shell Charcoal and Coconut Shell Activated Carbon in Sri Lanka: Drivers and Bottlenecks*. (n.d.). Retrieved July 30, 2025, from https://www.cabidigitallibrary.org/doi/pdf/10.5555/20183230597
2. Kelaiya, S., Dobariya, U., & Makavana, J. (n.d.). *Experimental Investigation on Open-Core Downdraft Gasifier for Bio-Char Production and Gaseous Fuel from Caster Stalk—Google Search*.
3. Perera, K. D. M., Ratnaweera, H. G. J. N., & Nilanka, A. A. P. (2024, October). *Design and Development of a 50kW Producer Gas Generator in Sri Lanka*. SLIIT International Conference on Engineering and Technology. https://rda.sliit.lk/handle/123456789/3801
4. Rahman, M. M., Aravindakshan, S., & Matin, M. A. (2021). Design and performance evaluation of an inclined nozzle and combustor of a downdraft moving bed gasifier for tar reduction. *Renewable Energy*, *172*, 239–250. https://doi.org/10.1016/j.renene.2021.02.156

Comparison of Pile Driving Equations

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ABSTRACT

In Sri Lanka, remote highway projects, driven piles are installed in large quantities mainly as a ground improvement where the soft soil thickness is very high and closer to the bridges to decrease the settlements. In building sector as well, the installation of the driven piles are very common to decrease the foundation construction time and has seen the installation of driven piles as the settlement reduction means. Recently, silent pile installation technology has increased and the Sri Lankan investors has invested large sum of money for the silent hammers.

Capacities of the piles can be estimated using the pile driving equations during installation of the piles. This is very convenient to determine the capacities of the piles without performing a pile load test. On the other hand, this can be reducing the site investigation requirements to a minimum. As the capacities of the piles are estimated during installation, it can take into account in-situ subsurface conditions. The rapidly varying ground conditions, especially in Sri Lanka, or any other location, can be captured by pile driving records. Recently, especially in Sri Lanka, the installation of the PHP piles with a hollow area at the middle of a pile section has increased. The design community multiplies the area of the pile cross section by the end bearing capacity to obtain the end bearing force whether it is a PHP pile or a solid pile.

This research will compare the pile driving equations with each other and select the best pile driving equations which predict the capacity very close to the measured capacity as an extension of the earlier research done by Thilakasiri and Jayaweera (2009). In addition the mobilization of the end bearing capacities in PHP piles with a hollow area at the middle of a pile section is compared with a solid pile and a relationship is derived to predict the capacity of the hollow area as a function of the hollow area as a percentage of the total area of the pile cross section.

Keywords: Diven piles*, pile driving equations, pile driving records, PHP pile, Capacity og the pile*

Introduction

The sound and ground vibrations are two major issues for driven piles but in Sri Lanka, where effect of these problems do not matter like remote Highway projects these piles are installed in large numbers. Large investments have gone in to the silent pile driving equipments. Fastness of construction and use of Pile driving equations and medium load carrying capacity are some of the major advantageous of driven piles. There are significant numbers of driven piles are installed in spite of the ground vibrations and noise issues during installation of driven piles.

In Sri Lanka, “Guidelines for Interpretation of site investigation data for estimating the carrying capacity of single pile for design of bored and cast in-situ reinforced concrete pile” Publication number ICTA/DEV/15 is there to guide the designer regarding bored piles but similar guidelines are not there for driven piles mainly due to lack of research done regarding driven piles in Sri Lanka. This research is done in Sri Lanka to compare the measured and theoretically determined carrying capacity of from pile driving equations. Moreover, a very recently popular PHP, mobilizations of the end bearing capacities are compared with the solid piles.

Four driven pile were installed very close to the two boreholes drilled (at the location of TP 1& TP 2, BH 7 + 669N L1 and at the location of TP 03 & TP 4, BH 7 +720L were drilled) and these four piles were tested using Pile Driving Analyzer test (PDA). The locations of the piles tested are given in Figure 1 and the borehole logs drilled at this location is given in Figure 2a and 2b. Out of the four piles tested at these locations, two piles are 300mm x 300mm precast-concrete piles (TP 01 and TP 03) and the other two piles (TP 02 and TP 04) are 400 mm diameter spun piles with the 210mm diameter hollow space at the middle of the pile crossection.

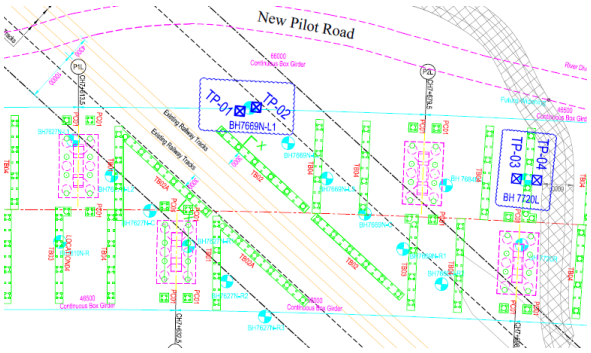

Figure 1 – The plan view of the location test piles and the borehole locations

2.0 Ground condition

Subsurface conditions at the location of TP1 and TP2 is given by BH 7 + 669NL1 and the subsurface condition of TP3 and TP 4 is given by BH 7 + 720 L. Those borehole logs are given by the Figure 2a and 2b.

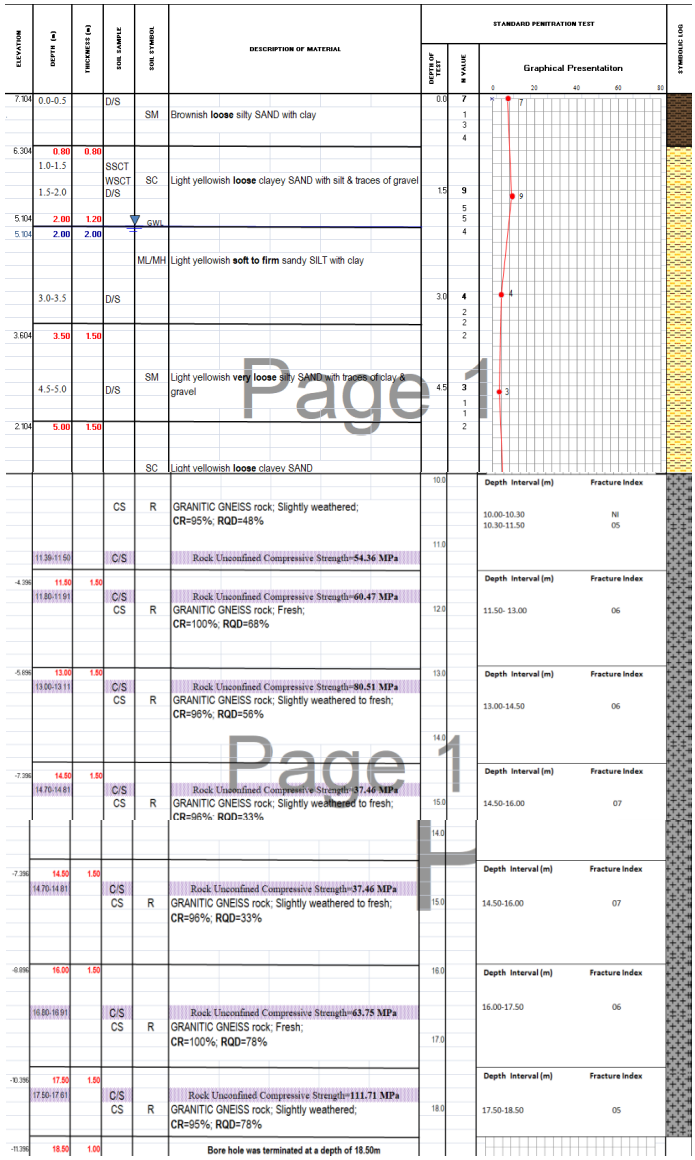

Figure 2a – Borehole log of the BH 7 + 669NL1 with the SPT blow counts

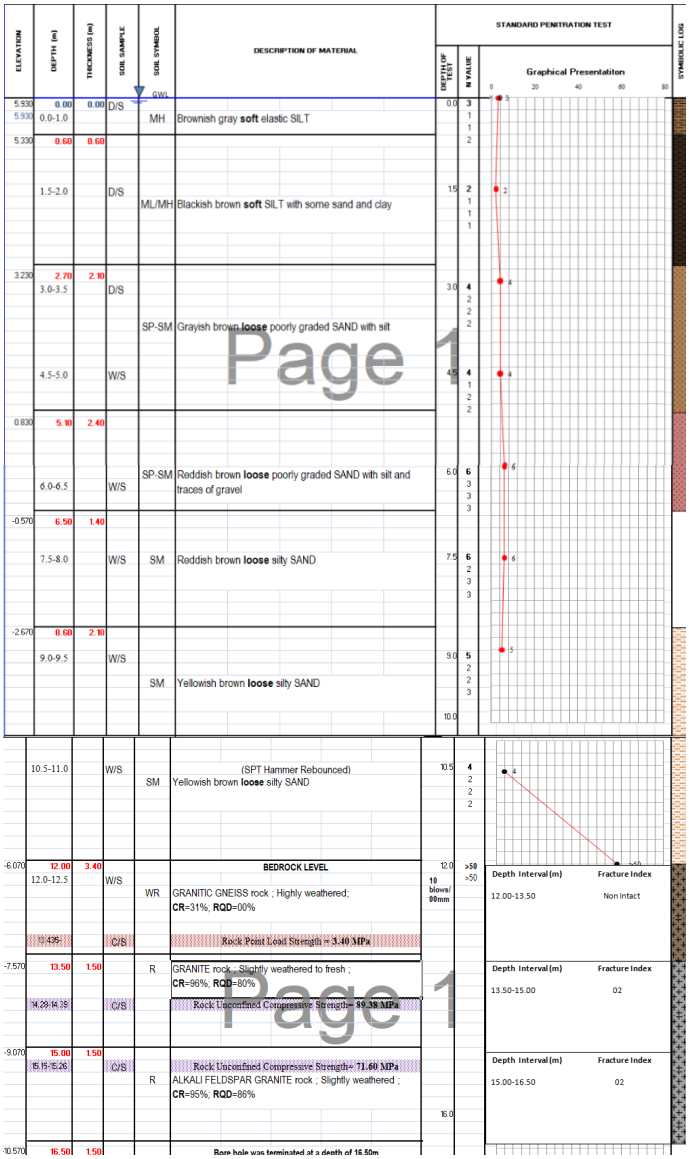

Figure 2b - Borehole log of the BH 7 + 720 L with the SPT blow counts

Based on the borehole records, the subsurface condition given in Table 1.

Table 1 – The subsurface conditions at the Borehole locations

BH 7 + 669 N L1			BH 7 + 720L		
Thickness (m)	N_{Field}	Strength properties (c_u (kPa) or ϕ')	Thickness (m)	N_{Field}	Strength properties (c_u (kPa) or ϕ')
0.80	7	ϕ' = 29	0.60	3	c_u = 35 kPa
1.20	9	ϕ' = 27	2.10	2	c_u =15 kPa
1.50	4	c_u = 20 kPa	2.40	4	ϕ' = 25
1.50	3	ϕ' = 23	1.40	6	ϕ' = 26
2.00	5	ϕ' = 24	5.50	4 - 6	ϕ' = 23 - 25
1.50	11	ϕ' = 27	-		

The material strength parameters are determined from the method outlined in Bowles (1997)

The depth to the bedrock at the locations of the BH 7 + 669NL1 is 8.5m below the ground surface and the same at BH 7 + 720L is 12m. The depth of the installation of the piles TP 01 and TP 02 at the location of BH 7 + 669NL1 are 9.27m and 9.763m with the terminated at the pile penetration set of 10mm/10 blows and the 09/10 blows respectively using a hydraulic hammer with a weight of 4 tons and a stroke of 1m whereas the same quantities for the Piles T03 and T04 are at the location of at BH 7 + 720L are 15.005m and 15.541m at the 1mm/ 10 blows and 6mm/10 blows respectively. According to the pile penetration and the borehole logs, the TP 01 has penetrated into rock 0.77m (9.27 – 8.50) at 1mm per blow and TP 02 has penetrated in to rock 1.263m (9.763 - 8.5) at 0.9 per blow respectively. Same quantities for piles T03 and T04 are 3.005m (15.005-12.00) at 0.1 mm per blow and 3.541m (15.541 – 12.000) at 0.6mm per blow respectively.

All the piles have penetrated some distance in to the bedrock and are sitting on the bedrock. Penetration of the pile to bedrock at the location of TP 01 and TP 02 having CR 83, RQD 23 and unconfined compression stress of 42.73 MPa. The bedrock is identified as slightly weathered granitic gneiss. The location of TP 03 and T P04, the bedrock is having highly weathered granitic gneiss rock having CR 31, RQD 00 and unconfined compression stress of 3.40 MPa (from the point load index tests) from 12.0m to 13.5m. Below that level, slightly weathered to fresh bedrock is present with CR 96 and RQD 80 with the UCS equal to 89.38MPa. Penetration of the piles 1.505m and 2.041m into this rock cannot be anticipated if the ground conditions are different than this at the locations of pile installation or the pile is broken at the tip.

3.0 PDA Results

A summary of the PDA results of the four piles are shown in Figure 3a and 3b respectively for the pile TP 01 & TP 02, and TP 03 & TP 04 respectively

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CAPWAP SUMMARY RESULTS

Total CAPWAP Capacity: 2971.7; along Shaft 1588.8; at Toe 1382.9 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile kN	Sum of Ru kN	Unit Resist. (Depth) kN/m	Unit Resist. (Area) kPa
				2971.7			
1	4.2	3.0	146.3	2825.4	146.3	49.39	41.16
2	6.3	5.1	205.4	2620.0	351.7	98.00	81.66
3	8.4	7.2	492.7	2127.3	844.4	235.07	195.89
4	10.5	9.3	744.4	1382.9	1588.8	355.15	295.96
Avg. Shaft			397.2			171.76	143.14
Toe			1382.9				15365.56

Soil Model Parameters/Extensions Shaft Toe

CAPWAP SUMMARY RESULTS

Total CAPWAP Capacity: 2627.0; along Shaft 1560.9; at Toe 1066.1 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile kN	Sum of Ru kN	Unit Resist. (Depth) kN/m	Unit Resist. (Area) kPa	Quake mm
				2627.0				
1	2.1	1.4	61.1	2565.9	61.1	43.46	34.58	3.7
2	4.2	3.5	110.1	2455.8	171.2	52.78	42.00	3.7
3	6.3	5.6	221.0	2234.8	392.2	105.94	84.31	3.7
4	8.3	7.7	456.5	1778.3	848.7	218.84	174.15	3.7
5	10.4	9.8	712.2	1066.1	1560.9	341.42	271.69	3.4
Avg. Shaft			312.2			160.09	127.40	3.5
Toe			1066.1				8483.75	2.7

Soil Model Parameters/Extensions Shaft Toe

Figure 3a– PDA results of pile TP 01 & TP 02

CEP SECTION 1 (04-05-2022); Pile: TP-03_1 Test: 04-May-2022 11:16
300X300; Blow: 20 CAPWAP(R) 2014-3
ELS (Pvt) Ltd OP: AMILA

CAPWAP SUMMARY RESULTS

Total CAPWAP Capacity: 2996.0; along Shaft 1736.5; at Toe 1259.5 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile kN	Sum of Ru kN	Unit Resist. (Depth) kN/m	Unit Resist. (Area) kPa	Quake mm
				2996.0				
1	3.1	2.6	84.7	2911.3	84.7	32.98	27.49	7.1
2	5.2	4.6	101.7	2809.6	186.4	49.08	40.90	7.1
3	7.3	6.7	203.9	2605.7	390.3	98.41	82.01	7.1
4	9.3	8.8	220.9	2384.8	611.2	106.61	88.84	7.1
5	11.4	10.9	240.9	2143.9	852.1	116.26	96.89	7.1
6	13.5	12.9	301.2	1842.7	1153.3	145.37	121.14	6.4
7	15.5	15.0	583.2	1259.5	1736.5	281.47	234.56	5.4
Avg. Shaft			248.1			115.77	96.47	6.4
Toe			1259.5				13994.44	5.4

Soil Model Parameters/Extensions Shaft Toe

CAPWAP SUMMARY RESULTS

Total CAPWAP Capacity: 2190.0; along Shaft 1336.6; at Toe 853.4 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile kN	Sum of Ru kN	Unit Resist. (Depth) kN/m	Unit Resist. (Area) kPa	Smith Damping Factor s/m
				2190.0				
1	3.1	2.8	41.3	2148.7	41.3	14.96	11.91	0.53
2	5.1	4.8	44.5	2104.2	85.8	21.81	17.36	0.53
3	7.1	6.8	56.1	2048.1	141.9	27.50	21.88	0.53
4	9.2	8.9	67.2	1980.9	209.1	32.94	26.21	0.53
5	11.2	10.9	173.1	1807.8	382.2	84.85	67.52	0.53
6	13.3	13.0	375.7	1432.1	757.9	184.17	146.56	0.53
7	15.3	15.0	578.7	853.4	1336.6	283.67	225.73	0.56
Avg. Shaft			190.9			89.11	70.91	0.54
Toe			853.4				6791.14	0.27

Soil Model Parameters/Extensions Shaft Toe

Figure 3b – PDA results of piles TP 03 & TP 04

In the bedrock the piles TP01 and TP02 skin frictions are mobilized at 7.2m depth below the grade 195.89 kPa and at 7.7m depth below the grade 174.15 kPa respectively whereas in the bedrock of TP 03 and TP 04 mobilizes skin friction mobilized at 12.9m below the grade is equal to 121.14 kPa and at 13m below the grade 146.56 kPa respectively. Therefore, the skin friction of the weathered rocks or soils may vary from 121.14 kPa to 195.89 kPa.

4. Pile Driving Records

The pile penetration record is shown in Figure 4.

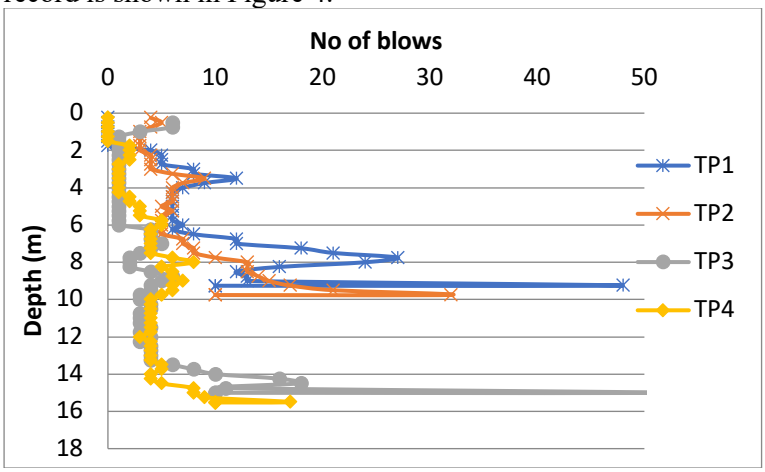

Figure 4 – Pile driving record

5.0 Static capacity estimation

To estimate the skin friction (SF) of pile (f_s) for clayey soils was initially proposed by Tomlinson (1971) as $f_s = \alpha c_u$ (units of c_u)

where α = Coefficient from Figure 5 (Re-produced by Bowles (1997)

c_u = average cohesion (or s_u) for the soil stratum of interest

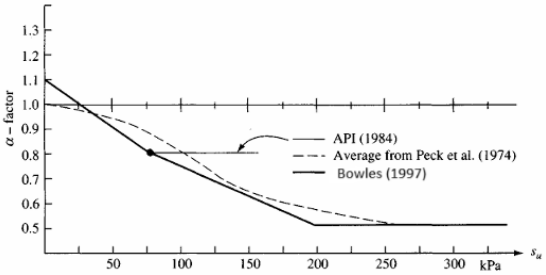

Figure 5 - Relationship between the adhesion factor α and undrained shear strength s_u

Based on the standard penetration test (SPT), following relationships are presented in Bowles (1997). Accordingly,

(i) Meyerhof (1956, 1976) suggested obtaining skin friction (F_s) as: $f_s = \chi_m N_{55}$ (kPa)

Where χ_m = 2.0 for piles with large-volume displacement
χ_m = 1.0 for small-volume piles
N_{55} = Statistical average of the blow count in the stratum (and with any corrections)
(ii) Shioi and Fukui (1982) suggested the following:
For driven piles: $f_s = 2N_{S,55}$ for sand; $= 10N_{c,55}$ for clay
For sandy soils for driven piles, skin friction is given by $f_s = 2N_{S,55}$.
Using the above relationships the SF of the soil is calculated. However, the piles are penetrated into rocks as well. The rock's SF and end bearing (EB) capacities are determined from the PDA results. Accordingly, EB capacities of the 300 x 300mm square piles are taken as 13994 kPa (Lowest value of EB capacity mobilized) whereas same for the spun files are determined to be 6791 kPa. Similarly, the skin friction capacity value is taken as 225 kPa (Smallest value of the mobilized SF of the final element). Taking those SF and EB capacities, the static capacities of the piles were determined.

5 Comparison of predicted capacities

The Pile driving equations are used to determine the capacities of the pile. The capacity of the pile determined were compared with the measured capacities of the pile in are shown in Table 2. It should be noted here that the pile driving equations and the parameters were obtained from Poulos and Davis (1980)

Table 2 – Capacity measured and capacity predicted

Capacity estimation method	Capacity (kN)	Pile considered	Measured capacity (kN)	Factor of safety (FoS) with respect to the measured capacities
Hiley pile driving equation	2090	TP 1	2971	0.703
Gate pile driving equation	1052			0.354
Danish pile driving equation	1414			0.476
ENR pile driving equation	1503			0.506
Janbu pile driving equation	2449			0.823
Static capacity using soil properties	2056			0.692
Hiley pile driving equation	1961	TP 2	2627	0.746
Gate pile driving equation	1136			0.432
Danish pile driving equation	1456			0.554
ENR pile driving equation	1503			0.506
Janbu pile driving equation	2450			0.930
Static capacity using soil properties	1774			0.676
Hiley pile driving equation	1954	TP 3	2996	0.652
Gate pile driving equation	1253			0.418
Danish pile driving equation	1478			0.493
ENR pile driving equation	1503			0.506
Janbu pile driving equation	2323			0.775
Static capacity using soil properties	2104			0.702
Hiley pile driving equation	1935	TP 4	2190	0.883
Gate pile driving equation	1100			0.502
Danish pile driving equation	1442			0.658
ENR pile driving equation	1503			0.506
Janbu pile driving equation	2423			1.106
Static capacity using soil properties	3480 -			1.588

7.0 Data Analysis

The static capacity estimation method gives a factor of safety (FoS) of 0.696 – 1.588 with respect to the measured capacities. Few observations are made based on the data resented in this paper. First it is shown that the Hiely formula is the closest conservative one to the measured capacity with a factor of safety ranges from 0.652 – 0.883. Even though Janbu method of capacity estimation method gives closer to measured value values than Hiely method for three cases, the other pile capacity slightly estimated over the measured capacity with a factor of safety of 0.775 – 1.106. However, it is noted that a FoS that goes with

these capacity estimation methods of 3.0, the over prediction shown by Janbu method is negligible. It is noted that the Janbu method of capacity prediction using pile driving equation is always more closer to the measured capacity than static capacity prediction using soil properties,. The Engineering News Record (ENR) method even with a simple method of calculation, yields a FoS of 0.506. The Danish pile driving equation with a FoS of 0.476 to 0.658. The Gate's pile driving method under predict the measured capacities with a FoS of 0.354 – 0.502.

In the bedrock the piles TP01 and TP02 end bearings mobilized are 15365.56 kPa and 8483.75 kPa respectively whereas in the bedrock of TP 03 and TP 04 mobilized end bearing capacities are equal to 13994.44kPa and 6791.41kPa (for TP 2 and TP 4, area of the entire pile section without considering the hollow area ($\pi x0.4^2/4$)) respectively. Unlike in SF, even though the cross sectional areas of solid piles and the PHP piles 90,000mm^2 and 91,027 mm^2 are approximately equal, probably because of the middle hollow area of the PHP piles, it consistently mobilized the lower end bearing capacities considering the actual cross sectional areas of the piles 91,027mm^2. In the bedrock, the end bearing capacities mobilized for solid piles varies from 15365 kPa to 13994 kPa.

8 Conclusions

Even though pile capacities of the driven piles can be determined using pile driving equations, despite some theoretical drawbacks, is easy way of determining capacities. It is proven by the capacities measured and the capacities estimated in various pile driving equations are given in Table XX, some method predicts closer than other methods to the measured capacities. That shows the importance selection of pile driving equation method for the problem you are working on. From this research the best pile driving method has immerged as the method proposed by Janbu with a Factor of Safety (FoS) 0.775 – 1.102 with the measured capacities. Hiely method is the conservative method of capacity prediction with a FoS of 0.652 – 0.883 with the measured capacity. The other pile driving equations like ENR method or Danish methods have a factor of safety around 0,5, according to this study, are not suitable to determine the driven pile capacities. The Gates method over predict the capacity,

The other conclusion can be made that the PHP piles with a hollow area at the middle of the pile cross section it consistently shows that the measured end bearing capacities are significantly lower than the end bearing capacities of the solid piles without the hollow area at the middle of the pile cross section. When four piles are considered, end bearing capacities mobilized without a hollow area in the pile cross sections are 15365 and the 13994 kPa, and with the hollow area at the middle of the pile cross section are 11711.9 kPa and 9371.9 kPa (considering actual cross sectional area of the pile = 91027 mm^2). It can be speculated that about 66.9 to 76.2 prcent of the capacities are mobiles, if the pile cross section to the hollow area cross section is 25%. The other conclusion it can be drawn from this study is the even though presence of a hollow area in the middle of the pile cross section affects the end bearing capacity of the pile, the skin friction is not affected.

9 References

1. Boles, J. E. (1997), Foundation Analysis and Design, International Edition, McGraw-Hill,
2. Meyerhof, G. G. (1956), Penetration Tests and Bearing Capacity of Cohesionless Soils. JSMFD, ASCE, vol. 82, SM l,pp. 1-19.
3. Meyerhof G. G. (1976), Bearing Capacity and Settlement of Pile Foundations, JGED, ASCE, vol. 102, GT 3, March, pp. 195-228 (Terzaghi Lecture).
4. Poulos, H. G. and Davis E, H. Foundation Analysis and Design, 1980, Rainbow-bridge Book co.
5. Shioi, Y. and J. Fukui, (1982), Application of N-Value to Design of Foundations in Japan, 2nd ESOPT, vol. l, pp. 159-164.
6. Skempton, A. W. (1986), Standard Penetration Test Procedures , Geotechnique, vol. 36, no. 3, pp. 425-447.
7. *Thilakasiri, H. . and Jayaweera, R.*, (2009)**,** Investigation of the Accuracy of the Dynamic methods of Capacity Estimation of Piles, *Engineer, J. of Inst. of Engineers, Sri Lanka, Vol 42, No 04, 2009*, pp. 75 – 85.

Smart Train-Elephant Collision Management System

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ABSTRACT

This paper presents a novel solution for the Train-elephant collision issue. It is a national-level issue, and a higher number of elephants die yearly. Approximately 47 elephants died from 2021 to 2024 due to a train-elephant collision. Therefore, we introduce a novel technical management system to avoid train-elephant collisions. The primary objective of this work is to explore the details of the issue and implement the system to repel the elephant using a real-time warning system. Simulation and hardware implementation were both carried out for the final outputs. In addition, introduce a communication system to make the train driver and the two nearby stations aware. The study demonstrates the potential real-time implementation system for the train-elephant national-level issue.

KEYWORDS: *Elephant detection system, Warning system, Elephant-Train collision, YOLOv8n.*

INTRODUCTION

At present, elephants are facing very crucial and saddest situations all over the world. Due to various human activities, human-elephant conflict increases day by day. According to the data of the Department of Wildlife Conservation, more than 170 people and nearly 500 elephants were killed due to human-elephant conflicts [1]. In addition, nearly 20 elephants were killed due to train-elephant collisions, and there is an annual number of elephant deaths in Sri Lanka. This is one of the main impacts on the wildlife system.

Figure 1 shows the total number of elephant deaths from 2012 to 2025 (up to 7 March 2025), including deaths due to train collisions. According to the statistics, nearly 47 elephants have died between 2021 and 2024. Compared to 2024 and 2025, there were a higher number of elephant deaths due to train collision incidents. Nowadays, train-elephant collisions are a national-level issue and are still unable to find a practical solution to this matter.

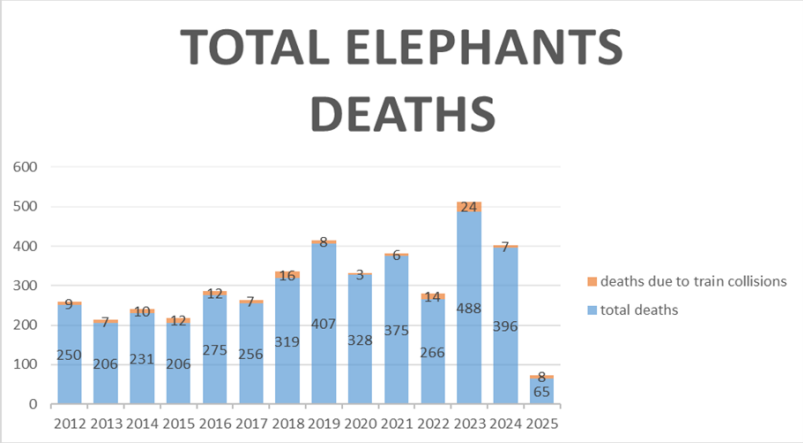

Figure 1. Total elephant deaths from 2012 to 2025 (up to date 7 March 2025), including deaths due train collisions.

Figure 2 shows the identified elephant-train collision that frequently occurred areas. However, the Department of Zoology and Environmental Sciences, University of Colombo, Sri Lanka, investigated elephant-train collision data from 2010 to 2023 and identified six critical collision hotspots. Those are 1.

Galgamuwa to Maho 2. Kekirawa to Palugaswewa 3. Manampitiya to Welikanda 4. Aluth Oya to Kanthale 5. Gal Oya to Minneriya 6. Palugaswewa to Gal Oya [2].

Figure 2. Areas that are identified as elephant-train collisions frequently occur.

The main contributions of the paper are:

1. Identify the real-time implementation system through the survey.
2. Implement the elephant detection system and emergency warning system.
3. Conceptual design to implement the communication system under future works using the existing railway communication between two railway stations.

When we were researching train elephant collisions, we found a few similar research papers. The first paper describes a system that fixes an overhead camera in a railway crossing area where railway accidents happen, which can monitor the crossing. Using the SSD object detection algorithm will detect animals that cross the railway line, and an alert will be sent to the train stations. If the object is detected in 30 seconds. Here, the main issues were that if an elephant is detected, a message is sent to the nearest station. Also, if the camera detects an elephant when it passes the station, there is no way to notify the train driver. Also, the message goes to the station 30 seconds after the camera detects the elephant. In our project, we send the signal directly to the train driver, which increases its accuracy.
The second one is based on visual elephant detection by utilising the YOLO V3 CNN-based object detection framework. An Arduino board with a SIN800L GSM/GPRS module was interfaced with the Nvidia Jetson board of the detection unit. Utilising this module, the detection unit can send periodic SMS messages. The mobile app also updates the distance to the detection unit on a real-time map along with the detection status. However, no action is taken to remove the elephant from that location. In our project, a siren and a blinking light are used to remove the elephant, and a signal is sent to the train driver. Our unit turns on after the train arrives at the relevant station.

SYSTEM DESIGN

Here, we design the overall system model for the smart train elephant collision management system. Further, we focus on implementing the system at the elephant crossing point “Alimankada”. Figure 3 shows the block diagram of the overall system model. There are three main parts of this system: an elephant detection system, an emergency warning system, and a communication system.

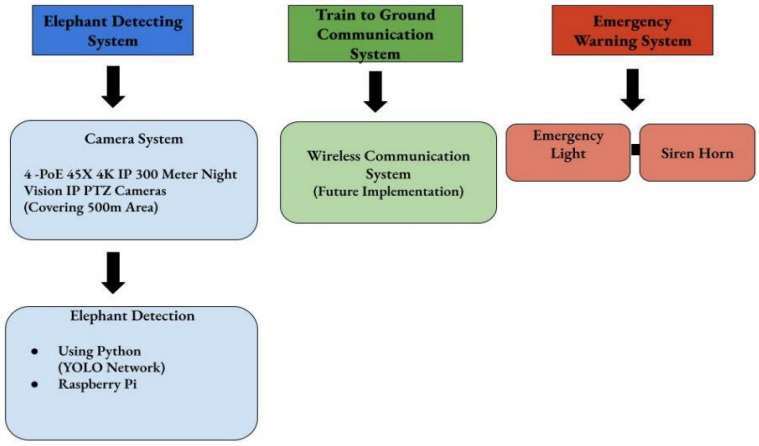

Figure 3. The block diagram of the overall system.

Figure 4 shows the overall system flow chart and how the system works step by step. Initially, we turn on our camera unit manually when a train comes to one of those two stations. After that, our system will continuously detect if an elephant is detected by our camera unit, immediately send a warning to the train indicating a red light on the train, and our emergency siren system will start automatically to drive away the elephant from the railway line. If there weren't an elephant, we would send a signal to the train to say that the railway line is safe by indicating a green light on the train. One of the special features of our unit is that when elephants try to cross the railway from left to right, we activate only our right-side emergency system to make sure that the elephant will return to the forest instead of crossing the railway line. Same as for the other side.

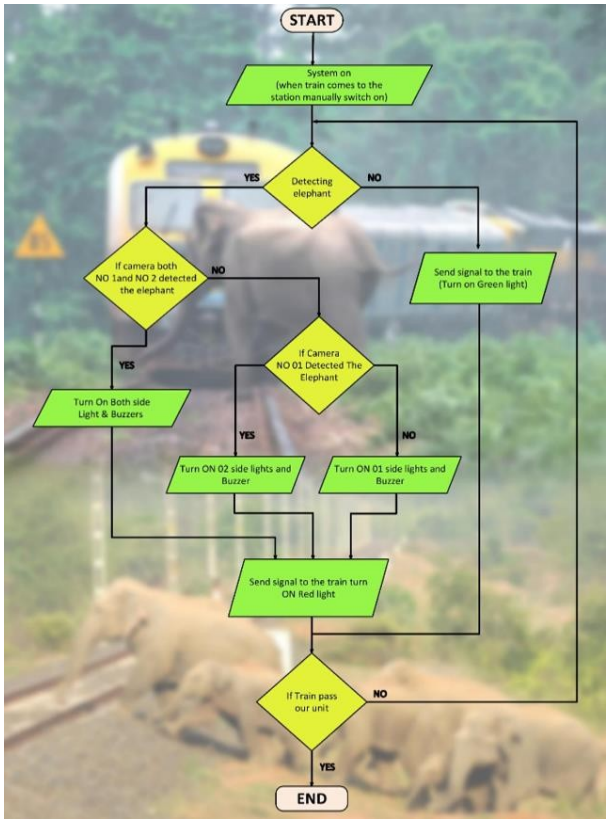

Figure 4. Overall system flow chart.

Elephant Detection System and Emergency Warning System

This system aims to identify the elephant at the elephant crossing point “Alimakada”. Figure 5 shows the exact idea of the system model, and it shows the way they place cameras and buzzers. Figure 6 shows the camera unit placement at the “Alimankada”. There are four cameras along with four emergency lights and two sirens' horns. All units are perpendicular to the railway line.

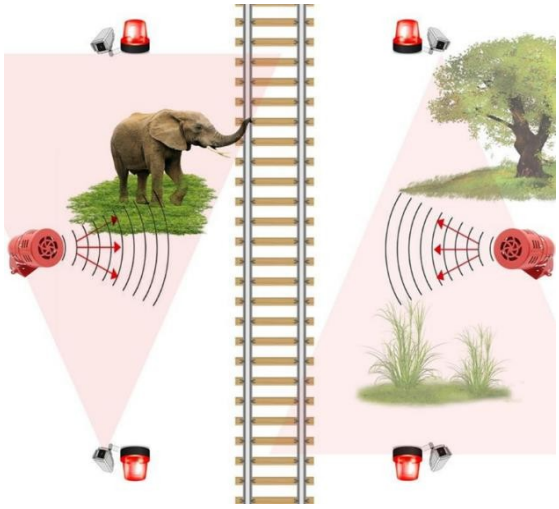

Figure 5. Overall view of the elephant detection system.

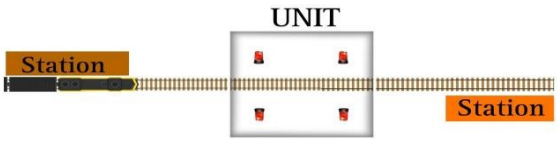

Figure 6. The camera unit placement at the “Alimankada”.

When the train comes to one of the railway stations, we will switch on our camera unit. After that, our camera unit will detect elephants using YOLOv8n. YOLO is a single-shot detector that uses a fully Convolutional Neural Network (CNN) to perform object detection in static images by classifying objects, localising their positions using bounding boxes (a visual representation of coordinates on an image defined by a rectangular or square region), and recognising the objects based on their predicted class labels and probabilities. If the image of the camera is detected as an elephant, we send three output signals (12V) by using our Raspberry Pi board to the train, emergency light, and siren horn through a relay module. The relay module is controlled by manual switches on each station.
When the train comes to the station switch turns on our relay module, and it stays on until the train comes to the other station. After the train comes to the other station, the manual switch turns off at that station. Our cameras detect elephants and send a signal to the train by indicating green (no elephant detected) and red (Elephant detected) lights in the train continuously when trains are between our two stations. With that information, the engine driver can make decisions about whether to go, stop, or slow down. When an elephant detects and sends the signal to the train, at the same time, our emergency warning unit will activate. The siren horn will trigger the repellent sound with a 1450Hz [3] frequency to drive away elephants back into the forest, and the emergency light will make a huge impact at night. All these “Alimankada” areas are close to national parks and forests; therefore, we use solar power to power up the system.

1.1.1 Camera Unit

We use Hikvision TandemVu PTZ cameras to detect elephants. The TandemVu PTZ cameras feature Hikvision’s next-generation camera design, integrating multiple lenses in one security camera to provide

a big picture and small details in tandem. It has two main views first one super wide view: Panoramic channel supports a 180° ultra-wide view. Second one, smart linkage: Automatic target detection via the panoramic channel with instant target tracking via the PTZ channel. It has a ColorVu feature that provides colour images overnight with a fixed, F1.0 lens that lets in as much light as possible. Also, it has DarkFighter: Pan, tilt, and zoom for vivid details even in low light. It provides high-quality imaging with 6 MP resolution for the bullet channel and 8MP for the PTZ channel. Maximum resolution in the bullet channel is 3680 × 1656, and in the PTZ channel is 3840 × 2160. Figures 7 and 8 show the performance of our PTZ camera in day and night.

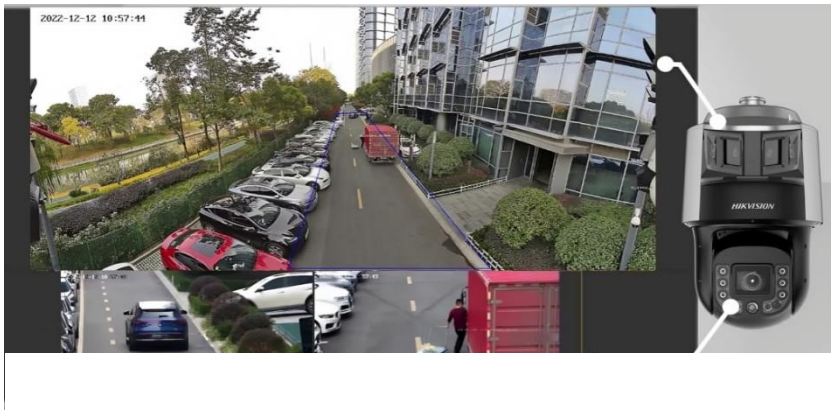

Figure 8. Night light camera performance.

1.1.2 Power Unit

In the system, most power is consumed by the 4 cameras and the unit (elephant detection process unit). When considering other components, such as siren horns and blinking lights in the warning system, those components are not working all the time. It will trigger only if an elephant is detected while the train is between the relevant two stations. Because of that, we can neglect siren horns and emergency lights. Table 1 shows the power consumption of our system for two days.

Table 1. Table of power consumption of the system.

component	power consumption (W)	amount	Power consumption for two days (Wh)
camera	24	4	4608
unit	20	1	960
Total			5568

We use a 314Ah Prismatic Lithium-Ion Cell Battery. Each battery has 3.2V, and we can create a 12V battery pack using four cell batteries. Using two battery packs, we can get a total of 7536Wh. There will be a 20% loss due to heat. However, that can give power to the system for two complete days without a solar power unit. The system powers up solar panels and uses the battery to store the energy.

2 RESULTS AND DISCUSSION

Figure 9 shows the elephant that correctly identified the system. Using the YOLOv8n algorithm enhanced the accuracy of detecting only elephants, and our basic requirement was satisfied. There are four cameras installed in the total system, and each camera can identify the elephant correctly within a range of 300 m. Figure 10 shows the implemented prototype overall system. It shows the emergency warning system and activates the siren and emergency light to repel the elephant. In addition, send the signal to the train to make it aware of the situation.

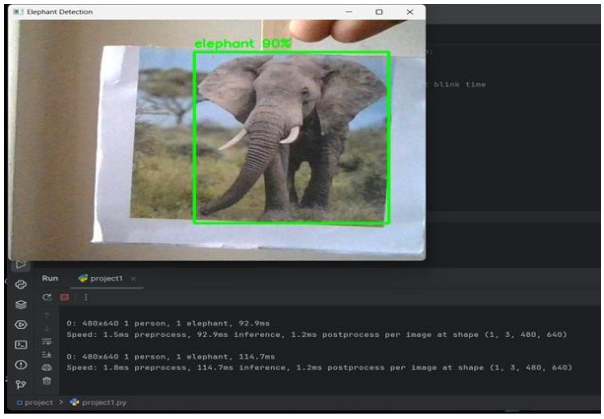

Figure 9. The system identified the elephant using YOLOv8n.

Figure 10. The prototype implemented an elephant detection system and an emergency warning system.

3 CONCLUSIONS

This paper investigates a novel solution for the Train-elephant collision issue. In conclusion, the hardware-implemented prototype system successfully met the objectives. The prototype system has undergone various tests and finally achieved the expected outcomes. This paper mentioned all technical details and component details briefly. This paper provides a strong foundation for future work in communication systems. Before implementing this in real real-time system needs to be tested by choosing a frequent hotspot such as Palugaswewa–Gal Oya Junction. At most 3 months should be spent studying in the camera unit before implementing this in other hotspots. In the future system will develop to detect other animals as well as people. This system is the solution to the burning issue of saving wildlife as well as the people in Sri Lanka.

4 FUTURE WORKS

Future work could involve a communication system in this project. This future work could explore communication between Alimankada and the train driver, and between Alimankada and to railway station to be aware of the situation at Alimankada. Figure 11 shows the conceptual design for future implementation.
We are using fibre optics to communicate between Alimankada and the stations. There are a few reasons why we are using fibre optics, such as High Bandwidth, which supports long-distance data transmission with minimal signal loss.
Communicating between Alimankada and the train driver, we are using 3 ESP32 boards. Using Wi-Fi can create a simple client or peer-to-peer network between ESP32 boards. It is relatively straightforward to implement, has potentially higher data transfer rates, and can be extended to larger networks.

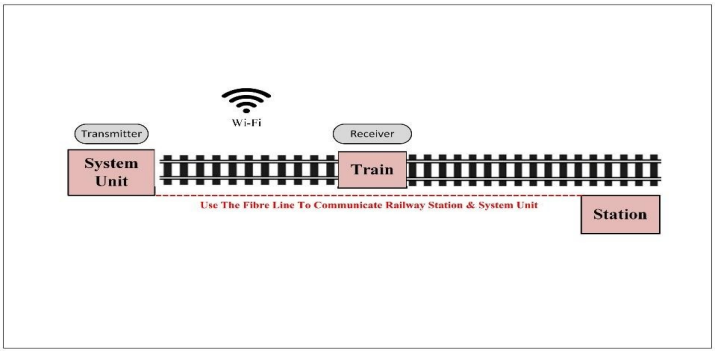

Figure 11. Conceptual design for the communication system.

REFERENCES

1. M. Rodrigo. (7 March 2025). As Sri Lanka's rail tracks continue to claim elephant lives, experts suggest solutions. MONGABAY. https://news.mongabay.com/2025/03/as-sri-lankas-rail- tracks-continue-to-claim-elephant-lives-experts-suggest-solutions/.
2. Tanya Karunasena, "Assessment of landscape and railway features associated with elephant train collisions.https://www.researchgate.net/publication/385242663_Assessment_of_ landscape_and_railway_features_associated_with_elephant-_train_collisions.
3. E. M. Eng.S.Jeyarama, "Design and Development of Elephant Repellent System," International Journal of Research Publications, 2022.
4. L. R. Omkar Vivek Sabnis, "A novel object detection system for improving safety at unmanned railway crossings," IEEE, Chennai, India, 2019.
5. M. J. N. H. L. S. G. D. Shanaka Gunasekara, "A Convolutional Neural Network Based Early Warning System to Prevent Elephant-Train Collisions," IEEE, Kandy, Sri Lanka, 2021.

Enhancing Patient Safety with the MedAlert SYstem (MASY): A Low-Cost Timer for Medication Administration Alerts

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NSBM Green University Homagama

ABSTRACT

When it comes to patient safety, the timely administration of medication tends to be a critical factor in almost all the healthcare related environments, especially in hospital wards of any scale and clinics where multiple patients simultaneously require any form of medication. In many small to medium scale hospital wards and rural healthcare environments, where commercially available systems which are developed for patient management tend to be extremely costly to deploy due to many factors such as the scale of the facility and lack of staff with the necessary knowledge to run and maintain such a sophisticated system, staff always seem to rely on logbooks for the purpose of tracking the issued doses and the times at which these specific medications are issued. This process is prone to human error, inefficiency, data tampering, and lack of accountability. This paper therefore presents an economical solution addressing the issues mentioned above: the MedAlert System (MASY), which is a low-cost, standalone timer unit specifically designed and developed for healthcare settings. This system, based on the popular Arduino open-source platform, enables medical staff members to manage multiple medication timers simultaneously with no reliance on any logbooks or other external references. This system also offers both visual and auditory alerts to ensure that medication is always administered at the correct time. Unlike commercial patient monitoring systems implemented in large-scale hospitals, MASY can operate independently, with no reliance on servers or internet connections. Due to its simplicity, this system can be easily modified and implemented according to local workflows. This paper discusses the system's software, design, human machine interaction, and the future scope of the system's development. It is believed that implementing such a simple device has the potential to reduce missed or delayed medication doses and, in turn, improve patient safety in almost any setting.

KEYWORDS: *Alert System, Arduino, Digital Time Controls, Medication, Patient Safety*

1.0 INTRODUCTION

Medication safety continues to be a pressing issue in healthcare settings (World Health Organization, 2022). Administering medications at the right time is crucial, as delays can extend recovery and pose a threat to the medication safety in the patients (Nagar & davey, 2015). In many hospitals and clinics in rural areas, staff heavily rely on a manually maintained logbook to issue time sensitive medicine to patients, and it increases the potential risk factor for human error, missed dosages, and minimal accountability (Kaufmann et al., 2012). Integration of digital health tools to practice becoming a solid solution in addressing these drawbacks (Religioni et al., 2025).

1.1 Background

In large scale hospitals and private care centers, sophisticated patient monitoring systems exist. However, such systems are extremely costly, making it impractical to be implemented in small hospitals and rural clinics where resources are heavily constricted (Bates & Gawande, 2003). In such settings, medical staff rely on logbooks to issue medication to patients. This manual approach has disadvantages such as human error, omissions, data tampering, and inconsistencies which can affect patient safety (Koppel et al., 2018). More to add, a hospital ward is a busy environment where each staff member is held responsible for more than one patient, which increases the cognitive load on staff and in turn increases the risk of a wrong or missed dose (Kohn et al., 2000; Gurses et al., 2008). These missed doses will lead to poor therapeutic outcomes and prolong hospital stays which add costs to the healthcare system as well as to patients, whereas developing automated strategies which could be used at the patient's bedside lead to minimizing events of missed, early or late doses and reduce the length of hospital stays (Patel et al., 2019).

1.2. Problem Identification

The unavailability of a simple, affordable, and reliable system that will track and alert staff regarding medicine dosages creates a gap in current healthcare workflows in many hospitals world-wide since manual logbooks cannot offer automated reminders and rely on accurate maintenance. Existing systems are often too costly and complex to implement in wards with only a few patients. Additionally, usability challenges of such systems can hinder their effectiveness in improving patient safety (Pruitt et al, 2023). Therefore, there is a clear need for a simple and cost-effective system that can track multiple medication intervals simultaneously, provide clear visual and auditory alerts for medical staff, ensure accountability by being by the patient's bedside to dismiss alarms, and operate entirely on its own with no reliance on external connections. Hence, this project aims to develop an intuitive, user-friendly MedAlert System to bridge the gap between the aforementioned facts.

1.3. Objective

The objective of this project is to build a cost-effective timer unit which will be adaptable to any local workflow in hospital wards and care centers, especially in environments with limited resources with no reliance on external servers or other connections.

2.0 METHODOLOGY

This unit was built around similar concepts previously implemented by developers of the Arduino platform (Medicine Reminder with Arduino, 2023). It is also based on embedded system principles, in this case with the use of microcontroller-based automation for time-dependent tasks (Arduino, 2025). MedAlert System design and implementation took a methodical approach with the combination of hardware assembly and software development into a functional and cost-effective medical alert system to improve working conditions of medical staff.

2.1 Requirement Analysis

The project began by investigating the technical and functional specifications of an intuitive medical alert system. The key specifications were adjustable timers, visual and auditory alerts, low power usage, a simple user interface, and low-cost components. Comparison with commercial solutions and MASY was also done to decide missing features and guide future enhancement (Hayes et al., 2009).

2.2 System Design and Working Principles

2.2.1 System Design

System design was performed based on requirements with the Arduino Nano platform because it finds the balance between cost, portability, and functionality. The final design consists of an input interface with membrane buttons for timer usage, a 16x2 I2C LCD display, LED, and audio buzzer for alerts and user interaction, and a 5V power input. Modular construction was used to allow for future expansion (e.g., for more timers or communication modules).

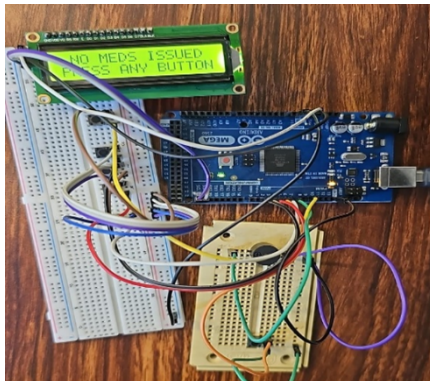

Figure 2.1- Apparatus in pre-development stage

2.2.2 Working Principles

(i) Microcontroller Systems

A microcontroller is an integrated circuit designed to manage specific operations in embedded systems. The MASY uses the Arduino Nano due to its low power usage, sufficient I/O capability, and compact size (Arduino, 2025). The use of an Arduino platform offers easy integration of peripherals, and software-programmable logic.

(ii) Timer Implementation

The timer operation is at the heart of MASY. Unlike real-time clocks (RTCs), MASY is based on countdown timers, which are implemented using the millis function. The function returns the number of milliseconds passed since the system started and supports non-blocking delay, such that different timers can be executed without inhibiting system operation (Banzi et al., 2014).

Figure 2.1 – How timers are displayed on MASY

(iii) Human-Machine Interface (HMI)

User operation is offered via membrane buttons and an LCD display. MASY's current button functionality is as follows. The three buttons that are mounted on the front of the unit (Red, Yellow, Green) are programmed to trigger individual timers and the blue button mounted in the front is to cycle between active timers. Another button is mounted in the underside of the unit to abort active timers if they are triggered accidentally. Plus, a button is mounted at the bedside of the patient which will be used to dismiss the alarms when the countdown timers hit zero. The use of I2C interface simplifies wiring and conserves microcontroller pins, providing for future expansion (Last Minute Engineers, 2020).

Figure 2.3 – MASY button layout (main unit)

Figure 2.4 – Model example of dismiss button mounting

(iv) Alert Mechanisms

When the timer runs out, LEDs and a buzzer are activated to provide visual and auditory feedback. This two-modality provides redundancy and enhances the chance of the user perceiving the alarm, which is important in a hospital setting. The alerts are triggered through digital output pins and manipulated in the program logic.

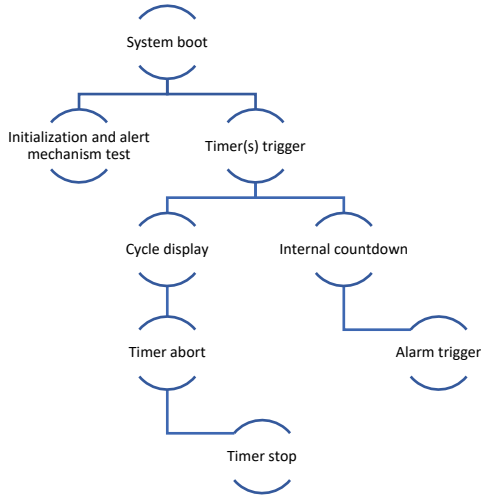

Figure 2.5 – Procedural framework of MASY

2.3 Testing and Validation

The complete system was subjected to a series of functional tests to validate timer independence and accuracy, visual and auditory alert functionality, user interface clarity and responsiveness. Any issues presented were resolved iteratively during development. All the testing and validation criteria were adopted from past literatures on similar projects (Mankhair et al., 2025; Naveen kumar et al., 2023; Ni et al., 2019)

3.0 RESULTS & DISCUSSION

3.1 Results

Tests proved that MASY was reliable under simulated clinical environments. MASY is equipped with three timers that are fully adjustable through the source code and can run simultaneously. Software strain tests proved that any timer can be triggered and run with accuracy with no interference to any other functions. This observation ensures that MASY can handle multiple timers accurately. A simple self-test was programmed at the startup of the system where all the components are triggered to detect any failures during startup which eliminates chances of hardware faults. Hardware was implemented so that off-the-shelf components can be used to cut costs. The system showed exceptional performance during each testing phase where no issues were detected. MASY was developed with no ties to costly component supply chains which makes it ideal for resource-constricted facilities where using advanced patient management systems is impractical. Arduino's form factor and programming language further justifies its sustainability and ease for deployment under any condition. MASY is modular, and development processes proved that the system can be assembled in many layouts. This versatility factor proved that it can be integrated into any workflow with necessary modifications. To sum up, MASY demonstrated strong hardware and software performance in a small form factor. It also proved to align with necessities of small healthcare facilities where the system is to be deployed, validating its effectiveness of replacing logbook systems of recording medication timing intervals.

3.2 Discussion

Strengths

According to Hayes et al., 2009, simple time-based reminders are effective in improving compliance with medications. MASY represents a significant step towards simple, adaptable medical reminder systems. Its design offered an operational and portable prototype that was particularly suited for medical settings such as hospital wards and single-bed treatment centers. The system is simple to use with clean controls ensuring ease of operation. The result is similar to the Medicine Reminder and Indicator system developed using the Arduino platform in India (Naveen kumar et al., 2023).

Figure 3.2 – Example for application of Med Alert system in a single-bed treatment center.

Microcontroller based medicine reminder alarm systems with automated medication boxes is reported to be cost-effective (Ni et al., 2019). Although MASY does not include a pill box component, it breaks cost barriers for institutions that are unable to access commercial solutions. MASY can be tailored to specific needs, which is particularly beneficial for small or underfunded clinics. MASY is advanced with comparative Performance. When compared to other commercial options in the market such as Med-Q and LiveFine, MASY has extra features like complete local workflow customizability.

Limitations

Despite its benefits, the current MASY prototype has several limitations. It lacks data logging capabilities, making it unsuitable for tracking patient compliance. Additionally, the absence of a Real-Time Clock (RTC) means the system relies solely on countdown timers rather than scheduled alerts. Its scalability is limited, supporting only a small number of timers with. Furthermore, the system does not include user authentication features such as password protection or RFID access, which are often essential in secure clinical environments.

Future Scope

MASY can be significantly enhanced through future developments. Adding an SD card module would allow data logging, while integrating a Real-Time Clock (RTC) module will enable precise alerts beyond basic countdown functionality. Incorporating communication technologies such as Bluetooth would support system expansion and remote monitoring. Furthermore, implementing security features like RFID tags or pin protection would help eliminate chances of unauthorized access. Collectively, these enhancements could transform MASY into a more robust and semi-automated medication management solution, extending its use in a wider range of clinical environments.

4.0 CONCLUSION

This paper presented MASY, a low-cost medication alert system designed to improve patient safety. MASY addresses the limitations of manual logbooks by providing a simple interface for managing multiple medication timers simultaneously, with both visual and auditory alerts. Based on the Arduino platform, MASY offers advantages in cost-effectiveness, portability, and adaptability to local workflows. Testing validated the system's reliable timer functionality and effective alert mechanisms. Future development could incorporate features like data logging, an RTC module, and enhanced security measures to expand its functionality and applicability. MASY represents a significant step towards improving patient safety, in resource-limited environments.

6.0 REFERENCES

1. Arduino. (2025). *Nano | Arduino Documentation*. Docs.arduino.cc.https://docs.arduino.cc/hardware/nano/
2. Banzi, M., Shiloh, M., & Ja'c. (2014). *The Open Source Electronics Prototyping Platform Make:*
3. *Getting Started with Arduino 3rd Edition*. https://barreirolab.com/wp-content/uploads/2016/12/c0ee2-make_getting_started_with_arduino_3e_9781449363338.pdf
4. Bates, D. W., & Gawande, A. A. (2003). Improving Safety with Information Technology. *New England*
5. *Journal of Medicine*, *348*(25), 2526–2534. https://doi.org/10.1056/nejmsa020847
6. Gurses, A.P., Carayon, P., & Wall, M. (2008). Impact of performance obstacles on intensive care nurses'
7. workload, perceived quality and safety of care, and quality of working life. *Health Services Research*, *16*,32-38. https://www.researchgate.net/publication/313568514_Impact_of_performance_obstacles_on_intensive_care_nurses
8. Hayes, T. L., Cobbinah, K., Dishongh, T., Kaye, J. A., Kimel, J., Labhard, M., Leen, T., Lundell, J.,
9. Ozertem, U., Pavel, M., Philipose, M., Rhodes, K., & Vurgun, S. (2009). A Study of Medication-Taking and Unobtrusive, Intelligent Reminding. *Telemedicine and E-Health*, *15*(8), 770–776. https://pmc.ncbi.nlm.nih.gov/articles/PMC2998278/
10. Kohn, L. T., Corrigan, J. M., & Donaldson, M. S. (2000). *To err is human: Building a safer health*
11. *system*. PubMed. https://pubmed.ncbi.nlm.nih.gov/25077248/
12. Koppel, R., Wetterneck, T., Telles, J. L., & Karsh, B.-T. . (2018). Workarounds to Barcode Medication
13. Administration Systems: Their Occurrences, Causes, and Threats to Patient Safety. *Journal of the American Medical Informatics Association*, *15*(4), 408–423. https://doi.org/10.1197/jamia.m2616
14. Kaufmann, J., Laschat, M., & Wappler, F. (2012). Medication Errors in Paediatric
15. Emergencies. *Deutsches Aerzteblatt Online*. https://doi.org/10.3238/arztebl.2012.0609
16. Last Minute Engineers. (2020, November 8). *Interface an I2C LCD with Arduino*. Last Minute
17. Engineers; Last Minute Engineers. https://lastminuteengineers.com/i2c-lcd-arduino-tutorial/
18. Mankhair, A., Rathi, G., Gole, S., Naphade, G., Patil, A., & Student. (2025). *Medicine Box Using*
19. *Arduino Uno*. *11*. https://ijirt.org/publishedpaper/IJIRT176886_PAPER.pdf?utm_source=chatgpt.com
20. *Medicine Reminder With Arduino*. (2023, January 21).
21. https://justdoelectronics.com/medicine-reminder-with-arduino/
22. Nagar, S., & davey, nicola. (2015). Reducing avoidable time delays in immediate medication

23. administration - learning from a failed intervention. *BMJ Quality Improvement Reports*, *4*(1), u206468.w2612. https://doi.org/10.1136/bmjquality.u206468.w2612
24. Naveen kumar Y, Vinod, Suresh, R., & N Jagadeeswaran. (2023). Movable Automatic Medicine
25. Reminder and Indicator Using Arduino. *Journal of Mines Metals and Fuels*, 173–179. https://doi.org/10.18311/jmmf/2022/31223
26. Ni, N., Hlaing, S., & San, S. (2019). Alarm System for Medicine Reminder Based on Microcontroller
27. of the Creative Commons Attribution License (CC BY 4.0). *International Journal of Trend in Scientific Research and Development (IJTSRD) International Journal of Trend in Scientific Research and Development*, *5*, 791–794. https://doi.org/10.31142/ijtsrd26518
28. Patel, C. N., Swartz, M. D., Tomasek, J. S., Vincent, L. E., Hallum, W. E., & Holcomb, J. B. (2019).
29. The Effects of Missed Doses of Antibiotics on Hospitalized Patient Outcomes. *The Journal of Surgical Research*, *233*, 276–283. https://doi.org/10.1016/j.jss.2018.08.015
30. Pruitt, Z. M., Kazi, S., Weir, C., Taft, T., Busog, D. N., Ratwani, R., & Hettinger, A. Z. (2023). A
31. systematic review of quantitative methods for evaluating electronic medication administration record and bar-coded medication administration usability. *Applied Clinical Informatics*, *14*(01), 185-198.
32. Religioni, U., Barrios-Rodríguez, R., Requena, P., Borowska, M., & Ostrowski, J. (2025). Enhancing
33. Therapy Adherence: Impact on Clinical Outcomes, Healthcare Costs, and Patient Quality of Life. *Medicina*, *61*(1), 153–153. https://doi.org/10.3390/medicina61010153
34. World Health Organization. (2022). *Medication without harm*. World Health Organization. https://www.who.int/initiatives/medication-without-harm

Faster Than the Teacher, Smarter Than the Student: Classifying with Wisdom via Knowledge Distillation in LLMs

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ABSTRACT

Large language models (LLMs) have achieved remarkable success across various natural language processing (NLP) tasks, driven by their ability to capture complex language patterns through large-scale pretraining. However, their substantial computational demands limit their deployment in resource-constrained environments. To address this, this research introduced Knowledge distillation-based framework for text classification using a multiclass approach across three domains: entertainment, sports, and politics. We utilize both hard labels (ground-truth categories) and soft labels (logits from a teacher model) to train a student and a distilled model. The teacher model is accurate but computationally expensive. The student model is lightweight and fast, yet less accurate. Through distillation, we derive a task-specific distilled model that balances speed and accuracy. We also compare the performance of these models against traditional classifiers such as LSTM, SVM, and Naive Bayes. Traditional models excel comparing to the LLMs. Considering only task agnostic language models, evaluation shows that the distilled model performs significantly better than the student and competitively against the teacher, offering a practical trade-off. Our study demonstrates the value of soft label transfer and semantic alignment for improving classification performance in resource-constrained environments. The text classification code can be found at: https://github.com/Abishethvarman/KD-Text-Classification

KEYWORDS: *Knowledge Distillation, Text Classification, Multiclass Classification, Teacher-Student Framework.*

INTRODUCTION

The advent of the Transformer architecture has (Vaswani et al., 2017) revolutionized the field of natural language processing (NLP), enabling the development of powerful large language models (LLMs). Transformers rely entirely on attention mechanisms to model long-range dependencies in text, replacing traditional recurrent and convolutional structures. Building on this foundation, models such as BERT (Devlin et al., 2019), GPT (Radford et al., 2019), T5, and PaLM (Chowdhery et al., 2023) demonstrated unprecedented performance across a wide range of NLP tasks through pre-training on large text corpora and fine-tuning or prompting techniques. More recent advances have led to the emergence of multimodal and highly scalable models such as GPT-4, Gemini, LLaMA 2, and Gemma, capable of handling multiple input modalities and processing extensive contexts. These LLMs exemplify the scalability and generalization potential of the Transformer architecture, enabling few-shot, zero-shot, and even instruction-following abilities with minimal task-specific supervision.

Text classification (Kowsari et al., 2019), is a fundamental task in natural language processing, vital for applications like news categorization, sentiment analysis (Miah et al., 2024), and content filtering (Vörös et al., 2023). The introduction of large language models significantly changed the landscape of Natural Language Processing (NLP), providing new capabilities across a wide range of tasks like translation, summarization, classification and question answering. While these large language models (LLMs) offer remarkable performance in classification tasks, they are often computationally intensive. This makes the

implementation difficult in situations with limited hardware capacity, such as mobile applications, real-time systems, and edge computing devices. Furthermore, the operational costs associated with proprietary models may limit their accessibility. This creates a need for lighter models that retain much of the LLM's intelligence but can be deployed efficiently. Knowledge distillation is one such technique that enables training smaller student models to replicate the behavior of a larger teacher model.

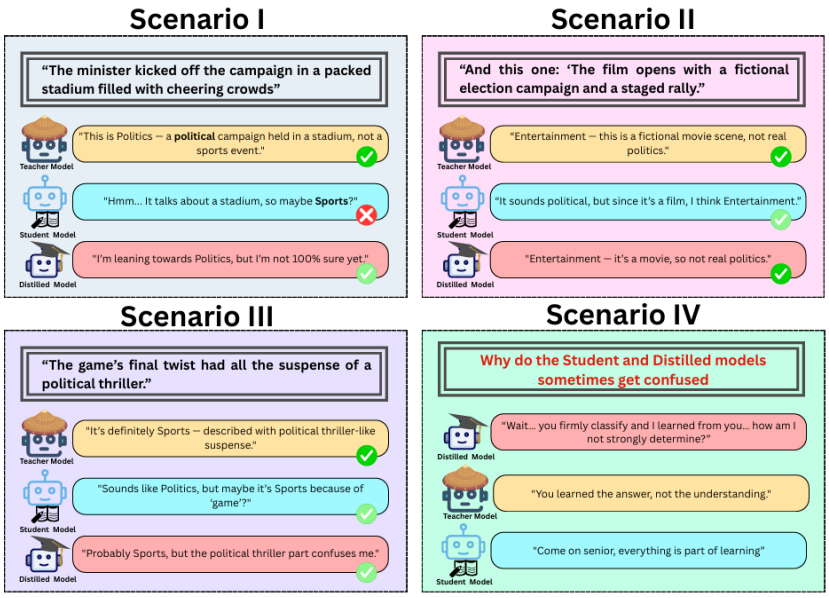

Figure 6:Explanatory diagram of text classification in teacher, student and distilled model

Knowledge distillation addresses this issue in a practical way by moving learned knowledge from a high-performing, computationally intensive teacher model to a smaller, more efficient student model. This teacher-student learning paradigm allows for the preservation of a considerable percentage of the teacher's knowledge while also enabling faster, lighter models suitable for real-world deployment. The ability to capture both hard label accuracy and subtle soft label distributions enables distillation models to generalize more well, particularly in multiclass contexts with overlapping semantics between classes.

In this study, we explore this concept for a zero-shot multiclass text classification problem using categories from real-world domains: entertainment, politics, and sports. We investigate the performance of teacher, student, and distilled models in terms of both accuracy and computational efficiency. Even though classification is challenging in the task agnostic distillation (see Figure 1) Additionally, traditional machine learning models such as Support Vector Machines (SVM), Long Short-Term Memory (LSTM) networks, and Naive Bayes are evaluated to provide baseline comparisons. These models were chosen after analyzing recent literature, which consistently ranks LSTM, CNN, SVM, and Naive Bayes as among the best for text categorization tasks. The comparison to these baselines allows us to evaluate not only the raw performance gains, but also the practical benefits of applying knowledge distillation to real-world classification problems.

LITERATURE REVIEW

This study builds on several foundational concepts in natural language processing and machine learning. Knowledge distillation (Pangakis & Wolken, 2024) is the process of transferring the generalization ability of a large model (teacher) into a smaller, more efficient model (student) by mimicking the teacher's output distributions. Historically, prior to the era of LLMs the knowledge distillation techniques primarily concentrated on transferring knowledge from complex, often complicated neural networks to more compact and efficient networks. After the arrival of transformer-based architectures, notably BERT (Bidirectional Encoder Representations from Transformers), GPT, and its variations, knowledge distillation approaches became popular in the field of Natural Language Processing (NLP). The current phase of knowledge

distillation in LLMs switches the focus beyond simple architectural model compression to knowledge elicitation and richer transfer of knowledge.

Knowledge Distillation (KD) has emerged as a powerful technique for model compression, where a smaller student model learns to mimic a larger teacher model. Extensive surveys explore KD in diverse domains including computer vision, graphs, large language models (LLMs), and federated learning. The teacher–student paradigm remains central to KD's effectiveness (Hu et al., 2023). KD for LLMs has attracted increasing attention due to computational demands, with works exploring data-efficient methods (Li et al., 2024), synthetic data, domain-specific distillation, and privacy-preserving data augmentation. Multi-aspect distillation frameworks and performance-guided strategies improve task alignment, particularly in text classification. Logic-based distillation techniques show promise in planning and decision-making (Chen et al., 2024). Approaches like MiniLLM provide scalable methods for LLM distillation (Gu et al., 2023), while sparse logit sampling(Zaidi et al., 2025) and smoothed distillation target hallucination and efficiency. Mitigating KL divergence limitations and enabling knowledge transfer across modalities such as provenance analysis (Zuo et al., 2025) and graphs broaden KD applications. KD also supports specialized tasks including anomaly detection and automatic scoring. Compression techniques like quantization-aware training (Liu et al., 2023), sub-4-bit distillation (Du et al., 2024), and pruning are essential for efficient deployment. Studies also assess compression's impact on parametric knowledge. Multi-teacher strategies have been explored for tasks such as reasoning-based machine reading comprehension. Furthermore, federated KD frameworks are evolving to address privacy and communication constraints. With increasing demand for scalable, generalizable, and low-resource NLP solutions, KD continues to be a critical research area across domains and architectures.

Table 1: Comparison of related works with our research

Previous Study	Primary Objective	Difference from Our Research
DistilBERT(Sanh et al., 2019)	Reduce BERT model size while retaining most of its performance on general NLP tasks.	Focuses on task-specific zero-shot text classification rather than general-purpose NLP.
TinyBERT(Jiao et al., 2019)	Knowledge distillation for efficient transformer models, both task-specific and general-purpose.	Evaluates zero-shot classification ability of distilled models without extensive task-specific fine-tuning.
PGKD(Di Palo et al., 2024)	Active-learning KD where task-specific student models are trained using LLM-generated hard negatives.	Employs few-shot, task-specific distillation with both hard and soft labels, without active learning, to balance accuracy and efficiency in resource-limited settings.
KDH-MLTC(Song et al., 2024)	Applies KD for multi-label medical text classification using PSO and sequential fine-tuning to boost student performance.	Directly transfers teacher knowledge to the student via few-shot, task-specific distillation without further fine-tuning.

Text classification is a fundamental operation in natural language processing that assigns specific groups to new text based on its semantic content. Multiclass classification (Yuan et al.) introduces further challenges by requiring models to learn nuanced differences between categories, particularly when categories may have overlapping language styles or semantics. This complexity grows when categories have comparable terminology or when textual expressions are ambiguous, as in sectors such as entertainment, sports, and politics. Our approach emphasizes the synergy between soft and hard labels, as well as the use of both semantic and task-specific evaluation metrics.

Knowledge Elicitation (Du et al., 2025) is the process of extracting useful and feasible knowledge from expert sources. Knowledge elicitation ensures that the knowledge transferred is not simply shallow imitation but rather reflects the teacher's profound language and semantic understanding.

Hard labels are true category labels assigned to each data sample, which are commonly expressed as discrete class identifiers. In contrast, soft labels, which include probability distributions or logits, offer richer

learning signals than hard labels alone, making them especially valuable for distillation. By combining both hard and soft labels during training, models can learn to match ground-truth assignments while also mimicking the teacher's more sophisticated prediction distributions. Logits are the raw, unnormalized output values produced by a neural network prior to the use of any activation function, such as SoftMax. They reflect the model's internal confidence scores for each class. During distillation, logits from the teacher model are utilized to generate soft labels that assist the student model in learning not just the proper class but also the relative relationships across classes.

Divergence-based loss functions, such Kullback-Leibler (KL) divergence (Wu et al., 2024), compute the difference between the teacher's soft label distribution and the student's projected distribution. By reducing divergence during training, the student model learns to closely replicate the teacher's behavior, integrating its understanding into a smaller, more efficient model. Table 1 summarizes recent studies on knowledge distillation techniques for task-specific text classification.

METHODOLOGY

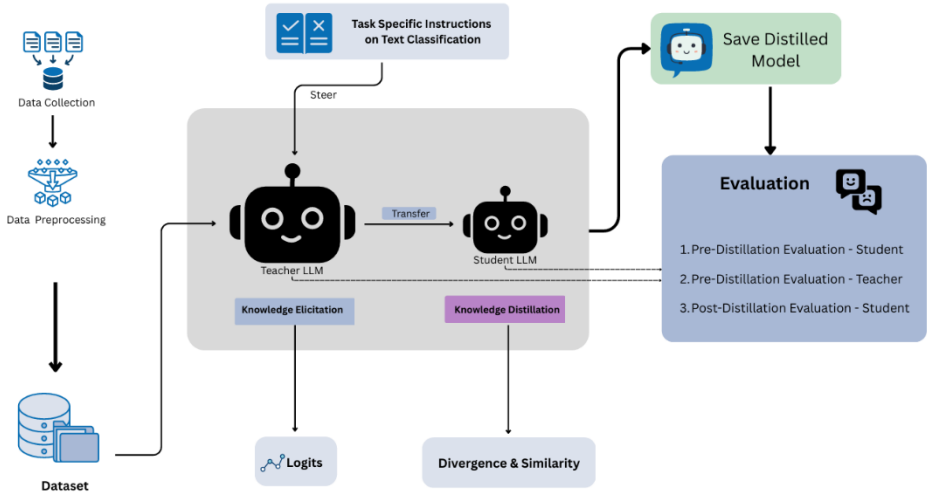

Figure 7: Methodology

Our research is to address the gap of making a task specific distilled model which should perform better than the student model and avoid hallucinations. We curated a dataset comprising text samples labeled under three categories: entertainment, sports, and politics. After initial preprocessing such as text normalization and cleaning, the dataset was prepared for model evaluation and training phases. As the methodology diagram shows, the whole methodology is divided into several stages, such as evaluation of teacher and student models, knowledge elicitation, knowledge distillation, and traditional baseline comparisons.

In the first phase, the preprocessed dataset was fed into the student model for preliminary evaluation. The student model used in this research is the LLaMA 3.1:8B model. During this step, the student model was given each input text sample without its corresponding label. The model made predictions using a prompt-based instruction style, with each sentence assigned to one of three target categories: sports, politics, or entertainment. The forecasts were then compared to the original ground truth labels. Due to computational restrictions, only 50 samples from CNN/DailyMail dataset were used for this Evaluation. Prior to distillation, performance indicators including as accuracy, precision, recall, F1-score, and confusion matrix were used to evaluate the student model's classification capability.

The same evaluation technique was used on the teacher model, which is the larger LLaMA 3.1: 70B model. The teacher model used the same prompt-based classification function as the student model. Predictions were created, and classification metrics were calculated by comparing the predicted labels to the actual

labels. Because of its larger parameter size, the teacher model performed better with complicated and semantically confusing examples.

After acquiring baseline results from both student and teacher models, the distillation step proceeded. During this stage, the labeled dataset consists of 3,000 samples from the CNN/DailyMail dataset was run through the teacher model to extract soft label outputs in the form of logits, which represented the teacher's confidence distribution across the three categories for each sample. The logits were then employed as supervisory signals during distillation training.

A divergence-based loss function was used to retrain the student model with both hard labels (ground truth) and soft labels (teacher logits). The distillation loss was estimated using a weighted combination of cross-entropy loss (on hard labels) and Kullback-Leibler divergence loss (on soft logits), allowing the student model to better approach the teacher's decision boundaries.

$$L_{KD} = \alpha L_{CE}(y_{pred}, y_{true}) + (1 - \alpha)T^2 \, KL(P_T \,||\, P_S)$$

Here, L_{CE} represents the cross-entropy loss between the student's predicted tokens and the ground-truth summaries, while KL(•) defines the divergence between the softened output distributions of the teacher (P_T) and student (P_S), with T as the temperature parameter that controls the softness of the probability distributions. The hyperparameter α balances the contributions of these two loss components. The combined loss function allows the student model to learn from both the real labels and the nuanced information included in the teacher's output probabilities, resulting in better semantic comprehension as well as improved predictions.

The distillation training approach allowed the student to acquire more information from the teacher while remaining lightweight and efficient. Following training, the distilled model was preserved for further review. The saved distilled student model was then evaluated with the same test data and standards as the initial student and teacher models. The distilled model's performance was evaluated by comparing its predictions to the ground-truth labels and again computing accuracy, precision, recall, and F1-score measures. In addition, average processing times were measured to compare the response times of these models. This allowed for direct comparisons between all models (see Figure 3).

In addition to the teacher-student distillation architecture, classic machine learning methods were used to set performance benchmarks. The models used are: LSTM, SVM, CNN and Naive Bayes. The dataset was divided into an 80:20 train-test ratio to ensure a balanced evaluation of the models. Prior to training, preprocessing processes such as tokenization, vectorization, and padding were used to turn the raw text input into formats suited for each method.

The Support Vector Machines (SVM) model employed TF-IDF to turn the text into feature vectors for classification. The Long Short-Term Memory (LSTM) model was trained on tokenized and padded word sequences, with embeddings representing the text inputs. The Naive Bayes (MultinomialNB) classifier also trained on TF-IDF features. To capture text patterns, the Convolutional Neural Network (CNN) model used tokenized and padded sequences that were fed through convolutional layers. The traditional models were evaluated using the same set of classification criteria as the distilled and LLM-based models, which included accuracy, precision, recall, and F1-score. This extensive examination provides useful comparative insights into the success of knowledge distillation vs traditional classification methodologies, emphasizing the distilled model's balance of computational efficiency and predictive performance.

RESULTS AND DISCUSSION

The teacher model achieved an accuracy of 55.3%, precision of 51.1%, recall of 58.0%, and F1-score of 56.7%, setting an upper benchmark in classification performance, but took a large amount of processing time. Its exceptional performance can be due to its large parameter set, which enables it to capture complicated linguistic patterns and contextual connections. However, this advantage comes at the expense of high computing requirements, rendering it unsuitable for implementation in real-time or resource-constrained contexts. The average reaction time for the teacher model was roughly 6-7 seconds per sample, whereas the student and distilled models were around 2-3 seconds per sample.

The student model classified quickly but performed poorly, particularly in semantically confusing scenarios. It struggled with classifications that included small overlaps between categories, such as texts

citing sports events in political contexts or technology concerns embedded inside entertainment tales. This is demonstrated in its relatively poor accuracy of 31.0%, precision of 29.0%, recall of 21.0%, and F1-score of 35.5%. The student model's lightweight design hindered its capacity to handle complex circumstances requiring fine-grained contextual comprehension.

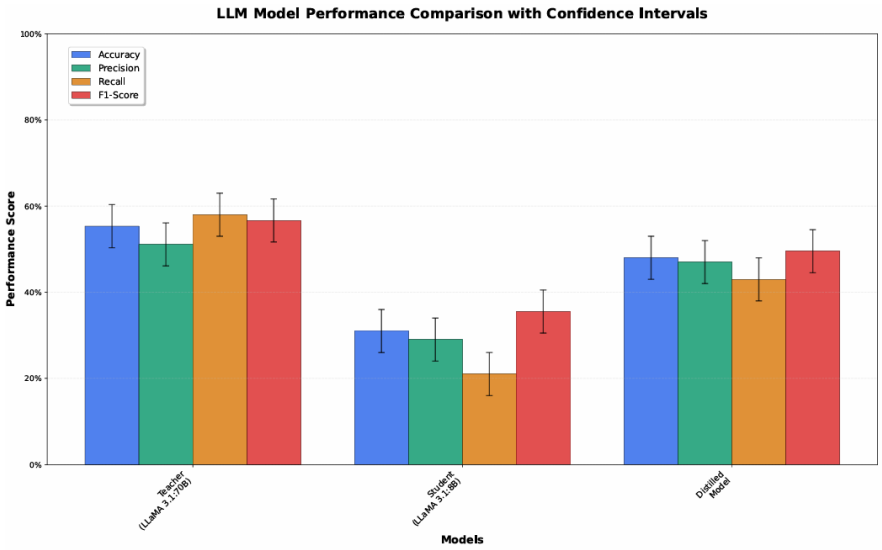

Figure 8: Model Performance Comparison of LLM models in Text Classification:

The distilled model demonstrated a solid balance, providing performance comparable to the teacher while being significantly faster. It achieved an accuracy of 48.0%, precision of 47.0%, recall of 43.0%, and F1-score of 49.5%. By adding the teacher's soft label distributions generated during distillation, the student model learnt to understand nuanced correlations between courses even when explicit cues were restricted. This resulted in better generalization, especially in borderline circumstances when hard labels alone may not offer adequate learning signals. The distilled model regularly displayed improved adaptability across domains, effectively retaining the teacher's reasoning abilities while minimizing computational footprint (see Figure 3).

Table 2:Performance Comparison of Teacher, Student, Distilled, and Traditional Models

Model	Accuracy	Precision	Recall	F1 Score
Teacher (LLaMA 3.1:70B)	0.5534	0.5111	0.5801	0.5668
Student (LLaMA 3.1:8B)	0.3100	0.2900	0.2101	0.3552
Distilled Model	0.4800	0.4700	0.4300	0.4952
LSTM	0.6770	0.6900	0.6055	0.6385
CNN	0.6100	0.7286	0.6300	0.6800
SVM	0.8010	0.8250	0.7200	0.7971
Naive Bayes	0.8440	0.8850	0.8600	0.8971

Traditional models like LSTM, CNN, and SVM fared well across multiple categories. Naive Bayes and SVM performed well on clearly separable samples with Naive Bayes reaching an accuracy of 84.4%, precision of 88.5%, recall of 86.0%, and F1-score of 89.7%, and SVM closely following with an accuracy of 80.1%, precision of 82.5%, recall of 72.0%, and F1-score of 79.7%. LSTM and CNN generated reasonable results by detecting sequential and local patterns in the text. However, these models demonstrated shortcomings when dealing with semantically ambiguous scenarios involving overlapping features between categories. In comparison, the distilled model struck a good mix between accuracy and computational efficiency while efficiently absorbing knowledge from the teacher model. While the

distilled model did not outperform all traditional models, it did show greater generalization over the initial student model, particularly in complicated classification cases. The detailed comparative results of all models are presented in Table 2.

Our findings indicate that task-specific distillation effectively compresses the teacher's knowledge into a lightweight model while maintaining relevant classification performance. The distilled model outperforms the student model and competes with standard models for domain-specific nuances, as evidenced by qualitative error analysis. Furthermore, analysis of misclassified instances revealed that the distilled model was more likely to reflect the teacher's conclusion when several semantic signals were present, suggesting its ability to grasp fine-grained distinctions across overlapping categories.

CONCLUSION

We developed a knowledge distillation framework tailored for multiclass text classification in entertainment, sports, and politics. Our **distilled model** combines the best of both worlds: the teacher's reasoning ability and the student's efficiency. This framework enables effective implementation in real-world applications with resource constraints. Beyond its immediate application, this approach provides a scalable solution that may be applied to a variety of topics and languages. The distilled model effectively captures nuanced semantic patterns by using both hard and soft labels, making it suited for challenging classification applications. Our methodology shows that knowledge distillation not only decreases computing needs but also maintains meaningful task-specific performance, indicating that it has the potential for widespread use in a variety of NLP applications. The performance of language models in any NLP task is comparatively low consider to traditional models which learns from the hard label. But Language models itself it is classifying in context of knowledge it has. So, task specific wise the model performance is low. But as task agnostic it is better in concurrent scenario. Further it can extend to expand the classification knowledge to the large language models as traditional models.

LIMITATIONS

Our work is currently limited to three domains and single-language datasets. The distilled model, while effective, still depends on the quality of the teacher model's outputs. Research is conducted only for the LLaMa model yet, but we had 4 different models in our pipeline. Due to resource constrained we developed one only.

Additionally, the semantic alignment was limited to textual similarity metrics; incorporating structural or contextual features could enhance performance further. Future work could explore multilingual classification, multimodal inputs, and further improvements in few-shot learning. Since our study largely focused on zero-shot classification, we intend to further our analysis into one-shot and few-shot learning contexts to better understand the benefits of knowledge distillation with limited labeled data sets. While the distilled model outperforms the student model, it falls short of the teacher model. This discrepancy may indicate insufficient fine-tuning or limited task adaptation. Due to resource constraints, we could not fully fine-tune the large language models, possibly limiting their effectiveness.

REFERENCES

1. Chen, D., Zhang, S., Gao, F., Zhuang, Y., Tang, S., Liu, Q., & Xu, M. (2024). Logic Distillation: Learning from Code Function by Function for Planning and Decision-making. *arXiv preprint arXiv:2407. 19405*.
2. Chowdhery, A., Narang, S., Devlin, J., Bosma, M., Mishra, G., Roberts, A., Barham, P., Chung, H. W., Sutton, C., Gehrmann, S., & Others. (2023). Palm: Scaling language modeling with pathways. *Journal of Machine Learning Research*, *24*(240), 1-113.
3. Devlin, J., Chang, M.-W., Lee, K., & Toutanova, K. (2019, 2019). *Bert: Pre-training of deep bidirectional transformers for language understanding* Proceedings of the 2019 conference of the North American chapter of the association for computational linguistics: human language technologies, volume 1 (long and short papers),
4. Di Palo, F., Singhi, P., & Fadlallah, B. (2024). Performance-Guided LLM Knowledge Distillation for Efficient Text Classification at Scale. *arXiv preprint arXiv:2411. 05045*.

5. Du, D., Zhang, Y., Cao, S., Guo, J., Cao, T., Chu, X., & Xu, N. (2024). Bitdistiller: Unleashing the potential of sub-4-bit llms via self-distillation. *arXiv preprint arXiv:2402. 10631*.
6. Du, Y., Sun, Z., Wang, Z., Chua, H., Zhang, J., & Ong, Y.-S. (2025, 2025). *Active large language model-based knowledge distillation for session-based recommendation* Proceedings of the AAAI Conference on Artificial Intelligence,
7. Gu, Y., Dong, L., Wei, F., & Huang, M. (2023). MiniLLM: Knowledge distillation of large language models. *arXiv preprint arXiv:2306.08543*.
8. Hu, C., Li, X., Liu, D., Wu, H., Chen, X., Wang, J., & Liu, X. (2023). Teacher-student architecture for knowledge distillation: A survey. *arXiv preprint arXiv:2308. 04268*.
9. Jiao, X., Yin, Y., Shang, L., Jiang, X., Chen, X., Li, L., Wang, F., & Liu, Q. (2019). Tinybert: Distilling bert for natural language understanding. *arXiv preprint arXiv:1909.10351*.
10. Kowsari, K., Jafari Meimandi, K., Heidarysafa, M., Mendu, S., Barnes, L., & Brown, D. (2019). Text classification algorithms: A survey. *Information*, *10*(4), 150.
11. Li, J., Nag, S., Liu, H., Tang, X., Sarwar, S., Cui, L., Gu, H., Wang, S., He, Q., & Tang, J. (2024). Learning with Less: Knowledge Distillation from Large Language Models via Unlabeled Data. *arXiv preprint arXiv:2411. 08028*.
12. Liu, Z., Oguz, B., Zhao, C., Chang, E., Stock, P., Mehdad, Y., Shi, Y., Krishnamoorthi, R., & Chandra, V. (2023). Llm-qat: Data-free quantization aware training for large language models. *arXiv preprint arXiv:2305. 17888*.
13. Miah, M. S. U., Kabir, M. M., Sarwar, T. B., Safran, M., Alfarhood, S., & Mridha, M. F. (2024). A multimodal approach to cross-lingual sentiment analysis with ensemble of transformer and LLM. *Scientific Reports*, *14*(1), 9603.
14. Pangakis, N., & Wolken, S. (2024). Knowledge distillation in automated annotation: Supervised text classification with llm-generated training labels. *arXiv preprint arXiv:2406. 17633*.
15. Radford, A., Wu, J., Child, R., Luan, D., Amodei, D., Sutskever, I., & Others. (2019). Language models are unsupervised multitask learners. *OpenAI blog*, *1*(8), 9.
16. Sanh, V., Debut, L., Chaumond, J., & Wolf, T. (2019). DistilBERT, a distilled version of BERT: smaller, faster, cheaper and lighter. *arXiv preprint arXiv:1910.01108*.
17. Song, Y., Zhang, J., Tian, Z., Yang, Y., Huang, M., & Li, D. (2024). LLM-based privacy data augmentation guided by knowledge distillation with a distribution tutor for medical text classification. *arXiv preprint arXiv:2402. 16515*.
18. Vaswani, A., Shazeer, N., Parmar, N., Uszkoreit, J., Jones, L., Gomez, A. N., Kaiser, Ł., & Polosukhin, I. (2017). Attention is all you need. *Advances in neural information processing systems*, *30*.
19. Vörös, T., Bergeron, S. P., & Berlin, K. (2023, 2023). *Web content filtering through knowledge distillation of large language models* 2023 IEEE/WIC International Conference on Web Intelligence and Intelligent Agent Technology (WI-IAT),
20. Wu, T., Tao, C., Wang, J., Yang, R., Zhao, Z., & Wong, N. (2024). Rethinking kullback-leibler divergence in knowledge distillation for large language models. *arXiv preprint arXiv:2404. 02657*.
21. Yuan, B., Chen, Y., & Zhang, Y. Label-Guided Self-Knowledge Distillation for Multi-Class Text Classification. *Available at SSRN 5081643*.
22. Zaidi, M. A., Kedia, A., Ahn, J., Kwon, T., Lee, K., Lee, H., Lee, J., & Others. (2025). Sparse Logit Sampling: Accelerating Knowledge Distillation in LLMs. *arXiv preprint arXiv:2503. 16870*.
23. Zuo, F., Rhee, J., & Choe, Y. R. (2025). Knowledge Transfer from LLMs to Provenance Analysis: A Semantic-Augmented Method for APT Detection. *arXiv preprint arXiv:2503. 18316*.

Integrating Large Language Models into Personalized Diabetes Care: A Systematic Review of Clinical Applications, Model Adaptation Strategies, and Ethical Implications

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ABSTRACT

This systematic review examines the integration of Large Language Models (LLMs) into personalized diabetes care, focusing on clinical applications, adaptation strategies, and ethical considerations. As diabetes management demands increasingly personalized approaches, LLMs including GPT-3 and GPT-4 show promise for patient education, clinical decision support, and diagnostic assistance. This review synthesizes findings from studies published between 2018 and 2025 to evaluate LLM clinical applications and assess adaptation techniques. Key applications include conversational agents for patient education, personalized decision-making systems, and predictive modeling for diabetes-related complications. Model adaptation through domain-specific training and multimodal integration demonstrates enhanced performance in clinical settings. However, significant challenges persist, including data privacy concerns, model fairness issues, and limited real-world validation. Ethical considerations encompass training bias and data security, highlighting the need for privacy-preserving approaches. The review identifies critical gaps in current research and proposes future directions emphasizing explainable AI models to build trust among healthcare professionals and patients. While LLMs offer transformative potential for personalized diabetes care, their responsible integration requires addressing technical, ethical, and regulatory challenges. This synthesis provides a foundation for advancing LLM applications in diabetes management while ensuring patient safety and equitable care delivery.

Keywords: *Large Language Models (LLMs), Personalized Diabetes Care, Clinical Decision Support Systems, Patient Education, Model Adaptation, Ethical Considerations, AI in Healthcare.*

INTRODUCTION

Diabetes affects over 400 million people worldwide, with projections reaching 628.6 million by 2045 (Standl et al., 2019). This chronic condition requires personalized management approaches that consider clinical, personal, and psychosocioeconomic characteristics to reduce complications and improve outcomes (Khalifa & Albadawy, 2024; Vuohijoki et al., 2020). Large Language Models (LLMs), including GPT-3 and GPT-4, represent transformer-based deep learning systems increasingly adapted for healthcare applications through fine-tuning on domain-specific data. These models show promise in clinical decision-making, self-management support, and patient engagement. However, despite growing interest in healthcare LLM applications, limited consolidated evidence exists specifically addressing diabetes care integration. While emerging studies explore LLM potential in diabetes management, a comprehensive synthesis of clinical applications, adaptation strategies, and ethical considerations remains lacking. This gap is particularly significant given diabetes care's complexity and the need for personalized, culturally sensitive approaches that LLMs could potentially address. This systematic review addresses these needs by examining current evidence on LLM integration in diabetes care. Our objectives are to: (1) **evaluate clinical applications** of LLMs in patient education, diagnostic support, and treatment management; (2) **examine adaptation strategies** employed in LLMs for diabetes-related tasks; (3) **discuss ethical considerations** related to LLM integration in diabetes care, focusing on data privacy, fairness, and model transparency; and (4) **identify research gaps** and provide recommendations for responsible LLM implementation in personalized diabetes care.

METHODOLOGY (PER PRISMA 2020)

A comprehensive literature search was conducted across four academic databases: PubMed, Scopus, IEEE Xplore, and Web of Science to identify relevant studies for this systematic review. The search focused on the integration of LLMs into personalized diabetes care and covered publications from 2018 to 2025. Search terms encompassed four key categories: diabetes-related terms (including "diabetes care," "Type 1/2 diabetes," "diabetes management," and "diabetes prevention"), personalization terms ("personalized medicine," "patient-centered care," "precision medicine," and "chronic disease management"), AI/LLM-related terms ("Large Language Models," "GPT-3/4," "BERT," "Med-PaLM," and "clinical decision support systems"), and ethical/regulatory terms ("trust in AI," "model transparency," "FDA/EMA positions," and "AI tools regulation").
Studies were included if they met the following criteria: (1) peer-reviewed publications in English; (2) published between 2018 and 2025; and (3) involved the application of LLMs in diabetes care. Exclusion criteria comprised non-human studies, non-peer-reviewed sources (e.g., editorials, opinion pieces), and studies unrelated to either LLMs or diabetes care. The study selection process is summarized in the PRISMA flow diagram (See Figure 1). The findings were thematically organized into five categories: (1) clinical applications of LLMs, (2) model adaptation strategies, (3) ethical considerations, (4) limitations and (5) future directions.

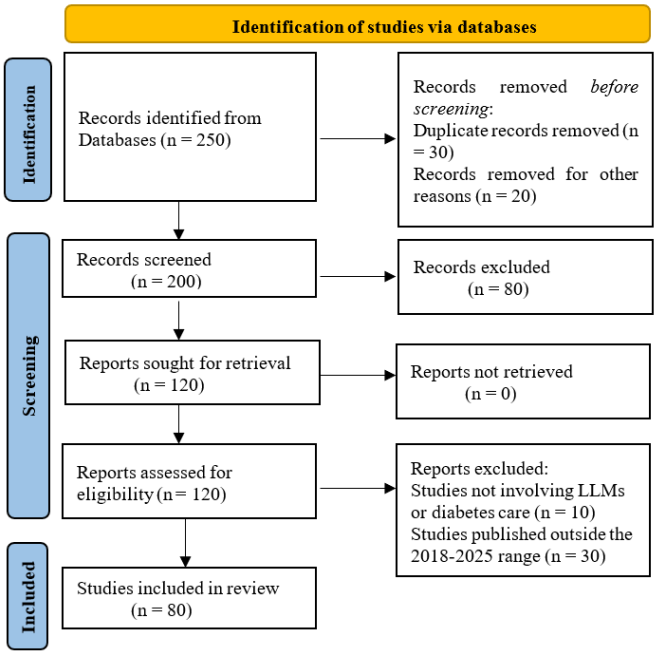

Figure 9:PRISMA flow diagram

CLINICAL APPLICATIONS OF LLMS IN DIABETES CARE

LLM-powered conversational agents show strong promise for personalized patient education. Dao et al. (2024) developed a multimodal system using 466 Q&A pairs for educational interventions, while Kelly et al. (2024) achieved 75% alignment with clinical guidance through a ChatGPT-based educational chatbot. These applications effectively support patient self-management through accessible, personalized interactions. Clinical decision support applications yield mixed results that depend heavily on implementation. Liu et al. (2023) found AI-generated recommendations were rated as relevant and safe, though performance varied significantly with prompt design. Williams et al. (2024) demonstrated through analysis of over 250,000 Emergency Department notes that GPT-4 matched or exceeded physician performance in specific areas like antibiotic prescribing, but showed clear limitations in complex clinical judgment tasks. Predictive modeling emerges as the most promising application area. Choi et al. (2025) used ChatGPT-4 in a code-free pipeline to develop risk calculators for diabetic retinopathy and diabetic macular edema, achieving AUCs of 0.786 and 0.835 respectively. These results are comparable to traditional machine learning methods, such as random forest models achieving AUC of 0.90 for end-stage

renal disease prediction (Zou et al., 2022), while offering enhanced interpretability and natural language interfaces. LLM integration with electronic health records shows substantial potential for improving clinical workflow efficiency. Verma et al. (2025) demonstrated GPT-4o's capability to generate verifiable summaries of longitudinal patient records while maintaining clinical accuracy. Van Veen et al. (2024) showed GPT-4's superior performance over medical experts in clinical summarization with fewer hallucinations. These capabilities are being operationalized through real-world deployments, including Epic Systems' partnership with Microsoft for patient response drafting and visit summarization.

MODEL ADAPTATION AND TECHNICAL STRATEGIES

Successful deployment of Large Language Models in diabetes care requires sophisticated adaptation strategies encompassing domain-specific training, prompt optimization, multimodal integration, and clinical evaluation. Fine-tuning approaches, exemplified by Med-PaLM's use of Low-Rank Adaptation (LoRA) techniques on medical datasets, enhance accuracy for clinical tasks (Bui et al., 2025; Yang et al., 2023), while prompt engineering optimizes performance with limited data, as demonstrated by Pachetti and Colantonio (2024) through structured clinical inputs like blood glucose levels for personalized treatment decisions. Multimodal integration represents a transformative advancement, with AlSaad et al. (2024) showing how combining Continuous Glucose Monitoring data with LLMs enables real-time treatment plan adjustments. Clinical evaluation frameworks ensure reliability and safety, with Singhal et al. (2023) introducing the MultiMedQA benchmark to assess accuracy and reasoning while revealing gaps like hallucinations and biases, complemented by Ho et al. (2024)'s emphasis on patient-centeredness metrics and Park et al. (2021)'s observation that high AUROC values require real-world validation to confirm clinical utility.

ETHICAL, LEGAL, AND SOCIAL IMPLICATIONS

The integration of Large Language Models (LLMs) into personalized diabetes care presents significant Ethical, Legal, and Social Implications (ELSI). The literature reveals that biases within training datasets can lead to disparities in model performance across different demographic groups. For example, dermatological AI systems trained primarily on fair-skinned individuals have demonstrated reduced diagnostic accuracy for conditions such as melanoma in darker-skinned patients (Marko et al., 2025). Such biases are not limited to dermatology but extend across healthcare AI applications, where models trained on unrepresentative datasets fail to accurately diagnose conditions in marginalized populations. Chinta et al. (2025) underscore that these biases could exacerbate existing healthcare disparities, leading to less accurate recommendations or even missed diagnoses in communities that already face significant healthcare challenges. Addressing these issues requires the diversification of training datasets to ensure LLMs provide equitable care. Additionally, the ethical and legal frameworks governing AI in healthcare must evolve to promote inclusivity and mitigate systemic biases in AI tools. However, the successful deployment of LLMs must also address another pressing concern: data privacy and security. Unauthorized access or data breaches, particularly through advanced techniques such as model inversion or membership inference, could compromise patient confidentiality (Dodevski et al., 2024).

CHALLENGES AND LIMITATIONS

The integration of LLMs into personalized diabetes care faces multifaceted challenges that significantly hinder widespread adoption. Technical barriers pose the most prominent obstacles, particularly the substantial computational resources required to handle large, unstructured healthcare data (Nagarajan et al., 2024) and the complexities of integrating LLMs with existing hospital systems that rely on outdated technology unsuited for seamless AI integration (Mackenzie et al., 2024; Nagarajan et al., 2024). Real-world validation remains critically limited, as AI models demonstrating potential in controlled environments lack documentation of performance in diverse clinical settings, especially within underrepresented populations where healthcare systems are less equipped for advanced AI deployment (Campanella et al., 2024; Guan et al., 2023). Furthermore, gaps in interdisciplinary collaboration between clinicians and AI developers create a disconnect between practical healthcare needs and technical expertise, resulting in AI models that fail to align with clinical realities and limiting their practical usefulness.

Overcoming these technical barriers, evidence limitations, and collaboration gaps is essential for successful LLM integration into clinical diabetes care.

FUTURE DIRECTIONS

The future of LLM applications in diabetes care encompasses four interconnected trajectories requiring coordinated advancement across technological, privacy, cultural, and clinical integration dimensions. Personalized AI agents represent the most transformative frontier, with systems continuously evolving through dynamic learning from health data and behavioral patterns, as demonstrated by early prototypes providing tailored feedback based on real-time glucose levels (Ellahham, 2020) and advanced AI-driven insulin pumps showing proven effectiveness in autonomous treatment delivery (Campanella et al., 2024). Privacy-preserving federated learning frameworks offer promising solutions for collaborative model development while maintaining patient confidentiality through decentralized training (Hasan et al., 2024; Takahashi et al., 2021), though challenges persist regarding computational limitations and the need for high-quality, representative datasets across diverse healthcare systems (Schachner et al., 2020; Yang & Li, 2025). Ultimately, successful clinical integration necessitates explainable AI systems that build trust through interpretable recommendations aligned with clinical practices (Saraswat et al., 2022), coupled with patient-centered co-design processes ensuring AI tools meet individual health needs and real-world diabetes management demands (Ayobi et al., 2021; Turchi et al., 2024), collectively indicating that the practical impact and clinical adoption of LLM-based diabetes care solutions will depend on interdisciplinary collaboration across these convergent elements.

DISCUSSION & CONCLUSION

This systematic review examined the integration of LLMs into personalized diabetes care, focusing on their clinical applications, model adaptation strategies, and ethical implications. Table 1 presents an overview of the various LLM applications in diabetes care, summarizing different use cases, target conditions, AI/technologies employed, and their respective purposes.

Table 1. Overview of LLM Applications in Diabetes Care

Application	Models	Purpose	Supporting Literature
Patient Education & Conversational Agents	Custom Multimodal LLM, GPT-3.5	Enhance adherence, simulate diagnostic dialogues, evaluate diabetes education	(Dao et al., 2024; Kelly et al., 2024)
Clinical Decision Support	GPT-3.5/4, AI-SCE	Provide clinical recommendations, support treatment planning	(Liu et al., 2023; Williams et al., 2024)
Predictive Modeling	GPT-4, DeepDR-LLM, Time-LLM	Risk prediction for complications, glucose forecasting	(Choi et al., 2025; Lara-Abelenda et al., 2025)
EHR Integration	GPT-4o, Med-PaLM 2, AMIE	Automate record summarization, streamline documentation	(Van Veen et al., 2024; Verma et al., 2025).

Building on these findings, the implications for various stakeholders, clinicians, patients, policymakers, and developers are multifaceted. Table 2 explores the model adaptation strategies employed to optimize LLMs for the specific needs of diabetes care,

Table 2. Model Adaptation Strategies for Healthcare LLMs Grouped by Task Type

Task Type	Key Models	Adaptation Methods	Main Benefits	Supporting Literature
Clinical Decision Support	GPT-4, Claude, BERT, T5	Prompt engineering, fine-tuning, reinforcement learning	High accuracy, clinical relevance, privacy preservation	(Barra et al., 2025; Wang et al., 2021)
Medical QA & Decision	Med-PaLM, BioBERT, ChatGLM	Domain pretraining, instruction tuning, LoRA fine-tuning	Superior biomedical reasoning, patient-centered responses	(AlSaad et al., 2024; Yang et al., 2023)
Patient Engagement	ChatGPT, ClinicalBERT, Gemini	Prompt chaining, QLoRA fine-tuning, medical dialogue training	Empathetic communication, enhanced provider interactions	(Alavi et al., 2024; Song et al., 2025)
Diagnostic Support	GPT-4, LLaVA-Med, SciBERT	Domain pretraining, visual integration, prompt-based tuning	Improved diagnostic precision, automated reporting	(Alavi et al., 2024; Bautista et al., 2023)
Multimodal Integration	PandaGPT, LLaMA2, Time-LLM	Multimodal encoders, time-series modeling, knowledge injection	Robust reasoning, complex domain communication	(Bui et al., 2025; Song et al., 2025)

These findings collectively suggest that while LLMs offer substantial promises for transforming diabetes care, they should be viewed as augmentative tools, not replacements for healthcare professionals. Table 3 highlights the ethical, legal, and social implications (ELSI) related to the deployment of LLMs in diabetes care. The table underscores key issues such as bias, fairness, data privacy, and the need for explainable AI models.

Table 3. Ethical, Legal, and Social Implications of LLMs in Personalized Diabetes Care

LLM Models	Key Applications	Main Challenges	Ethical Considerations	Supporting Literature
GPT-3/4, Med-PaLM, LLaMA	Clinical decision support, diagnostics	Privacy, fairness, transparency	Patient data protection, bias prevention	(He et al., 2025)
GPT-3/4, BioBERT	Patient care optimization, diagnosis	Data bias, privacy issues	Medical data ethics, decision transparency	(Nassiri & Akhloufi, 2024)
GPT-4, ClinicalBERT	Medical analysis, virtual assistants	Inaccurate diagnosis, interpretability	Healthcare fairness and accountability	(Wang & Zhang, 2024)
GPT-3.5/4, PaLM	Documentation, predictive modeling	Inconsistent performance, AI errors	Bias mitigation, outcome transparency	(Mesko & Topol, 2023)
GPT-3.5, Clinical-T5	Healthcare robotics, diagnostics	Physical task accuracy, data bias	Autonomous medical robot ethics	(Pashangpour & Nejat, 2024)

This systematic review addressed three key objectives regarding LLM integration into personalized diabetes care. The evaluation of clinical applications revealed significant potential in patient education, diagnostic support, and clinical decision-making, contributing to more personalized and data-driven diabetes management. The examination of adaptation strategies, including fine-tuning, domain-specific training, and multimodal integration, demonstrated their importance in optimizing model performance for diabetes-specific needs. The analysis of ethical considerations emphasized critical concerns regarding data privacy, fairness, and transparency that must be addressed for responsible clinical implementation.

By synthesizing current knowledge, this review provides recommendations for future research to refine LLMs for optimal use in personalized diabetes care while addressing identified literature gaps.

REFERENCES

1. Alavi, A., Cha, K., Esfarjani, D. P., Patel, B., Than, J. L. P., Lee, A. Y., Nebeker, C., Snyder, M., & Bahmani, A. (2024). *Harnessing Large Language Models to Uncover Insights in Diabetes Wearable Data*.
2. AlSaad, R., Abd-Alrazaq, A., Boughorbel, S., Ahmed, A., Renault, M. A., Damseh, R., & Sheikh, J. (2024). *Multimodal Large Language Models in Health Care: Applications, Challenges, and Future Outlook*. https://www.ncbi.nlm.nih.gov/pubmed/39321458
3. Ayobi, A., Stawarz, K., Katz, D., Marshall, P., Yamagata, T., Santos-Rodriguez, R., Flach, P., & O'Kane, A. A. (2021). Co-Designing Personal Health? Multidisciplinary Benefits and Challenges in Informing Diabetes Self-Care Technologies. *Proceedings of the ACM on Human-Computer Interaction*, *5*(CSCW2), 1-26. https://doi.org/10.1145/3479601
4. Barra, F. L., Rodella, G., Costa, A., Scalogna, A., Carenzo, L., Monzani, A., & Corte, F. D. (2025). From prompt to platform: an agentic AI workflow for healthcare simulation scenario design. *Adv Simul (Lond)*, *10*(1), 29. https://doi.org/10.1186/s41077-025-00357-z
5. Bautista, Y. J. P., Lima, V., Theran, C., & Aló, R. (2023). *Health disparities through generative ai models: comparison study using A domain specific large language model*. https://arxiv.org/abs/2310.18355
6. Bui, N., Nguyen, G., Nguyen, N., Vo, B., Vo, L., Huynh, T., Tang, A., Tran, V. N., Huynh, T., Nguyen, H. Q., & Dinh, M. (2025). Fine-tuning large language models for improved health communication in low-resource languages. *Comput Methods Programs Biomed*, *263*, 108655. https://doi.org/10.1016/j.cmpb.2025.108655
7. Campanella, S., Paragliola, G., Cherubini, V., Pierleoni, P., & Palma, L. (2024). Towards Personalized AI-Based Diabetes Therapy: A Review. *IEEE J Biomed Health Inform*, *28*(11), 6944-6957. https://doi.org/10.1109/JBHI.2024.3443137
8. Chinta, S. V., Wang, Z., Palikhe, A., Zhang, X., Kashif, A., Smith, M. A., Liu, J., & Zhang, W. (2025). AI-driven healthcare: Fairness in AI healthcare: A survey. *PLOS Digital Health*, *4*(5), e0000864. https://doi.org/10.1371/journal.pdig.0000864
9. Choi, E. Y., Choi, J. Y., & Yoo, T. K. (2025). Automated and code-free development of a risk calculator using ChatGPT-4 for predicting diabetic retinopathy and macular edema without retinal imaging. *Int J Retina Vitreous*, *11*(1), 11. https://doi.org/10.1186/s40942-025-00638-9
10. Dao, D., Teo, J. Y. C., Wang, W., & Nguyen, H. D. (2024). Llm-powered multimodal ai conversations for diabetes prevention. Proceedings of the 1st ACM Workshop on AI-Powered Q&A Systems for Multimedia,
11. Dodevski, Z., Pavleska, T., & Trajkovik, V. (2024). *Leveraging Federated Learning for Secure Transfer and Deployment of ML Models in Healthcare* Proceedings of Chat Gpt in Medicine 2024,
12. Ellahham, S. (2020). Artificial Intelligence: The Future for Diabetes Care. *Am J Med*, *133*(8), 895-900. https://doi.org/10.1016/j.amjmed.2020.03.033
13. Guan, Z., Li, H., Liu, R., Cai, C., Liu, Y., Li, J., Wang, X., Huang, S., Wu, L., Liu, D., Yu, S., Wang, Z., Shu, J., Hou, X., Yang, X., Jia, W., & Sheng, B. (2023). Artificial intelligence in diabetes management: Advancements, opportunities, and challenges. *Cell Rep Med*, *4*(10), 101213. https://doi.org/10.1016/j.xcrm.2023.101213
14. Hasan, M. R., Li, Q., Saha, U., & Li, J. (2024). Decentralized and Secure Collaborative Framework for Personalized Diabetes Prediction. *Biomedicines*, *12*(8). https://doi.org/10.3390/biomedicines12081916
15. He, K., Mao, R., Lin, Q., Ruan, Y., Lan, X., Feng, M., & Cambria, E. (2025). A survey of large language models for healthcare: from data, technology, and applications to accountability and ethics. *Information Fusion*, *118*. https://doi.org/10.1016/j.inffus.2025.102963
16. Ho, C. N., Tian, T., Ayers, A. T., Aaron, R. E., Phillips, V., Wolf, R. M., Mathioudakis, N., Dai, T., & Klonoff, D. C. (2024). Qualitative metrics from the biomedical literature for evaluating large language models in clinical decision-making: a narrative review. *BMC Med Inform Decis Mak*, *24*(1), 357. https://doi.org/10.1186/s12911-024-02757-z

17. Kelly, A., Noctor, E., & Van de Ven, P. (2024). Design, architecture and safety evaluation of an AI chatbot for an educational approach to health promotion in chronic medical conditions. *Procedia Computer Science*, *248*, 52-59.
18. Khalifa, M., & Albadawy, M. (2024). Artificial intelligence for diabetes: Enhancing prevention, diagnosis, and effective management. *Computer Methods and Programs in Biomedicine Update*, *5*. https://doi.org/10.1016/j.cmpbup.2024.100141
19. Lara-Abelenda, F. J., Chushig-Muzo, D., Peiro-Corbacho, P., Wägner, A. M., Granja, C., & Soguero-Ruiz, C. (2025). Personalized glucose forecasting for people with type 1 diabetes using large language models. *Computer Methods and Programs in Biomedicine*, *265*, 108737. https://doi.org/https://doi.org/10.1016/j.cmpb.2025.108737
20. Liu, S., Wright, A. P., Patterson, B. L., Wanderer, J. P., Turer, R. W., Nelson, S. D., McCoy, A. B., Sittig, D. F., & Wright, A. (2023). Using AI-generated suggestions from ChatGPT to optimize clinical decision support. *J Am Med Inform Assoc*, *30*(7), 1237-1245. https://doi.org/10.1093/jamia/ocad072
21. Mackenzie, S. C., Sainsbury, C. A. R., & Wake, D. J. (2024). Diabetes and artificial intelligence beyond the closed loop: a review of the landscape, promise and challenges. *Diabetologia*, *67*(2), 223-235. https://doi.org/10.1007/s00125-023-06038-8
22. Marko, J. G. O., Neagu, C. D., & Anand, P. B. (2025). Examining inclusivity: the use of AI and diverse populations in health and social care: a systematic review. *BMC Medical Informatics and Decision Making*, *25*(1), 57. https://doi.org/10.1186/s12911-025-02884-1
23. Mesko, B., & Topol, E. J. (2023). The imperative for regulatory oversight of large language models (or generative AI) in healthcare. *NPJ Digit Med*, *6*(1), 120. https://doi.org/10.1038/s41746-023-00873-0
24. Nagarajan, R., Kondo, M., Salas, F., Sezgin, E., Yao, Y., Klotzman, V., Godambe, S. A., Khan, N., Limon, A., Stephenson, G., Taraman, S., Walton, N., Ehwerhemuepha, L., Pandit, J., Pandita, D., Weiss, M., Golden, C., Gold, A., Henderson, J., Shippy, A., Celi, L. A., Hogan, W. R., Oermann, E. K., Sanger, T., & Martel, S. (2024). Economics and Equity of Large Language Models: Health Care Perspective. *J Med Internet Res*, *26*, e64226. https://doi.org/10.2196/64226
25. Nassiri, K., & Akhloufi, M. A. (2024). Recent Advances in Large Language Models for Healthcare. *BioMedInformatics*, *4*(2), 1097-1143. https://doi.org/10.3390/biomedinformatics4020062
26. Pachetti, E., & Colantonio, S. (2024). A systematic review of few-shot learning in medical imaging. *Artif Intell Med*, *156*, 102949. https://doi.org/10.1016/j.artmed.2024.102949
27. Park, S. H., Choi, J., & Byeon, J. S. (2021). Key Principles of Clinical Validation, Device Approval, and Insurance Coverage Decisions of Artificial Intelligence. *Korean J Radiol*, *22*(3), 442-453. https://doi.org/10.3348/kjr.2021.0048
28. Pashangpour, S., & Nejat, G. (2024). The Future of Intelligent Healthcare: A Systematic Analysis and Discussion on the Integration and Impact of Robots Using Large Language Models for Healthcare. *Robotics*, *13*(8). https://doi.org/10.3390/robotics13080112
29. Saraswat, D., Bhattacharya, P., Verma, A., Prasad, V. K., Tanwar, S., Sharma, G., Bokoro, P. N., & Sharma, R. (2022). Explainable AI for Healthcare 5.0: Opportunities and Challenges. *IEEE Access*, *10*, 84486-84517. https://doi.org/10.1109/access.2022.3197671
30. Schachner, T., Keller, R., & F, V. W. (2020). Artificial Intelligence-Based Conversational Agents for Chronic Conditions: Systematic Literature Review. *J Med Internet Res*, *22*(9), e20701. https://doi.org/10.2196/20701
31. Singhal, K., Azizi, S., Tu, T., Mahdavi, S. S., Wei, J., Chung, H. W., Scales, N., Tanwani, A., Cole-Lewis, H., Pfohl, S., Payne, P., Seneviratne, M., Gamble, P., Kelly, C., Babiker, A., Scharli, N., Chowdhery, A., Mansfield, P., Demner-Fushman, D., Aguera, Y. A. B., Webster, D., Corrado, G. S., Matias, Y., Chou, K., Gottweis, J., Tomasev, N., Liu, Y., Rajkomar, A., Barral, J., Semturs, C., Karthikesalingam, A., & Natarajan, V. (2023). Large language models encode clinical knowledge. *Nature*, *620*(7972), 172-180. https://doi.org/10.1038/s41586-023-06291-2
32. Song, Z., Yan, B., Liu, Y., Fang, M., Li, M., Yan, R., & Chen, X. (2025). *Injecting Domain-Specific Knowledge into Large Language Models: A Comprehensive Survey*. https://arxiv.org/abs/2502.10708

33. Standl, E., Khunti, K., Hansen, T. B., & Schnell, O. (2019). The global epidemics of diabetes in the 21st century: Current situation and perspectives. *Eur J Prev Cardiol*, *26*(2_suppl), 7-14. https://doi.org/10.1177/2047487319881021
34. Takahashi, Y., Chang, H.-t., Nakai, A., Kagawa, R., Ando, H., Imakura, A., Okada, Y., Tsurushima, H., Suzuki, K., & Sakurai, T. (2021). Decentralized Learning with Virtual Patients for Medical Diagnosis of Diabetes. *SN Computer Science*, *2*(4). https://doi.org/10.1007/s42979-021-00564-1
35. Turchi, T., Prencipe, G., Malizia, A., Filogna, S., Latrofa, F., & Sgandurra, G. (2024). Pathways to democratized healthcare: Envisioning human-centered AI-as-a-service for customized diagnosis and rehabilitation. *Artif Intell Med*, *151*, 102850. https://doi.org/10.1016/j.artmed.2024.102850
36. Van Veen, D., Van Uden, C., Blankemeier, L., Delbrouck, J. B., Aali, A., Bluethgen, C., Pareek, A., Polacin, M., Reis, E. P., Seehofnerová, A., Rohatgi, N., Hosamani, P., Collins, W., Ahuja, N., Langlotz, C. P., Hom, J., Gatidis, S., Pauly, J., & Chaudhari, A. S. (2024). Adapted large language models can outperform medical experts in clinical text summarization. *Nat Med*, *30*(4), 1134-1142. https://doi.org/10.1038/s41591-024-02855-5
37. Verma, R., Alsentzer, E., Strasser, Z., Chang, L., Roman, K., Gershanik, E., Hernandez, C., Linares, M., Rodriguez, J., Thakral, D., Unlu, O., You, J., Zhou, L., & Bates, D. (2025). Verifiable Summarization of Electronic Health Records Using Large Language Models to Support Chart Review. *medRxiv*. https://doi.org/10.1101/2025.06.02.25328807
38. Vuohijoki, A., Mikkola, I., Jokelainen, J., Keinanen-Kiukaanniemi, S., Winell, K., Frittitta, L., Timonen, M., & Hagnas, M. (2020). Implementation of a Personalized Care Plan for Patients With Type 2 Diabetes Is Associated With Improvements in Clinical Outcomes: An Observational Real-World Study. *J Prim Care Community Health*, *11*, 2150132720921700. https://doi.org/10.1177/2150132720921700
39. Wang, D., & Zhang, S. (2024). Large language models in medical and healthcare fields: applications, advances, and challenges. *Artificial Intelligence Review*, *57*(11). https://doi.org/10.1007/s10462-024-10921-0
40. Wang, J., Shi, E., Yu, S., Zihao Wu, C. M., Haixing Dai, Qiushi Yang, Yanqing Kang, Jinru Wu,, Huawen Hu, C. Y., Haiyang Zhang, Yiheng Liu, Yi Pan, Zhengliang Liu, Lichao Sun,, & Xiang Li, B. G., Xi Jiang, Dajiang Zhu, Yixuan Yuan, Dinggang Shen, Tianming Liu, and Shu Zhang. (2021). Prompt Engineering for Healthcare:Methodologies and Applications. *JOURNAL OF LATEX CLASS FILES*, *14*(8). https://doi.org/http://dx.doi.org/10.48550/arXiv.2304.14670
41. Williams, C. Y. K., Miao, B. Y., Kornblith, A. E., & Butte, A. J. (2024). Evaluating the use of large language models to provide clinical recommendations in the Emergency Department. *Nat Commun*, *15*(1), 8236. https://doi.org/10.1038/s41467-024-52415-1
42. Yang, H., Li, J., Liu, S., Du, L., Liu, X., Huang, Y., Shi, Q., & Liu, J. (2023). *Exploring the Potential of Large Language Models in Personalized Diabetes Treatment Strategies*.
43. Yang, X., & Li, J. (2025). A clustering-based federated deep learning approach for enhancing diabetes management with privacy-preserving edge artificial intelligence. *Healthcare Analytics*, *7*. https://doi.org/10.1016/j.health.2025.100392
44. Zou, Y., Zhao, L., Zhang, J., Wang, Y., Wu, Y., Ren, H., Wang, T., Zhang, R., Wang, J., Zhao, Y., Qin, C., Xu, H., Li, L., Chai, Z., Cooper, M. E., Tong, N., & Liu, F. (2022). Development and internal validation of machine learning algorithms for end-stage renal disease risk prediction model of people with type 2 diabetes mellitus and diabetic kidney disease. *Ren Fail*, *44*(1), 562-570. https://doi.org/10.1080/0886022x.2022.2056053

Impact of IoT on Personal Area Networks (PANs)

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ABSTRACT

The Internet, as a revolutionary technology, continues to develop new technologies and software, making it accessible to all. Today, the most common forms of communication are either human-to-human or human-to-device communication; however, the Internet of Things (IoT) foresees a promising future for machine-to-machine (M2M) communication. Many novel wireless technologies, including ZigBee and Bluetooth, compete to provide the Internet of Things with low-power wireless communication solutions; however, in some IoT applications, the technological options are constrained by hardware resource limitations, low power consumption requirements, and overall device costs. Low power consumption is a basic prerequisite for enabling IoT expansion. Besides low power consumption, other requirements must be considered, such as technology cost, security, manageability, usability, wireless data rates, and communication ranges, among others. This paper discusses how the Internet of Things is transforming PANs, with particular focus on proximity communication protocols such as IEEE 802.15.4, Bluetooth, and ZigBee. The scope of this study extends beyond conventional device interconnection to cover new application areas like smart homes, healthcare, wellness, and wearables, succinctly presenting key trends and challenges from current literature, technology standards, and empirical evidence while analyzing critical factors in IoT-integrated PANs such as network scalability, privacy, interference control, and data security, which introduce new complexities to design and administration. This research offers details of IoT-PAN integration by conducting an analysis of wireless integrated personal area networks to identify research gaps and propose future directions. It defines the most important communication protocols and examines adequate levels of security and privacy, analyzing relevant literature to develop a robust framework that enables researchers and practitioners to address gaps in the literature regarding IoT-PAN integration. Therefore, this paper highlights the importance of PAN solutions that are secure, adaptable, and interoperable to enable next-generation IoT ecosystems by providing future insights.

KEYWORDS: *Internet of Things (IoT), Machine-to-Machine Communication (M2M), Personal Area Networks (PANs), SOHO (Small Office/Home Office), BLE (Bluetooth Low Energy)*

INTRODUCTION

The use of IoT devices and related technologies as catalysts for great shifts in our daily activities is becoming increasingly important. We may find ourselves sometimes observing, while at other times not recognizing, an IoT device embedded in everyday devices around us. To advance the public imagination, next-gen IoT applications, such as Internet-connected user gadgets, household control systems, and energy control systems, are emerging to bring about the manifestation of the "Smart home" concept and thus create further demand for Personal Area Networks (PANs).

Recent market data emphasizes rapid growth and the exciting potential of the IoT market. The global IoT market is projected to be approximately USD 64.8 billion in 2024 and grow to USD 153.2 billion by 2029, primarily driven by recent advances in connectivity, sensing capabilities, and cloud integration (MarketsandMarkets, 2024). The enterprise IoT market, specifically, has experienced rapid growth and is estimated to be approximately USD 600.8 billion in 2023, growing to more than USD 1.8 trillion by 2032 (Pangarkar, 2025) . Despite this predicted growth, enterprises still face challenges related to IoT adoption, such as successfully integrating IoT solutions into legacy systems, lengthy product development cycles (time-to-market has increased by over 80% in the last 4 years, to approximately 41 months), and ongoing

challenges regarding security, interoperability, and data management (Paraskevopoulos, 2024). These issues require robust architectural design, the use of standardized communication approaches, and better management approaches to fully realize the potential value of IoT-enabled systems.

A PAN is basically a computer network that interlinks computers or devices within an individual's immediate vicinity. A PAN limits networks to roughly 10 meters (33 feet) or less per person. This short-range network facilitates communication between devices or allows them to connect to the Internet and to higher-level networks, where a single master device serves as a gateway. A typical PAN consists of a computer and printer, a mobile telephone, a tablet, a PDA, and accessories for entertainment purposes such as video game consoles, TV remotes, wearables, and speakers, among others. PANs facilitate communication between devices in a SOHO (Small Office/Home Office) environment and allow resource sharing, data transfer, and application sharing using either wired or wireless connections. Therefore, IoT can be used to enhance PANs, which means that even greater demand arises from the continuous miniaturization of devices with technological evolution, facilitating data and resource sharing across different devices. Unlike traditional PANs, which have limited range and capabilities, PANs enhanced with Internet of Things (IoT) capabilities use more advanced protocols like ZigBee and BLE. The convergence of IoT with PANs therefore enhances energy efficiency, data transmission speed, cost efficiency, automation and control, and device interconnectivity within PANs.

While IoT-based PAN solutions are growing rapidly, existing research has gaps that remain unexplored that may prevent fully realizing this technology's potential. Research has emphasized protocol optimization, energy efficiency, and device interoperability, but has provided less focus on standardized security paradigms for IoT-enabled PANs. Many studies have focused on specific technical elements without creating integrated models combining security, scalability, and latency. Most studies assess performance in laboratory conditions rather than real-world large-scale implementations, particularly for heterogeneous PANs where multiple IoT devices from different vendors must work together. These gaps require longitudinal studies, rigorous cross-vendor compatibility testing, and developing adaptive protocols driven by network dynamics and emerging cyber threats. IoT integration into PANs has changed their uses and features. Once focused on simple device connection, PANs now support smart environments where multiple devices work together to automate tasks, monitor health, and improve daily life. This evolution brings technical challenges including security, energy efficiency, and scalability that must be resolved.

In pursuit of the objectives, this paper is structured in the following manner. Section 2 gives an overview of PAN technologies and their communication protocols. Section 3 describes key technologies and the applications of advanced technologies. Section 4 states the critical analysis, challenges, and limitations, and Section 5 states future directions and open issues. Finally, conclusion and implications for further research are presented in Section 6.

BACKGROUND

Definition of IoT and PAN

Personal Area Network (PAN)

PAN is a small-range network connection that connects devices within a range of 10 meters. Devices like smartphones, tablets, laptops, and Bluetooth devices communicate with each other using this network. There are two types of PANSs: wired and wireless.

Wired: Uses physical connections like cables to connect devices within about 10-15 meters. There are several examples of wired PANs. USB (Universal Serial Bus) is universal and most widely used for computers, peripherals, and smartphones. FireWire was a previous standard that allowed high-speed data transfer, typically used with video cameras and audio equipment. Thunderbolt is a connection standard that enables superfast transfers of large files between laptops, external storage, and displays, among other devices.

Wireless: A wireless network connects devices without cables or physical connections. It connects devices like smartphones, tablets, and personal computers to a small office or home space. Examples of wireless PANs include Bluetooth, Zigbee, Near Field Communication (NFC), Infrared (IR), and Wi-Fi Direct (Yasar, 2024).

Real-World PAN Developments: The practical implementations of PANs are ever-increasing across a variety of industries, and PANs are an important enabling technology that allows devices to

connect, and transfer data within short distances. In the health care industry, PANs allow for continuous monitoring of patients via wearable medical devices and enable the collection and transmissions of vital signs to providers (Kumar, et al., 2023). In smart home environments, PANs facilitate the pairing of various systems like lighting, smart thermostats, security cameras, and entertainment units to give automated control to the user (Li, et al., 2023). Similarly, industries use PANs to keep track of assets and to ensure worker safety through sensor-based wearables. Additionally, consumer electronics now rely heavily upon wireless PAN protocols like Bluetooth and Zigbee, allowing seamless connectivity of smartphones, headphones, fitness trackers, and peripherals. The increasing implementation of PANs demonstrates their significance as reliable infrastructures necessary to enable our everyday lives that are increasingly embedded within the IoT.

Protocols	Use case	Features
Bluetooth	Audio devices, wearables, mobile phones	Low latency, moderate power consumption.
Zigbee	Smart home sensors	Mesh networking, long battery life.
IEEE 802.15.4	Industrial IoT (6LoWPAN)	Ultra-low power, IPv6 compatibility.

Table 1. Comparison of PAN protocols based on use cases and key features

The Internet of Things (IoT)

IoT is a very vast system connected with the internet. This IoT is very important for many industries like healthcare, engineering, sports, transport, etc. Things are sensor-embedded with software, electronics, and networks. This technology helps to improve our work capacity, decision-making, real-time monitoring of our tasks, and automates different types of our work (2505).

EVOLUTION OF PAN TECHNOLOGIES AND IOT-ENABLED APPLICATIONS

Overview of traditional PAN technologies

Bluetooth

Bluetooth is a short-range wireless standard that allows electronic devices to connect wirelessly. The latest Bluetooth Low Energy technology has made exceptional enhancements, theoretically enabling connection with an infinite number of devices. The standard is very helpful for users and can be found nearly everywhere in small environments, like workplaces, homes, or vehicles. As many have discovered, Bluetooth is an extremely basic and helpful wireless innovation for connecting headsets, mobile phones, keyboards, and computers (ammattikorkeakoulu, 2010).

Industry Usages: Commonly found in consumer electronics, automotive, health care devices, wearables, and office peripherals for seamless cable-free connections.

Performance Data: Bluetooth Low Energy (BLE) enables low power consumption connections with range around 10 meters indoors (up to 100 meters for Class 1 devices). Data transfer rates achieve up to 1 Mbps for BLE and higher for classic Bluetooth, making it power efficient for frequently charged devices (Mitra, Brown, Huffman, & Hong, 2020).

Zigbee

ZigBee is an intelligent standard created for applications requiring low data rate remote networking, low battery consumption, and low operating costs. The standard provides exceptional flexibility compared to other network types, with robust and secure communication. Most advanced remote communications were designed to achieve higher data transmission with longer operating distances. However, components like sensors and controls in dynamic systems don't require high bandwidth but need extremely low battery consumption to conserve power. A ZigBee 802.15.4 system is designed to operate at 1mW of radio frequency power. It is the standard technology addressing applications like remote monitoring, control, and sensor network capabilities for short-distance communication.

Industry Application: Zigbee is aimed at home automation, industrial control, smart lighting, smart metering, and sensor networks requiring low-power operation and reliable secure communications.

Performance Data: Zigbee operates in the 2.4 GHz band at 250 kbps data rate. It supports mesh networking with up to 65,000 nodes, indicating much greater scale than Bluetooth. Zigbee reaches distances

of 10-100 meters with good wall penetration. It can run on batteries for years due to extremely low power consumption and uses 128-bit AES encryption for security.

IEEE 802.15.4

Low-Rate Wireless Personal Area Networks (LR-PAN) have become popular in recent years. These networks can be implemented with minimal or no infrastructure. The first standardization step for LR networks was taken in 2003 when IEEE 802.15.4 was approved. An updated version was released in 2006 as IEEE 802.15.4-2006 (802.15.4b). Neither standard supported ranging capabilities between nodes in the network. To support distance and location information, IEEE 802.15.4-2007 (802.15.4a) was approved. Standardization continued with newer standards like IEEE 802.15.4c and 4d being authorized recently (Salman, Rasool, & Kemp, 2010).

Industry Use: Supplies the physical and MAC layers that Zigbee and others use. It is a low-rate wireless standard used in applications requiring long battery life and low data rates for wireless communications, including wireless sensor networks in industries and smart homes.

Performance Information: First published in 2003 with multiple iterations (802.15.4-2006/7, etc.) adding capabilities like ranging and location. Data rates range from 20-250 kbps over distances up to 100 meters under appropriate conditions. Low power consumption enables extended sensor operation. (Hardesty, 2024).

Integration of IoT with PAN standards

Enhancements in low-power communication

Low-power communication is now supported by these PAN standards, which are crucial for Internet of Things devices. Many devices are powered by small batteries and don't need recharging for extended periods. Low-power communication enables effective data transmission while conserving energy. Devices using these technologies can operate without frequent charging and are used in wearable technology, smart homes, and health monitoring, making systems more reliable and suitable for daily use.

Network topology adaptations

IoT networks are structured networks where constrained devices are organized in hierarchies called topologies. IoT networks consist of sensors and actuators operating in various fields. These constrained sensor and actuator nodes communicate with each other and with external devices on the wider Internet. A common network arrangement involves nodes that collect environmental measurements and send them to a gateway or border router. A gateway typically has multiple network interfaces: a wireless interface for the low-power wireless network and a wired interface connecting to a local computer or the internet. Mesh-based topologies are the most suitable and popular among IoT applications.

Applications for IoT-enhanced PANs

Healthcare and wearables

In healthcare, IoT wearables are increasingly tied to AI-powered analytics platforms that forecast health risks and customize treatment plans based on continuous data streams. Devices such as smart ECG monitors, glucose sensors, and pulse oximeters connect through wireless PANs to mobile devices or gateways that securely transmit data to cloud-based health systems. This connectivity strengthens telemedicine, remote patient monitoring, and emergency response systems, ultimately reducing hospital utilization and operating costs. Healthcare providers can leverage 5G networks for low latency and reliable real-time data transfer, supporting critical monitoring during surgery or in intensive care units. An emerging example are FDA-approved wearable devices like the Apple Watch that detect atrial fibrillation, giving patients health insights while enabling a proactive approach to healthcare (Thottempudi, Konduru, Valiveti, Kuraparthi, & Kumar, 2025).

Smart homes and IoT appliances

Smart houses have numerous features. For example, automated lights detect the presence in a room and switch on automatically, or they can be voice-activated. Smart homes increasingly use integrated IoT ecosystems that combine PAN protocols such as ZigBee, Z-Wave, and Bluetooth Low Energy with cloud platforms, providing real-time interactions across devices through built-in automation and user configuration. An example is a smart thermostat that uses real-time occupancy and weather data to optimize its heating and cooling strategy, minimizing energy consumption without affecting occupant comfort. Smart

security systems use facial recognition cameras and AI tools for immediate emergency response through detection capabilities and provide remote management for entry and lockdown. Market leaders like Philips Hue and Google Nest demonstrate smart home technology integration that improves user experience and operational efficiency. The integration of smart home technologies enhances user experience while supporting energy sustainability goals and adding property value.

Fitness monitoring and body sensor networks

Fitness monitoring in IoT-enhanced PANs uses smart devices like fitness bands or smartwatches to track physical activities including steps, heart rate, sleep patterns, and burn calories. These devices create complex Body Sensor Networks (BSNs) that operate using wireless low-power communication protocols **to** gather health data from multiple sensors including accelerometers, gyroscopes, and heart rate monitors on or inside the body. BSNs support continuous monitoring with long battery life by combining collected data for biometric profiling (Peng, Zhang, & Pang, 2025).

Data can be processed locally on the device or offloaded to cloud platforms using machine learning algorithms to assess early warning signs of health abnormalities and provide fitness coaching. This enables real-time health monitoring, fitness routine improvement, and early detection of health issues by individuals and medical professionals. Commercial BSN implementations like Fitbit, Garmin, and WHOOP achieve adoption rates as high as 95% for activity recognition. APIs enables BSNs to connect with third-party health and nutrition applications, providing a comprehensive healthcare approach. Professional sports and healthcare providers use BSN data for performance optimization and rehabilitation.

Comparative Analysis

The evolution of PANs from traditional to IoT-based systems has brought changes in performance, energy consumption, and communications. (The ZigBee Alliance, 2015).

Table 2. Comparison between traditional PANs and IoT-enhanced PANs

Feature	Traditional PANs	IoT-Enhanced PANs
Example Technologies	Bluetooth Classic, Zigbee, IR	Bluetooth low energy (BLE), Zigbee Pro, Thread and 6LoWPAN
Power Consumption	Moderate to high	Optimized for ultra-low power operation
Data Rate	Moderate (up to 1 Mbps for Bluetooth)	Application-specific, optimized (125 kbps to 2 Mbps for BLE)
Range	Limited (10–30 meters)	3 Extendable to mesh networks (100+ meters)
Topology Support	Mostly star	Mesh, star, tree (dynamic and saleable)
Protocol Stack Complexity	Simple, often single purpose	Modular stack with IPv6 (e.g. 6LoWPAN) support
Application Scope	Device pairing (e.g., phones to headsets)	Health Care, Smart Home, Industrial IoT, Wearables
Security	Basic pairing encryption	Multiple layers of security (AES, ECC, session keys)
Interoperability	Often vendor-specific	Designed for multi-vendor IoT ecosystems

Diagram: Protocol Stack Comparisons

The following diagram shows the difference in stack architecture between traditional PAN and IoT-enhanced PAN implementations (Ala Al-Fuqaha, Guizani, Mohammadi, Aledhari, & Ayyash, 2015):

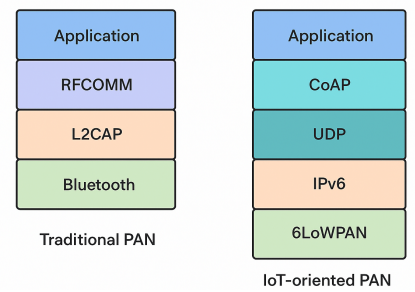

Figure 10. Protocol Stack Comparisons

CRITICAL ANALYSIS OF IOT-ENHANCED PANS

Key Challenges in IoT-Enhanced PANs

Security and privacy issues

According to (Aqeel-ur Rehman, Khan, Moiz, & Rehman, 2016) and, (Kumar, Zymbler, & Tiwari, 2019), major security issues include identification, authentication, data management, cyber-attacks, risks, and vulnerabilities. Many IoT devices have weak security because they are small and lack the power to support strong security methods, making them easily accessible to hackers. Data management is problematic because updating and managing numerous devices securely is difficult. Privacy is important for user comfort and security. IoT devices often collect personal data without user knowledge, creating significant problems. Better regulations, stronger but simpler security systems, and increased awareness about data protection in IoT environments are needed.

Power consumption and Energy efficiency

The discussion of power consumption and energy efficiency is crucial because many IoT devices run on batteries and are used in remote areas. Many IoT devices, such as sensors and cameras, need to work for extended periods without frequent charging or maintenance. Constant data transmission, sensing, and processing can quickly drain device power, creating significant problems in IoT environments. It is necessary to reduce power usage while keeping devices active and reliable. Techniques such as low-power communication protocols, energy harvesting, and smart sleep modes can improve energy efficiency (Mahmoud & Mohamad, 2016).

Quality of Service

According to (Kumar, Zymbler, & Tiwari, 2019), Quality of Service is another important challenge in the IoT environment. We can define it as a measure of the quality, efficiency, and performance of IoT devices. We can identify several problems with the quality of service: there are limited bandwidth, unreliable wireless connections, and power constraints. IoT devices should transfer data on time without delay. Some applications need real-time responses. For example, a health monitoring application needs to send data quickly and without delay. Also, managing these different requirements while many devices are connected simultaneously is challenging. IoT devices often can't fulfill these Quality-of-Service requirements because IoT devices are low-cost and have limited processing power. This makes it difficult to implement advanced QoS techniques. To improve the IoT environment, there is a need for a robust environment that includes reliable and high-speed connections; devices should be energy efficient, and capable of processing data quickly.

Heterogeneity

We can simply define the IoT environment as working with different types of devices, networks, platforms, and data formats. Additionally, IoT systems include a wide range of devices like sensors and cameras. These devices are manufactured by different manufacturers using different technologies. Apple vs Android is one of the best examples of different technologies. However, in an IoT environment, every device should share data and communicate, and connectivity is necessary. Therefore, IDRA (Integrated Data Routing Architecture) is a more suitable solution for this problem (Aqeel-ur Rehman, Khan, Moiz, &

Rehman, 2016). If the IoT environment does not implement such solutions, it cannot build scalable, reliable, and efficient IoT systems.

Scalability

On the Internet of Things context, scalability can be simply described as the ability of a system to manage a growing number of users, devices, and data while maintaining optimal performance levels (Asad Yasin, Maqbool hussain, 2024). Data overload, storage issues, and data quality are several challenges related to data volume and management. Bandwidth limitations, latency, and interference are challenges in network communications. Security, deployment, and maintenance are challenges in device management and configuration. To achieve good scalability, the system should use flexible architecture, cloud or edge computing, and efficient data management techniques.

FUTURE DIRECTIONS AND OPEN ISSUES

Emerging PAN standards for IOT

BLE Mesh

Bluetooth Low Energy, otherwise known as BLE, is a special kind of wireless technology that is meant for low-energy communication. The technology finds its application in a wide range of IoT applications. Meanwhile, BLE also finds usefulness in heart rate monitors for sending data to smartphones for health monitoring. BLE's working range is typically 10 to 100 meters. Apart from this, BLE possesses the capability of making multiple connections simultaneously.

Thread

Thread is also low power and wireless technology. It is suitable for larger and more complex networks. Thread is very good at security. It uses strong encryption. So, this helps to keep the network protected from hackers. Thread is an excellent choice for extensive smart home networks.

Trends in Miniaturization and Edge computing for PANs

Miniaturization

As technology advances, we can optimize electronics into compact parts, such as smartwatches, medical sensors and fitness trackers. These devices can now easily be placed onto the body or into everyday objects. Enhancements in the field of semiconductors, improved efficiency, reduced energy expenditure, and reduced overall expenditure are advantages of miniaturization.

Edge computing

Edge computing is unlike cloud computing. Edge computing means small devices can process data without the internet. The focus of edge computing is to decrease latency and increase responsiveness when processing data that requires real-time results. At the same time, it is used for autonomous cars, industrial automation, and real-time virtual environments.

The use of new technologies such as BLE Mesh and Thread will mark new advances in IoT-enabled PANs. Also, as devices become more advanced and smaller in size, and as edge computing becomes increasingly important in the enhancement of responsiveness, these IoT-enabled PANs will become more effective.

Potential of Artificial Intelligence and Machine Learning in PAN Management

The Artificial Intelligence (AI) system oversees how PAN devices communicate with each other through their networks. Every PAN includes multiple devices like sensors, fitness bands, and smartwatches. These devices need to work together while exchanging information. PANs require strong security measures when they handle health information and location data. Machine Learning (ML) also helps on the security side, as when a hacker tries to connect and access data, ML processes can handle unauthorized access by blocking access or sending warning messages. Since many PAN devices are powered by small batteries, saving energy is very important in the PAN system. Therefore, AI applications can help reduce the power usage of IoT-enhanced PANs.

Research Gaps and Future Exploration Areas

The innovative part of IoT-PAN integration is its potential to evolve traditional short-range networks into intelligent ecosystems which are applicable in healthcare, smart homes, and wearable technologies, enabling real-time applications. Future studies need to focus on creating uniform security standards for low power PAN devices, as the existing approaches are fragmented and limited to specific vendors. One more potential contribution is the AI and ML powered PAN management systems that automatically tune energy consumption, load balancing, and intrusion detection in heterogeneous networks. There are also gaps in cross vendor interoperability testing as most of the research is conducted in controlled laboratory environments as opposed to large-scale, real-world, uncontrolled settings. Other emerging technologies focus on integrating edge computing into PAN protocols, which would decrease latency and facilitate real-time IoT decision-making. In summary, the primary contribution is offering a roadmap showing how IoT-enabled PANs can evolve toward scalable, secure, and adaptive systems to drive the next generation of pervasive computing.

CONCLUSION

The combination of IoT and PANs has radically transformed the landscape of short-range communication, facilitating a new generation of networked devices that support smart, real-time applications across various fields such as healthcare, home automation, and fitness monitoring. By integrating protocols like Bluetooth, ZigBee, and IEEE 802.15.4, IoT-enhanced PANs demonstrate significant improvements in energy efficiency, data transmission rates, device interoperability, and automation capabilities. However, this development brings new challenges. Security and privacy remain primary concerns because the typically constrained processing power of IoT devices makes them vulnerable to attacks. Additionally, factors such as energy constraints, scalability, heterogeneity, and Quality of Service (QoS) limitations underscore the need for highly resilient adaptive solutions. Overcoming these challenges requires a multi-faceted approach based on sophisticated encryption techniques, standardized protocols, energy-aware design, and intelligent resource management methods. This research provides a comprehensive analysis of IoT-PAN integration by assessing proposed solutions for building secure and efficient PANs, conducting detailed protocol analysis, and identifying the primary obstacles and specific challenges in IoT-PAN integration. Furthermore, the comparison between traditional and IoT-enhanced PANs offers valuable insights for system designers regarding improvements in system efficiency, interoperability, and application scope. As the IoT ecosystem expands, PANs will become fundamental pillars of pervasive and secure communication between adjacent devices. Future research must therefore focus on designing scalable and interoperable architectures that provide security, privacy, and resilience while maintaining the lightweight and power-efficient characteristics of PANs. This will ultimately enable the development of sustainable, intelligent, and user-centric IoT applications that enhance quality of life.

REFERENCES

1. Ala Al-Fuqaha, Guizani, M., Mohammadi, M., Aledhari, M., & Ayyash, M. (2015, June 15). Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications. *IEEE Communications Surveys & Tutorials*, 2347–2376. doi:10.1109/COMST.2015.2444095
2. ammattikorkeakoulu, M. (2010). Retrieved from https://www.theseus.fi/handle/10024/15812
3. Aqeel-ur Rehman, A.-u., Khan, I. U., Moiz, M., & Rehman, S. u. (2016, December). Security and Privacy Issues in IoT. *International Journal of Communication Networks and Information Security (IJCNIS), x*, 147-157.
4. Asad Yasin, Maqbool hussain. (2024). Scalability Challenges and Solutions in Massive IoT Networks. *International Journal of Advanced Engineering Technologies and innovations, 10*.
5. Hardesty, G. (2024, November 08). ZigBee Compared to Bluetooth and Wi-Fi for IoT Applications. Retrieved August 12, 2025, from https://www.data-alliance.net/blog/zigbee-antennas-frequencies-types-applications/

6. Kumar, M., Kumar, A., Verma, S., Bhattacharya, P., Ghimire, D., Kim, S. h., & Hosen, S. (2023, April 28). Healthcare Internet of Things (H-IoT): Current Trends, Future Prospects, Applications, Challenges, and Security Issues. *Electronics*, 1-19. Retrieved Agust 12, 2025
7. Kumar, S., Zymbler, M., & Tiwari, P. (2019). Internet of Things is a revolutionary. *Journal of Big data*, December.
8. Li, M., Gu, W., Chen, W., He, Y., Wu, Y., & Zhang, Y. (2023). Smart Home: Architecture, Technologies and Systems. *131*, 393-400. Retrieved August 12, 2025, from https://www.sciencedirect.com/science/article/pii/S1877050918305994
9. Mahmoud, M. S., & Mohamad, A. (2016, January). A study of efficent power consumption Wireless communication Techniques. *Advances in Internet of Things, 6*, 19-29.
10. MarketsandMarkets. (2024, August). Retrieved August 12, 2025, from MarketsandMarkets: https://www.marketsandmarkets.com/Market-Reports/internet-of-things-market-573.html
11. Mitra, R., Brown, G., Huffman, M., & Hong. (2020). Telecommunications and Networking. Retrieved August 12, 2025, from UTSA Pressbooks: https://utsa.pressbooks.pub/networking/chapter/short-range-wireless/
12. Pangarkar, T. (2025, January 14). Retrieved August 12, 2025, from Market.us: https://scoop.market.us/enterprise-iot-statistics/
13. Paraskevopoulos, D. (2024, April 25). (I. Analytics, Editor) Retrieved August 12, 2025, from https://iot-analytics.com/challenges-iot-product-launches-why-time-to-market-has-increased-80-percent-in-4-years/
14. Peng, Y., Zhang, G., & Pang, H. (2025, march 12). Impact of Short-Duration Aerobic Exercise Intensity on Executive Function and Sleep. Retrieved from arxiv.org: https://arxiv.org/abs/2503.09077
15. Salman, N., Rasool, I., & Kemp, A. (2010). Overview of the IEEE 802.15.4 standards family for Low Rate Wireless Personal Area Networks. *7th International Symposium on Wireless Communication Systems.* York, UK: IEEE.
16. The ZigBee Alliance. (2015). *ZigBee Specification.* 508 Second Street ,Suite 206 ,Davis, CA 95616, USA: ZigBee Alliance, Inc.
17. Thottempudi, P., Konduru, R. M., Valiveti, H. B., Kuraparthi, S., & Kumar, V. (2025, February 25). Digital health resilience: IoT solutions in pandemic response and future healthcare scenarios. *6*. Retrieved August 12, 2025, from https://link.springer.com/article/10.1007/s43621-025-00886-7
18. Yasar, K. (2024, september 04). Retrieved 05 21, 2025, from https://www.techtarget.com/searchmobilecomputing/definition/personal-area-network

Evaluating the Role of Gamification on AI Technology tools for addressing Post-Traumatic Stress Disorders

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ABSTRACT

The VERA AI platform offers an innovative, AI-driven neuro-engineering approach to delivering scalable, trauma-informed interventions for Post-Traumatic Stress Disorder (PTSD) among ex- combatants and internally displaced persons (IDPs) in post-conflict Sri Lanka. By combining CBT, DBT, mindfulness, and gamification within a secure, GDPR-compliant ecosystem, it aligns with Disarmament, Demobilisation, and Reintegration (DDR) objectives, supporting both individual recovery and community reintegration.Integrating neuro-sensing technologies such as EEG and HRV with machine-learning models enables personalised, real-time therapy, while policy applications include strengthening DDR programme evaluation and informing national mental health strategies. Ethical deployment emphasising privacy, informed consent, and cultural sensitivity remains central. VERA AI demonstrates how gamified, AI-enabled neuro-engineering can provide effective, cost- efficient, and user-centred psychosocial rehabilitation, empowering individuals in Sri Lanka and other post-conflict settings to rebuild their lives and contribute to sustainable peace.

KEYWORDS: *PTSD, Artificial Intelligence, Neuro Sensing, Gamification, Veterans, Virtual Reality, resilience, CBT, DBT,*

INTRODUCTION

The emergence of Artificial Intelligence (AI) is progressively redefining development praxis by proposing innovative mechanisms for long-standing structural challenges. There is an increased use of geospatial AI in climate-resilience planning, as well as the application of Natural Language Processing (NLP) to support diversity-sensitive communication, the use of chatbots in delivering public services, and the application of Machine Learning (ML) models to model policies and optimise humanitarian logistics. These technologies can be used to further a data-driven, equitable, and participatory approach to enhancing governance, empowering marginalised groups, simplifying the delivery of aid, and making society more resilient to socio-political changes. AI can become a game changer in conceptualising and implementing development, especially in the critical frameworks of post-development theory that emphasise local agents, autonomy, and the rejection of universal theories on development.

This paper interrogates the application of AI and Gamification concepts to address Post- Traumatic Stress Disorder (PTSD) in post-conflict development contexts. It examines the gamified deployment of AI-powered mental health tools, namely virtual counsellors, trauma-informed care chatbots, predictive risk-screening models, and culturally localised Virtual Reality (VR) based therapies, to support the psychosocial reintegration of ex-combatants and Internally Displaced Persons (IDPs). The paper critically evaluates the degree to which such instruments enhance psychological well-being, restore agency, and dignity in post-war societies.

Disarmament, Demobilisation, and Reintegration activities are essential to post-conflict reconstruction. The effective reintegration into civil society depends on successful rehabilitation programmes for ex-combatants. The IOM report suggests that over thirty-five DDR programmes have been established in different parts of the world, and Sri Lanka was also one of the major case studies carried out during the last two decades (IOM, 2017). The conflict between the armed group Liberation Tigers of Tamil Eelam and the Government of Sri Lanka displaced over 3 million civilians and identified more than 10,000 as ex-combatants (WHO, 2022; Kirmayer & Pedersen, 2014).

Considering the challenges of this large group of ex-combatants and IDPs, the Government of Sri Lanka developed a policy framework called the National Framework for Reintegration (MDMHR, 2009). The

policy aimed to respect the human rights of ex-combatants and IDPs, promote sustainable peace and reconciliation, and provide economic opportunities for their reintegration. The Armed Forces of Sri Lanka pursued this programme, and it went beyond military measures to involve psychological reintegration activities (Ratnayake, 2012). The available interventions for psychosocial rehabilitation in Sri Lanka were counselling, vocational training, group therapy and community-based reintegration programs. These were only partially effective, burdened by limited resources and shortages of mental health professionals (Somasundaram, 2007).

Neuro-engineering and Brain Computer Interfaces (BCI) now present cutting-edge biomedical solutions that provide real-time monitoring, adaptive feedback, and personalised intervention within smart-health systems, thereby transforming mental-health delivery in post-conflict settings (Lange, 2012). Psychotherapeutic interventions for post-traumatic stress disorder, including face-to-face Cognitive Behavioural Therapy (CBT) and group counselling, require substantial resources, highly skilled personnel, and stable environmental conditions, which are unavailable in post-conflict settings (Gillespie, 2021). Under these conditions, it is important that scalable, technology-centred interventions be developed and implemented.

Even though there are several AI applications available for mental health care support, based on the available literature, medically/clinically tested Gamified AI Platform backed by neuro sensing data for mental health care which is conceptualised within post-development theory and the Capability Approach (Sen, 1999; Nussbaum, 2011; Escobar, 1995), to deliver personalised, scalable post-traumatic stress disorder care is not to be found. To strengthen methodological validity and address concerns about the lack of results, an in-depth comparative analysis with numerical data extracted from published evaluations of similar systems provides a clear justification for the chosen study design. The paper, therefore, presents the Virtual Emotional Resilience Advisor (VERA), a unique Gamified AI Platform, as a potentially effective and efficient mechanism for addressing post-traumatic stress disorder among ex-combatants, veterans and IDPs in post-conflict development settings.

COMPARATIVE ANALYSIS

System	Symptom Reduction	Engagement Rate	Target Population	Limitations Compared to Vera AI
Woebot (Fitzpatrick et al., 2017)	22% decrease in PHQ-9 scores after 2 weeks	85% daily check-in rate	Depression/anxiety (general population)	No neuro-sensing; no DDR, gamification limited to mood tracking
Wysa (Inkster et al., 2018)	31% reduction in GAD-7 scores over 8 weeks	72% weekly active use	General anxiety/stress	Limited biofeedback integration; not trauma-specific, no DDR,
Mindstrong Health (Dagum, 2018)	Improved cognitive decline ($p<0.05$)	Passive usage rates not disclosed	Severe mental illness	No direct therapy; no gamification and cultural context, no DDR
BioBeats (Schaefer et al., 2020)	HRV improvement ($p<0.01$)	68% app retention at 6 weeks	Workplace stress	No trauma protocols; no DDR integration, no gamification
Ellie – USC ICT (DeVault et al., 2014)	Increased disclosure rate by 25% vs humans	Session completion 90%	PTSD in veterans	Diagnostic only; no ongoing therapy, no DDR integration,
Bravemind – USC ICT (Rizzo et al., 2019)	Reductions in PTSD (CAPS-5, PCL-M) d=0.78–1.12	Session adherence ~80%	Combat veterans with PTSD	VR exposure therapy only; lacks integration with neuro-sensing, no DDR integration

CONTRIBUTIONS

The VERA AI platform integrates neuro-sensing devices, such as Electroencephalogram (EEG) headbands and Heart Rate Variability (HRV) monitors. This is to capture real-time physiological signals relevant to stress regulation and emotional imbalances (Brynjolfsson & McAfee, 2017). Such data are utilised to modulate the delivery of evidence-based interventions within the application, including cognitive behavioural therapy, Dialectical Behaviour Therapy (DBT), and mindfulness-based cognitive techniques, thereby offering context-specific, precise therapeutic support to end-users (Rizzo & Shilling, 2017; WHO, 2022).

The integration of brain-computer interface and neuro-engineering technologies provides precision psychotherapeutic treatments, allowing them to be calibrated according to individual neurophysiological states (Gillespie & Hall, 2021). Also, the incorporation of Trauma-Informed Care (TIC) principles, which prioritise safety, trust, and empowerment for users presenting substantial post- traumatic stress disorder symptoms (Kirmayer & Pedersen, 2014; WHO, 2022). By embedding these principles into Gamified AI chatbot dialogues and Gamified mindfulness modules, the VERA AI platform creates a personalised user environment that supports healing and emotional regulation (Molnar & Gill, 2018).

From a policy perspective, the VERA AI platform aligns with the objectives and frameworks of disarmament, demobilisation, and reintegration programs, which is the globally accepted mechanism developed by the United Nations for post-conflict peacebuilding and stabilisation (Gleichmann et al., 2004; UNDP, 2021). Psychosocial rehabilitation is a key component of disarmament, demobilisation, and reintegration, facilitating the reintegration of ex-combatants into civilian life and reducing the risk of recidivism and social marginalisation (Banholzer, 2013; Ager & Strang, 2008). The platform supports disarmament, demobilisation, and reintegration efforts by offering mental health services at affordable prices and with a scalability that encourages long-term community cohesion and resilience.

METHODOLOGY

The technical architecture of the VERA AI platform is organised as a layered, integrative framework that combines neuro-engineering, brain-computer interface, and advanced AI pipelines to deliver scalable, culturally relevant interventions for post-traumatic stress disorder among ex- combatants, veterans, and IDPs (Brynjolfsson & McAfee, 2017; WHO, 2022). The hardware layer comprises electroencephalogram and heart rate variability sensors, capable of capturing real-time neural and physiological signals, such as stress responses and hyperarousal markers prevalent in patients with post-traumatic stress disorder (Rizzo & Shilling, 2017). Signal preprocessing algorithms are implemented for artefact removal and noise reduction, thereby assuring data integrity prior to processing by the adaptive intervention system (Gillespie & Hall, 2021). Personalised calibration protocols adjust sensor thresholds to individual baselines, supporting the trauma-informed, culturally sensitive objectives of the system (Kirmayer & Pedersen, 2014).

The software architecture level of the VERA AI platform utilises a transformer-based natural language processing pipeline fine-tuned for local languages, enabling culturally contextual chatbot interactions that resonate with user experiences (Molnar & Gill, 2018). Generative Pre- Trained Transformers (GPT) layers trained on local counselling dialogue ensure responsive, empathetic, non-triggering, and consistent dialogue with cognitive behavioural therapy and dialectical behaviour therapy (WHO, 2022). The gamified chatbots facilitate real-time dialogues while continuously monitoring sentiments and intent. Additionally, this enables predictive models to identify escalation points that alert to potential escalations or abnormalities, thereby ensuring safety and responsiveness (Kuhfuß et al., 2021).

The gamification module further incorporates Virtual Reality (VR) and Augmented Reality (AR) enabled cognitive behavioural therapy and dialectical behaviour therapy learning loops, providing scenario-based emotional regulation exercises and mindfulness micro-interventions (Rizzo & Shilling, 2017). Reward structures incentivise repeated engagement, mitigating stigma associated with mental health support and reinforcing user adherence (Gillespie & Hall, 2021). These modules are optimised for low-bandwidth contexts, utilising offline-first architectures with local data caching and synchronisation; such capabilities are essential for deployment in post-conflict, infrastructure- constrained settings (UNDP, 2021).

With adequate data governance, the data pipeline enables the real-time ingestion and processing of data on neurophysiological and interaction data. Machine-learning models perform sentiment and behavioural risk stratification, providing clinicians and reintegration program managers with data for decision making (Brynjolfsson & McAfee, 2017). The use of AI tools considering the Ethical explainability layers offers

transparency, security, and compliance with GDPR-aligned protocols, incorporating multi-layer encryption, privacy preservation, and explicit user consent to safeguard sensitive health data (Molnar & Gill, 2018).

Seamless integration with disarmament, demobilisation, and reintegration frameworks, as well as existing healthcare infrastructures in Sri Lanka, enables synchronisation with case management systems used in reintegration programs. This facilitates real-time updates to user progress and intervention outcomes, which are crucial for program monitoring and evaluation (Gleichmann et al., 2004; Banholzer, 2013). Customisable analytics dashboards allow disarmament, demobilisation, and reintegration managers to assess community-level trends, informing policy adjustments and intervention targeting, thereby aligning VERA AI platform deployment with broader peacebuilding and reintegration objectives (Ager & Strang, 2008; UNDP, 2021).

Evaluating PTSD interventions requires careful selection of research methodologies that balance feasibility and contextual relevance. A range of alternative designs has been used in prior studies, each with distinct strengths and limitations. Single-case experimental designs are valuable for early-stage pilot testing of intervention feasibility but are limited in their generalisability (Kazdin, 2019). Pre and post-single-group studies provide rapid insight into short-term effectiveness but lack a control group, making it difficult to attribute changes directly to the intervention (Creswell & Plano, 2018). Quasi-experimental matched designs avoid the need for randomisation yet are susceptible to residual confounding (Shadish et al., 2002). Finally, qualitative and mixed-methods approaches provide rich contextual data on user acceptability, cultural fit, and lived experience, which is especially critical in post-conflict DDR contexts (Patton, 2015).

Despite the merits of these alternatives, a randomised controlled trial (RCT) remains the optimal design for evaluating Vera AI's effectiveness. They hold high policy-grade credibility, which is essential for DDR and health authorities considering large-scale adoption (WHO, 2021). RCTs can accommodate pre-specified subgroup analyses to address heterogeneity across gender, age, severity, and language, ensuring findings are generalisable within target populations (Moher et al., 2010). It also allows for cost- effectiveness analyses to be embedded alongside clinical outcomes (Drummond et al., 2015), providing a robust evidence base for decision-making in resource-constrained post-conflict settings.

THERAPEUTIC FRAMEWORK

The VERA AI platform employs an integrated therapeutic framework that merges cognitive behavioural therapy, dialectical behavioural therapy, mindfulness practices, and Trauma Informed Care (TIC) principles to deliver culturally sensitive and scalable interventions for ex-combatants, veterans and internally displaced persons with post-traumatic stress disorder in post-conflict Sri Lanka (WHO 2022; Kirmayer & Pedersen 2014). Neuro-engineering sensors such as Electroencephalography (EEG) and Heart Rate Variability (HRV) are embedded to monitor physiological signals in real time, to monitor the user's emotional and cognitive state (Rizzo & Shilling 2017). Predictive modelling, employing sentiment analysis and behaviour tracking, tailors cognitive behavioural therapy, dialectical behavioural therapy modules according to emotional regulation needs while avoiding triggers and adhering to trauma-informed care protocols (Molnar & Gill 2018; Kuhfuß et al. 2021).

Cognitive behavioural therapy modules within the VERA AI platform focus on identifying and reframing maladaptive thought patterns that contribute to hyperarousal and avoidance behaviours typical of post-traumatic stress disorder, using interactive chatbot dialogues and scenario-based microlearning activities to facilitate cognitive restructuring (Gillespie & Hall, 2021; WHO, 2022). Dialectical behaviour therapy modules address emotional dysregulation through skills training in distress tolerance, emotional regulation, interpersonal effectiveness, and mindfulness, operationalised via gamified exercises and VR-enabled role-play to enhance engagement (Rizzo & Shilling 2017). Mindfulness modules will be delivered via guided meditation, breathing exercises, and grounding techniques, and are integrated within session flows to address hypervigilance and dissociation symptoms, allowing users to practice self-regulation techniques contextualised to culturally relevant environments (Kirmayer & Pedersen 2014).

The platform ensures trauma-informed implementation by maintaining a safe, non-judgmental digital environment and prioritising user autonomy, thereby aligning with post-development and Capability Approach frameworks (Sen 1999; Nussbaum 2011; Escobar 1995). Gender and cultural sensitivities are embedded within therapeutic content to ensure that interventions respect social norms and individual

identities, which is critical for effective post-conflict reintegration (UNDP, 2021). Gamification elements encourage consistent participation and skill mastery through reward-based progression systems while reducing the stigma associated with mental health treatment (WHO 2022). Initial baseline assessments utilise standardised tools, such as the Generalised Anxiety Disorder Assessment (GAD-7), Patient Health Questionnaire (PHQ-9), and Posttraumatic Stress Disorder Checklist (PCL-5), to inform personalised intervention mapping (Kuhfuß et al., 2021). The user is guided through modular sessions, receiving feedback and reflective nudges, with content continuously updated by data-driven adaptations based on user progress and bio signal data. The feedback loop enables users to track improvement, and backend data informs clinical and reintegration program staff regarding user readiness for community reintegration, aligning therapeutic outcomes with DDR objectives (Ager & Strang, 2008; Gleichmann et al., 2004).

RESEARCH DESIGN AND CLINICAL VALIDATION

The study will be carried out within the framework of the convergent mixed-methods design: qualitative and quantitative data will be simultaneously collected, and subsequently, will be analysed separately, and only during the interpretation process, they will be combined with each other (Ytterstad & Olaisen, 2021). It allows getting an in-depth insight into the research issue through triangulation of results found due to the research design perspective (Creswell & Plano Clark, 2018).

The first phase involves stakeholder engagement and consultations with DDR-program managers, mental health professionals, community leaders, and ex-combatants to align therapeutic modules with local needs and cultural sensitivities, thereby developing the prototype of the VERA AI platform (Ager & Strang, 2008; UNDP, 2021). This participatory approach keeps in view the respect for the cultural norms, gender issues, and lives of ex-combatants and IDPs. The second stage involves developing the platform based on the feedback and conducting pilot testing of the VERA AI platform by ex-combatants and mental health professionals of national hospitals in Sri Lanka. Feedback from this stage guides iterative design improvements. (Kirmayer & Pedersen, 2014).

The clinical validation of the VERA AI platform will be conducted using a well-defined, multi- stage process that includes ethics, effectiveness, cultural fit, scalability, and general acceptability testing in a post-conflict Sri Lanka. The core evaluation will be a 24-week Randomised Controlled Trial (RCT) design using internationally validated psychometric instruments, namely GAD-7 for generalised anxiety, PHQ-9 for depression, and PCL-5 for PTSD symptom measurement (WHO, 2022; Kuhfuß et al., 2021). The participants will be randomly selected from the National Hospital of Sri Lanka and the Military Hospital in Sri Lanka and will be assigned to either the treatment group or the control group. The treatment group receives VERA AI interventions, while the control group receives standard care aligned with ethical standards (Molnar & Gill, 2018). The neuro-sensing components of the VERA AI platform (EEG and HRV) and BCI integration enable continuous monitoring, yielding objective physiological data that complement psychometric assessments and facilitate studies of bio-psycho- social correlations in PTSD treatment within post-conflict contexts (Rizzo & Shilling, 2017). Data management ensures secure, encrypted storage in line with GDPR and local data-protection laws (Brynjolfsson & McAfee, 2017; Cong & Zheng, 2021).

The data analysis involves paired-sample t-tests, ANCOVA, and machine-learning predictive modelling to assess the effects of symptom reduction, user engagement, and adherence, and to match the patterns to policies and practices. Progress during the trial is aligned with DDR monitoring frameworks to correlate psychosocial rehabilitation outcomes with reintegration success, thereby informing DDR planning and peacebuilding objectives (Gleichmann et al., 2004; Ager & Strang, 2008).

ETHICAL AND CULTURAL CONSIDERATIONS

Approvals for the proposed study will be obtained from the relevant ethics committees in Sri Lanka and partner academic institutions. This will also ensure adherence to the principles of informed consent, voluntary participation, psychological support throughout participation, and compliance with the principles of trauma-informed care (Kirmayer & Pedersen, 2014; WHO, 2022).

Data governance protocols conform to General Data Protection Regulation (GDPR) standards and employ

encryption, transparent consent, and secure data management to safeguard participant confidentiality (Brynjolfsson & McAfee, 2017; Cong & Zheng, 2021). Gender sensitivity and cultural nuances are embedded through local language interfaces, culturally resonant metaphors, and participatory design that respect local values and social norms, thereby ensuring relevance and dignity (UNDP, 2021). Trauma-informed care principles are integrated throughout the design to promote safety, trust, and user control, while preventing re-traumatisation, an essential safeguard for PTSD interventions in post-conflict environments (Kirmayer & Pedersen, 2014; WHO, 2022). Ongoing algorithmic bias mitigation and fairness auditing utilise explainable AI layers and iterative local stakeholder feedback to adjust interventions in response to evolving needs (Molnar & Gill, 2018).

Community trust is cultivated through sustained stakeholder engagement, collaboration with local actors, and participatory validation studies that feature community voices in shaping deployment (Ager & Strang, 2008). There is great respect for gender and religious identities, and clear precautions are taken to ensure that no one is excluded or hurt in interactions within the systems. The sensitivity to local contexts within scenario-based modules, as well as chatbot conversations that incorporate highly culturally adapted scenarios, ensures the cultural integrity of psychological interventions and mindfulness practices.

Informed consent is implemented beyond mere compliance, ensuring users comprehend the technology, its purpose, and their rights, including the right to withdraw without consequence (Brynjolfsson & McAfee, 2017). Local ethics committees and institutional review boards engage in rigorous oversight, aligning with international best practices for research ethics and digital health interventions (WHO, 2022). Security-by-design and privacy-by-design influence the development process, integrating ethical considerations at all levels of platform design.

CONCLUSION

The VERA AI platform constitutes a notable innovation of neuro-engineering, brain-computer interaction, and smart-health systems, offering scalable, trauma-informed interventions for Post- Traumatic Stress Disorder (PTSD) among ex-combatants and internally displaced persons (IDPs) in post-conflict Sri Lanka. The deployment of cognitive-behavioural therapy (CBT), dialectical- behavioural therapy (DBT), mindfulness practices, and gamification within an AI-regulated ecosystem aligns the platform with Disarmament, Demobilisation, and Reintegration (DDR) frameworks, thereby contributing to reintegration and peace-building initiatives (WHO, 2022; Ager & Strang, 2008).

The platform's integration of neuro-sensing devices, notably electroencephalography (EEG) and heart-rate variability (HRV) monitoring, combined with machine-learning models, facilitates real- time, individualised Gamified therapeutic delivery, addressing the heterogeneous presentation of Post-Traumatic Stress Disorder (PTSD) while adhering to ethical standards through compliance with the General Data Protection Regulation (GDPR) and adoptable explainability features in AI systems (Brynjolfsson & McAfee, 2017; Cong & Zheng, 2021). Policy implications of the VERA AI platform include its potential to enrich monitoring and evaluation frameworks in DDR programmes through data-driven insights that refine psychosocial support strategies and inform national mental health policies (Molnar & Gill, 2018; WHO, 2022). Ethical deployment emphasises user privacy, informed consent, and the prevention of harm to ensure that interventions remain trauma-informed and culturally responsive throughout the user journey (Kirmayer & Pedersen, 2014; Brynjolfsson & McAfee, 2017).

The VERA AI platform is used as an illustrative example of how a Gamified AI-based neuro- engineering solution could help address complex mental health issues during the post-conflict period. It offers an effective, cost-efficient, user-centred, scalable model of psychosocial rehabilitation; rooted in the latest technological innovations, but informed by ethical, cultural and therapeutic best-practices to enable ex-combatants, veterans and IDPs in Sri Lanka and other post-conflict countries around the world to rebuild their own lives and become contributors of a wider reintegration process in Sri Lanka and elsewhere.

REFERENCES

1. Ager, A., & Strang, A. (2008). Understanding integration: A conceptual framework. *Journal of Refugee Studies*, 21(2), 166-191. https://doi.org/10.1093/jrs/fen016
2. Brynjolfsson, E., & McAfee, A. (2017). *Machine, Platform, Crowd: Harnessing Our Digital Future*. W.W. Norton & Company. https://research.ebsco.com/c/5gld26/viewer/pdf/47zd3sq64z
3. Cong, G., & Zheng, W. (2021). Explainable AI: Interpreting, explaining and visualizing deep learning. *Springer*. https://mastersofmedia.hum.uva.nl/2021/10/building-a-feminist-dataset-confronting-algorithmic-bias-through-the-practice-ofthoughtful-data-collection/
4. Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and conducting mixed methods research* (3rd ed.). SAGE Publications
5. Dagum, P. (2018). Digital biomarkers of cognitive function. *npj Digital Medicine*, 1(1), 10.
6. DeVault, D., et al. (2014). SimSensei Kiosk: A virtual human interviewer for healthcare decision support. *Proceedings of AAMAS*, 1061-1068
7. Drummond, M. F., Sculpher, M. J., Claxton, K., Stoddart, G. L., & Torrance, G. W. (2015). *Methods for the economic evaluation of health care programmes* (4th ed.). Oxford University Press.
8. Escobar, A. (1995). Encountering Development: *The Making and Unmaking of the Third World*. Princeton University Press. https://voidnetwork.gr/wp-content/uploads/2016/09/Imagining-a-Post-development-Era-by-Arturo-Escobar.pdf?utm_source
9. Fitzpatrick, K. K., et al. (2017). Delivering cognitive behavior therapy to young adults with symptoms of depression and anxiety using a fully automated conversational agent (Woebot): A randomized controlled trial. *JMIR Mental Health*, 4(2), e19.
10. Gleichmann, C., Odenwald, M., & Schauer, E. (2004). *Demobilisation, Reintegration and Rehabilitation: A Practical Guide to Support the Reintegration of Ex-Combatants in Post-Conflict Countries*. GTZ. *https://au.int/sites/default/files/documents/39053-doc43._a_ddr_practical_field_and_classroom_guide_2004.pdf*
11. Inkster, B., et al. (2018). Digital health management tools: Wysa chatbot. *JMIR mHealth and uHealth*, 6(11), e12106.
12. Kirmayer, L. J., & Pedersen, D. (2014). Toward a new architecture for global mental health. *Transcultural Psychiatry*, 51(6), 759-776. https://journals.sagepub.com/doi/pdf/10.1177/1363461514557202
13. Kazdin, A. E. (2019). *Research design in clinical psychology* (5th ed.). Cambridge University Press.
14. Moher, D., Hopewell, S., Schulz, K. F., Montori, V., Gøtzsche, P. C., Devereaux, P. J., ... & Altman, D. G. (2010). CONSORT 2010 explanation and elaboration: Updated guidelines for reporting parallel group randomised trials. *BMJ*, 340, c869. https://doi.org/10.1136/bmj.c869
15. Molnar, A., & Gill, M. (2018). Ethical use of AI in humanitarian contexts. *Journal of International Humanitarian Action*, 3(1), 1-9. https://citizenlab.ca/wp-content/uploads/2018/09/IHRP-Automated-Systems-Report-Web-V2.pdf
16. MDMHR, (2009). National Framework Proposal for Reintegration of Ex-Combatants into Civilian Life in SL. https://www.ilo.org/wcmsp5/groups/public/---ed_emp/---emp_ent/---ifp_crisis/documents/publication/wcms_116478.pdf
17. Nussbaum, M. (2011). *Creating Capabilities: The Human Development Approach*. Harvard University Press. https://dokumen.pub/creating-capabilities-the-human-development approach-0674050541-9780674050549067406120997806740612 00.html
18. Patton, M. Q. (2015). *Qualitative research & evaluation methods: Integrating theory and practice* (4th ed.). Sage Publications.
19. Rizzo, A. "Skip," Hartholt, A., & Mozgai, S. (2021). From Combat to COVID-19 – Managing the Impact of Trauma Using Virtual Reality. *Journal of Technology in Human Services*, *39*(3), 314–347. https://doi.org/10.1080/15228835.2021.1915931
20. Ratnayake, M. G. (2012). Rehabilitation and Reintegration of Ex-combatants in the Post War

Sri Lanka. *Kotelawala Defence University:* http://ir.kdu.ac.lk/bitstream/handle/345/5023/11.pdf?sequence=1

21. Schaefer, A., et al. (2020). BioBeats: Using wearables to manage workplace stress. *Frontiers in Psychology*, 11, 257.
22. Sen, A. (1999). Development as freedom. Alfred A. Knopf. https://kuangaliablog.wordpress.com/wp-content/uploads/2017/07/amartya_kumar_sen_development_as_freedombookfi.pdf
23. United Nations Development Programme. (2021). Digital strategy 2022–2025: *Empowering digital transformation for sustainable development.* https://www.undp.org/publications/digital-strategy-2022-2025
24. World Health Organization. (2022). Delivering effective and accountable mental health and psychosocial support (MHPSS) during emergencies and beyond. https://www.who.int/news-room/feature-stories/detail/delivering-effective-and-accountable-mental-health-and-psychosocial-support-%28mhpss%29-during-emergencies-and-beyond?
25. Ytterstad, S., & Olaisen, J. (2021). Transformational Leadership: Developing Self-Confidence, Learning, and Creativity. https://shorturl.at/WSjdm

Mechanical Properties of OPC-Fly Ash Blended Cement Mortar Samples Utilizing Fly Ash from Sri Lankan Power Plants

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ABSTRACT

This paper presents findings of an investigation of the compressive strength and water absorption of fly ash blended cement mortar samples made using fly ash (FA) generated in power plants in Sri Lanka. Ordinary Portland Cement (OPC) was substituted partially by 10%, 20%, 30% and, 40% of FA by weight. The control mixture was made up entirely of 100% OPC. The ratio of Cement is to sand was 1:2.75 by volume. Three water to binder ratios were used in preparing mortar samples as 0.375, 0.4, and 0.425. A total of 180 mortar cubes of 50mm x 50 mm x 50mm were prepared and the mortar cubes were water cured. The mortar samples were tested for water absorption at age of 28 days and compressive strength at the ages of 3, 7, and 28 days. The test results show that water absorption increased with FA content, while compressive strength decreased slightly at early ages but remained within an acceptable range. At 28 days, FA replacement had no significant negative impact on strength, and the water absorption was inversely related to compressive strength and density. These findings indicate that OPC can be partially replaced by up to 40% FA without compromising mechanical performance, offering benefits in reducing CO_2 emissions, conserving energy, and promoting sustainable construction materials.

KEYWORDS: *High Energy Costs, CO2 Emission, Fly-Ash, Compressive Strength, Water Absorption, Sustainable Construction Material*

INTRODUCTION

Increasing levels of greenhouse gases in the environment are a significant reason for both global warming and climate change. Human activity is almost certainly responsible for the increase in global greenhouse gasses (GHG) and it is mainly due to industrial development and transportation [1]. Among the industrial sectors, the cement industry is responsible for a huge segment of GHG emissions. The emission of CO_2 from the production of cement lies in between 5-7% of the emission of CO_2 globally [2]. Each and every ton of cement which is produced will emit one ton of CO_2 into the atmosphere [3]. Production of Ordinary Portland Cement (OPC) requires a rigorous energy process; and from the total demand for the energy industry, it consumes about 15% [4]. On average, the nuclear power required is 3.4 GJ (in the dry process) and the required electrical energy is 110 kWh to produce one ton of cement. As a result, there is an urgent need to develop sustainable cement with a reduced environmental impact. Social research has shown that there are also social concerns about sustainable cement production [5]. In response, extensive research has been conducted to find alternative solutions that lower OPC consumption while preserving or even improving the performance of construction materials. One promising approach is partially replacing OPC with supplementary cementitious materials (SCMs). Commonly used supplementary cementitious materials include pozzolans such as fly ash, silica fume, ground granulated blast-furnace slag, red mud, rice husk ash, and sugarcane bagasse ash. [6, 7].

Fly ash (FA) is selected for this study over other pozzolanic materials because it is the most common pozzolanic material in Sri Lanka and also it is one of the by-product which is generated from the coal combustion process. According to the Coalition against coal (CAC), Lakvijaya Coal Power Station, Norochcholai, Sri Lanka will approximately generate 1000 tons of FA per day [8]. More than 400 tons

of FA are dumped daily into the nearby dumping yard. Spreading it along with the wind, causing significant environmental and community pollution. By increasing the use of FA for cement production these harms can be minimized.

Pedraza, Pineda, and Gutiérrez investigate the effect of unburned impurities in FA additions on the mechanical properties of cement mortars by partially replacing mortar cement cubes with FA fractions of 20, 40, 60, and 80% [3]. This research study mainly focused on the variation in compressive strength of mortar when FA added to the mix. According to the findings of this research, it revealed that 20% of cement can be replaced with FA without compromising quality. According to the research, combinations with a high percentage of FA are incompatible with the strength of 100% cement mortar. The compressive strength of FA incorporated cement mortar was examined by Kondraivendhan & Bhattacharjee, by replacing OPC in 10% increments from 0% to 40% [9]. Compressive strength of the FA blended cement mortar has been increased with age in all water to binder ratios and FA replacement levels, according to the study. In comparison to the control specimens, the strength of the specimens steadily decreased due to an increase in FA replacement. Properties of the mortar improves due to the pozzolanic reaction. Calcium Silicate Hydrates (CSH) produced during the pozzolanic reaction is primarily responsible for the strength of the cement and it reduces the size of the capillarity pores in the hardened cement paste [10, 11]. FA's pozzolanic action aids in the development of strength in later ages. According to a study conducted by Kondraivendhan and Bhattacharjee, up to 28 days of curing, the compressive strength of OPC-FA blended cement mortar declines with an increase in FA replacement level but, when compared to the control specimen, the compressive strength of OPC-FA blended cement mortar increases at 90 days of curing [9]. Cho, Jung, and Choi investigated the impact of the chemical composition of FA on the mechanical properties of FA blended cement mortar using 16 distinct types of FA present in South Korean ready-mixed concrete production plants as raw material [12]. They emphasized in their study that, while FA is a very beneficial cement additive, it has the disadvantage of performance of blended cement which is highly dependent on quality of the FA used.

Although extensive experiments and research have been conducted in this field, significant gaps remain, particularly in the Sri Lankan context, where such studies are limited. FA has a wide range of qualities, depending on the coal combustion process. As a result, this research study aimed to look into the mechanical properties of OPC-FA blended mortar prepared from FA generated in Sri Lankan power plants.

The objectives of this research are:

- To investigate the variation in compressive strength of mortar samples when ordinary Portland cement is partially replaced with fly ash.
- To examine the changes in water absorption of mortar samples with partial replacement of ordinary Portland cement by fly ash.
- To establish the relationship between density, water absorption, and unconfined compressive strength in mortar samples incorporating fly ash as a partial replacement for ordinary Portland cement.

The scope of this research may be limited to OPC–fly ash blended cement mortar samples made with fly ash that has similar properties to the one used in this study, which was obtained from power plants in Sri Lanka.

MATERIALS AND METHODOLOGY

To accomplish the study's objectives, an experimental methodology was adopted.

Materials Used

During the investigation, the materials which were used are given below;

- Cement – Ordinary Portland Cement, strength class 42.5 N, produced by Ultratech Cement Lanka (Pvt) Ltd, complying with SLS 107:2015 and BS EN 196-6:2010 standards [13, 14]

- Fly Ash - Class F fly ash obtained from Lakvijaya Coal Power Plant, Norocholai, Sri Lanka. The particle size distribution of the FA and its chemical composition was obtained from the sample and analysis certificate issued by SGS South Africa (Proprietary) Limited and are shown in Tables 1 and 2 respectively.

- Fine aggregate – Washed and sieved offshore sea sand obtained from Sri Lanka Land Development Corporation.

- Water – Clean, fresh, and potable tap water

Rationale of Selecting Materials

Ultratech OPC is the most widely used cement in Sri Lanka. Therefore, Ultratech OPC was used for the experimental program. Lakvijaya Coal Power Plant, Norocholai is the only coal power plant in Sri Lanka. Therefore, FA obtained from Lakvijaya Coal Power Plant, Norocholai was used for the experimental works. In Sri Lanka, sand obtained from different areas are different in quality and prices are also very different. But offshore sea sand which is obtained from Sri Lanka Land Development Corporation has a fixed price and quality. In addition, sea sand is kind of consistent material. Table 1 and Table 2 provide particle size distribution and chemical composition of fly ash specified by ASTM standards [15].

Table 1. Particle Size Distribution of the Fly Ash

Size Distribution		**Fractional Mass (%)**	**ASTM Standards**
-mm	+mm		D 4749
	50.00	1.5	
2.00	0.00	12.6	

Table 2. Chemical Composition of the Fly Ash

Mineral Ash Analysis (Dry Basis)	**Unit**	**Result**	**ASTM Standards**
Silicon as SiO_2	%	48.66	D 4326
Aluminum as Al_2O_3	%	27.99	D 4326
Iron as Fe_2O_3	%	3.41	D 4326
Calcium as CaO	%	9.15	D 4326
Magnesium as MgO	%	2.49	D 4326
Sodium as Na_2O	%	0.57	D 4326
Potassium as K_2O	%	0.66	D 4326
Phosphorous as P_2O_5	%	1.91	D 4326
Titanium as TiO_2	%	1.57	D 4326
Manganese Dioxide as Mn_3O_4	%	0.09	D 4326
Sulphur as SO_3	%	3.00	D 1757
Undermined	%	0.50	-
Total	%	100.00	-

Mix Proportions and Experimental Factors

According to ASTM C-109, the control mix for this study is 1:2.75 cement to sand by volume. To determine which mixture with FA additions exhibits greater compressive strength and other mechanical properties, a percentage of 10%, 20%, 30%, and 40% of FA is utilized as partial cement replacement. The experimental works included three water to binder ratios of 0.375, 0.4, and 0.425. Table 3 shows the proportions of FA blended cement mortar.

Table 3. Mix Proportions of Fly Ash Blended Cement Mortar

No. of cubes	w/c Ratio	FA (%)	OPC (%)	Cement (g)	FA (g)	Sand (g)	Water (ml)
12	0.375	0	100	1916	0	2476	719
12		10	90	1724	192	2476	719
12		20	80	1533	383	2476	719
12		30	70	1341	575	2476	719
12		40	60	1150	766	2476	719
12	0.4	0	100	1886	0	2437	754
12		10	90	1697	189	2437	754
12		20	80	1509	377	2437	754
12		30	70	1320	566	2437	754
12		40	60	1132	754	2437	754
12	0.425	0	100	1857	0	2399	789
12		10	90	1671	186	2399	789
12		20	80	1486	371	2399	789
12		30	70	1300	557	2399	789
12		40	60	1114	743	2399	789

Preparation of Mortar Cubes

Three water to binder ratios, three different curing ages, and five FA replacement levels were cast in 180 samples of 50 mm cubical cement mortar. The test specimens were cast in fiber molds with foam oil applied to the mold's inner side for easy removal. First, FA and cement were mixed well in a dry form, and then sand was added. After that water was added and mixed thoroughly using a mortar mixer until a uniform mixture is formed. It was then placed in molds and compacted thoroughly with a steel rod. The specimens were demolded and submerged in a water bath for 24 hours before being tested for cure.

Figure 1. Hardened mortar samples

Compressive Strength Test

ASTM C-109 is used to conduct the mortar compressive strength test. The cubes were tested at three different ages: 3, 7, and 28 days using three cubes per FA replacement. They were tested on a universal testing machine, as shown in Figure 2. The load is applied at a constant rate of 4.50 kN/s until the specimen failed. The representative compressive strength of each mortar mix was calculated using the average failure stress of three cubes.

Figure 2. Standard compressive strength apparatus

Water Absorption Test

At the age of 28 days, three cubes of each mixture were tested. The water absorption test process begins with the water curing mortar specimens being dried at 105°C in an oven for not less than 24 hours, till the weight does not drop more than 0.2% in 2 hours, as illustrated in figure 3. The mass of dried mortar specimens (W_d) is weighed. Subsequently, the dried mortar specimens were immersed in water, and readings were taken at 10, 20, 30, 60, 120, 180, and 240 minutes, as proposed by previous researchers [16] and shown in Figure 4. The specimens were placed on a cane net to ensure that all the faces were in contact with water. The mass of wet mortar specimens (W_s) is weighed based on the testing period and the percentage of water absorption is determined as follows:

$$\text{Water Absorption (\%)} = \frac{(W_s - W_d)}{W_d} \text{ x } 100\%$$

The water absorption of each three specimens was determined and the mean water absorption was computed.

Figure 3. Drying of Samples

Figure 4. Immersion of Samples in Water

RESULTS AND DISCUSSION

Compressive strength

The cubes were tested for compressive strength at the age of 3,7 and 28 days using three cubes per FA replacement and then the average compressive strength value for each FA replacement was calculated.

Figure 5 depicts the variation in the compressive strength of OPC-FA blended cement mortar samples with respect to the water to cement ratios of 0.375, 0.4, and 0.425. Compressive strength of the OPC-FA blended cement mortars increases from 3 to 28 days in all water to binder ratios and FA replacement levels, according to the findings. The continuation of cement hydration is responsible for the increase in compressive strength with age. When Portland cement is mixed with water, the initial reactions are mainly involved with the silicates contained in the cement. During their reaction with water both tricalcium silicate and dicalcium silicate produce a hard paste – gel made up of Calcium Silicate Hydrates (CSH). CSH is the major contributor to the strength of cement. It is known that compressive strength increases rapidly in the early stages and slowly in later stages [17]. Although the compressive strength of mortar specimens increases with age, it is observed that the compressive strength of the specimens decreased gradually as the amount of FA replaced increased as compared to the control specimens. The sluggish pozzolanic process is mostly responsible for the decrease in compressive strength. Silicates are reacting with water during the cement hydration process to produce CSH as well as at the same time it forms Calcium hydroxide. The amorphous silica in FA reacts with this excess Calcium hydroxide to reproduce CSH which forms further strength in cement. The reduction in free Calcium hydroxide makes the mixture chemically more stable. So, it also increases strength. During their research study Ahmed, 2019 revealed that, due to the secondary reactions, most pozzolanic cements develop strength beyond 28 days. The result obtained from the study is in line with that obtained by Kondraivendhan & Bhattacharjee [9].

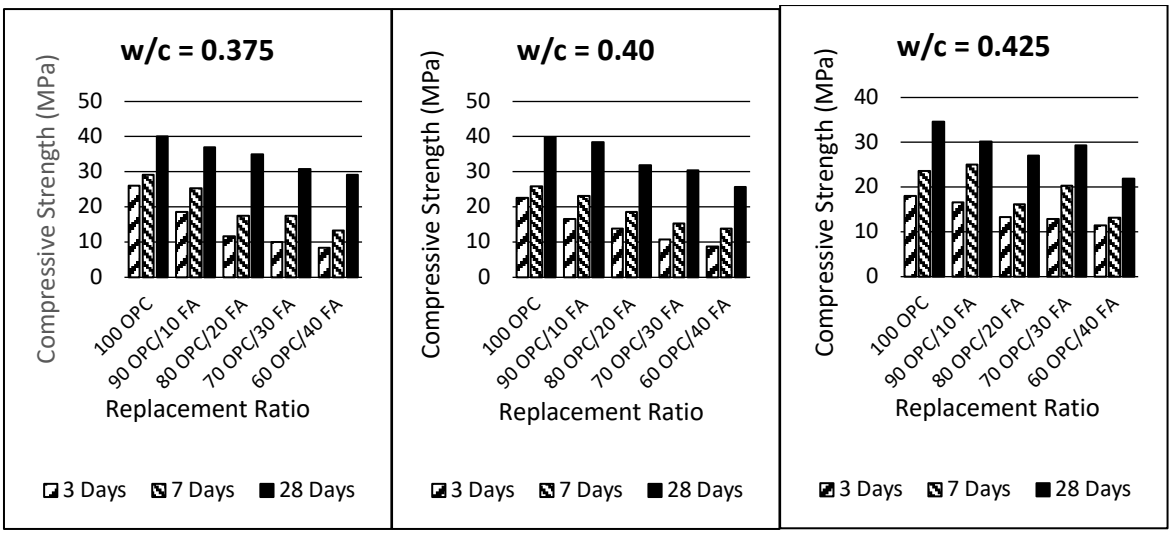

Figure 5. *Compressive* strength of OPC-FA blended cement mortar

3.1.1 Sensitivity to water to binder condition on strength

The sensitivity of compressive strength to the water-to-binder ratio was investigated using the 'Sensitivity Index' concept for samples cured in water for 28 days, as adopted by previous researchers [18].

Sensitivity Index (SI) = $\frac{f_{test} - f_{ref}}{f_{ref}} = \frac{f_{test}}{f_{ref}} - 1$

Where, f_{test} = Strength of the test mix
f_{ref} = Strength of the corresponding mix with reference water to binder ratio

The 'Sensitivity Index' can be defined as the difference of strength between the test mix and the reference mix as a ratio of the reference mix. The central water to binder ratio of the experimental program was 0.4. Therefore, to test sensitivity to water to binder ratio on compressive strength, a mixture with water to binder ratio of 0.4 was used as a reference. The mixtures with a w/binder ratio of 0.375 and 0.425 were taken as test mixtures for the analysis. If the sensitivity index is '0' it indicates that there is no sensitivity. The positive value of the sensitivity index indicates that the strength has been increased, while the negative value indicates the strength has been decreased. Figures 6 and 7 present sensitivity to w/binder ratio of 0.375 and 0.425 respectively. In Figure 6, all values except the 10% FA replacement level are positive; indicating that all mixtures are sensitive to water to binder ratio and that the strength increases as the water to binder ratio decreases from the datum. According to Figure 7, all the sensitivity index values are negative; and it indicates that all the mixtures are sensitive, and also strengths are decreased with the increase of water to cement ratio from 0.4 to 0.425.

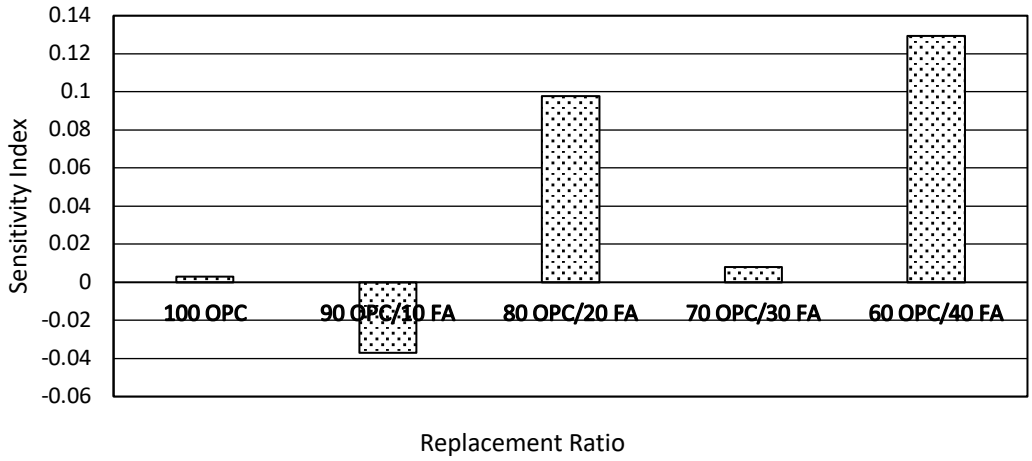

Figure 6. Sensitivity to w/c ratio on strength (w/c = 0.4 to 0.375)

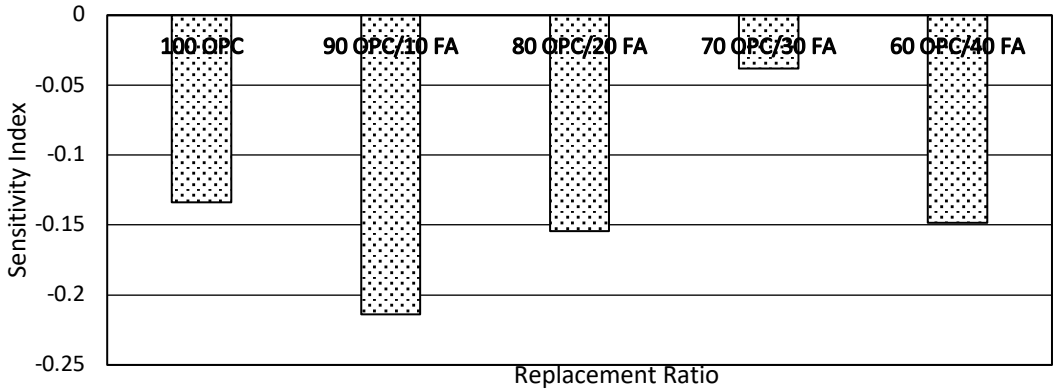

Figure 7. Sensitivity to w/c ratio on strength (w/c = 0.4 to 0.425)

Water Absorption

Figure 8 depicts the variation in water absorption of the FA blended cement mortar samples with the water to binder ratios of 0.375, 0.4, and 0.425. The water absorption of the FA blended cement mortar increases as FA replacement level increases in all water to binder ratios, according to the trendline of the results. The silica which is in the FA, reacts with excess free calcium hydroxide in the pozzolanic reaction to form CSH, which reduces the size of the capillarity pores. However, due to the insufficient CSH in the early ages of cement hydration, these capillary pores may not be filled. The results revealed that as the water to binder ratio increases, water absorption of the FA mixed cement mortar will also be increase. After obtaining the required amount of water for cement hydration, if any excess water remains in the mix, they remain as water in the sample. The results of this study are aligned with that obtained by Hatungimana, Taşköprü, İçhedef, Saç & Yazıcı [19]. With the increasing of the fraction of FA replacement, the values of water absorption of FA mortar mixtures will also be increased, according to the authors. Although the method proposed by Jung, Siang, Kwong & Boon [16] to determine water absorption was used for this study, the chemical composition of the mortar sample may change as the FA blended samples are heated in the oven at 105 °C. Therefore, it has the potential to affect the final results. So, it is recommended for future researchers to get the saturated weight first and then put it in the oven to take the dry weight.

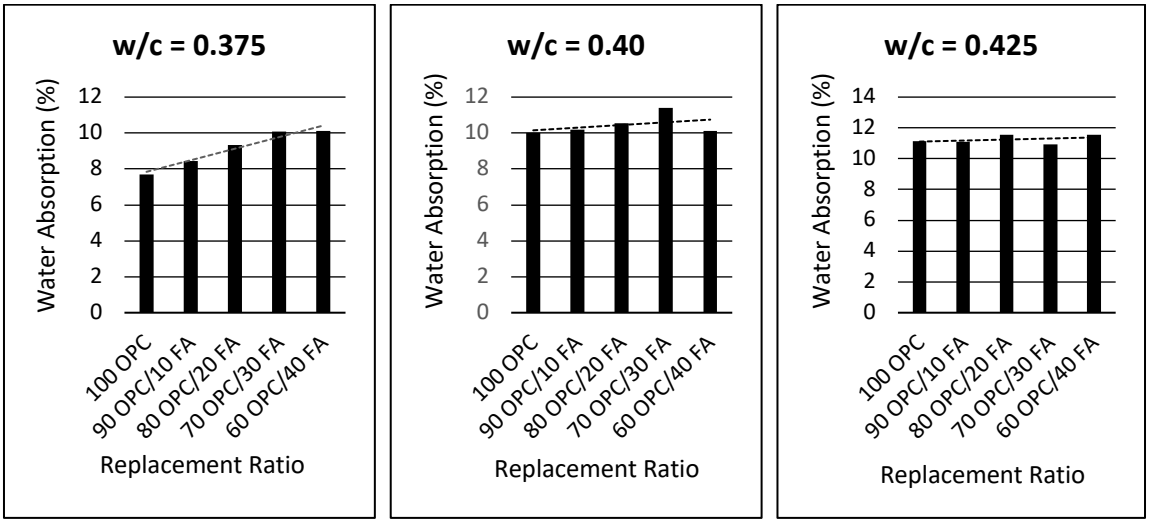

Figure 8. Water absorption of OPC-fly ash blended cement mortar

Density

The density variance of FA blended cement mortar samples with water to binder ratios of 0.375, 0.4, and 0.425, respectively, is shown in Figure 9.

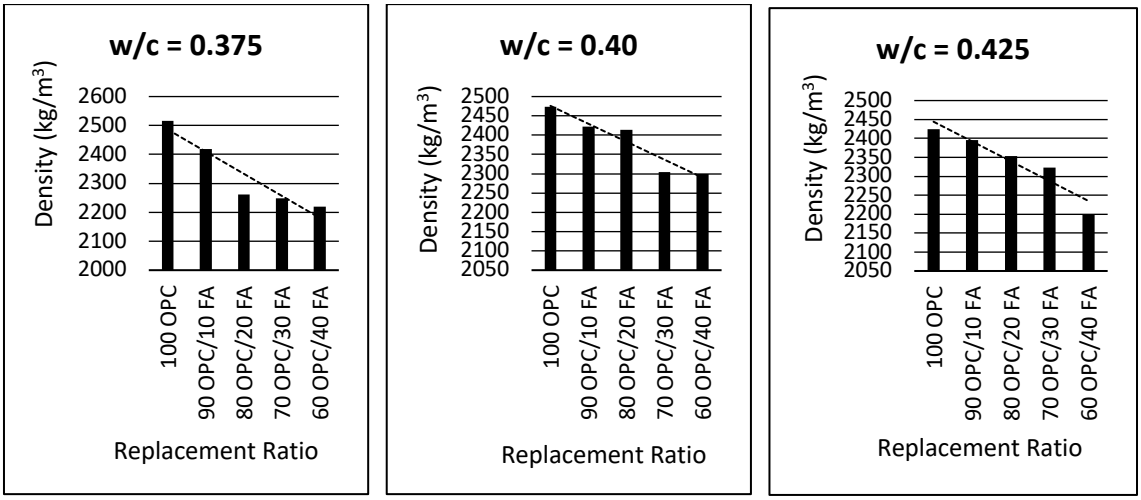

Figure 9. Density of OPC-fly ash blended cement mortar

According to the findings, the density of the FA blended cement mortar reduces as the FA replacement amount increases in all water to binder ratios. 28 days of cure is insufficient to complete the pozzolanic process. As a result, the CSH may not be sufficient to fill the capillary pores in the specimen at the age of 28 days. In comparison to the control sample, the number of pores in the specimen increases as the FA replacement level increases. As a result, when the FA level increases, the weight of the sample decreases, and then the density also increases.

The Relationship of Compressive Strength, Water Absorption and Density of Mortar

When water absorption decreases, the compressive strength and density of specimens increase. According to the results, the control sample which has 100% OPC shows the least water absorption. This is because the control sample has a larger concentration of CSH. The larger the quantity of CSH, the smaller the capillary pores in the specimen. Therefore, less water is absorbed into the specimen. Due to the lesser number of pores in the specimen, the compressive strength increases as the percentage of water absorption decreases.

CONCLUSION

The experimental results and analysis presented in this paper lead to the following conclusions;

1. At 28 days, compressive strength decreased slightly with higher FA content due to lower early-age CSH formation, but remained within acceptable limits.
2. The water absorption is inversely proportional to compressive strength and density at age of 28 days.
3. Due to the pozzolanic reactions induced by the presence of FA in the mixture, CSH is formed and thereby capillary pores in the specimen are reduced, resulting in increased compressive strength and durability.
4. Up to 40% OPC can be replaced with FA without significantly reducing strength, contributing to energy savings, lower CO_2 emissions, and sustainable material use.

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REFERENCES

1. Benhelal, E., Zahedi, G., Shamsaei, E., & Bahadori, A. (2013). Global strategies and potentials to curb CO2 emissions in cement industry. *Journal Of Cleaner Production*, *51*, 142-161. https://doi.org/10.1016/j.jclepro.2012.10.049
2. Worrell, E., Price, L., Martin, N., Hendriks, C., & Meida, L. (2001). CARBON DIOXIDE EMISSIONS FROM THE GLOBAL CEMENT INDUSTRY. *Annual Review Of Energy And The Environment*, *26*(1), 303-329. https://doi.org/10.1146/annurev.energy.26.1.303
3. Pedraza, S., Pineda, Y., & Gutiérrez, O. (2015). Influence of the Unburned Residues in Fly Ash Additives on the Mechanical Properties of Cement Mortars. *Procedia Materials Science*, *9*, 496-503. https://doi.org/10.1016/j.mspro.2015.05.022
4. Mokhtar, A., & Nasooti, M. (2020). A decision support tool for cement industry to select energy efficiency measures. *Energy Strategy Reviews*, *28*, 100458. https://doi.org/10.1016/j.esr.2020.100458
5. Kulasuriya, Chandana, Priyan Dias, and Vanissorn Vimonsatit. "Investigation of Social Concerns Regarding a Sustainable Cement." Journal of Engineering 30, no. 04 (2024): 1-20.
6. Islam, Md. M. and Islam, Md. S. (2010). Strength Behaviour of Mortar Using Fly Ash as Partial Replacement of Cement. Concrete Research Letters, 1(3), 98–106.
7. Kulasuriya, C., Vimonsatit, V., Dias, P. 2013. "Design of Alkali Pozzolan Cement: Early Compressive Strength." The First Australasia and South East Asia Conference in Structural Engineering and Construction (ASEA-SEC-1), Perth. https://doi.org/10.3850/978-981-08-7920-4_M-36-0310
8. Explosive report on hazards of Norochcholai coal power plant. (2021). Retrieved 23 November 2021, from https://energycentral.com/news/explosive-report-hazards-norochcholai-coal-power-plant
9. Kondraivendhan, B., & Bhattacharjee, B. (2015). Flow behavior and strength for fly ash blended cement paste and mortar. *International Journal Of Sustainable Built Environment*, *4*(2), 270-277. https://doi.org/10.1016/j.ijsbe.2015.09.001
10. Ahmed, A. (2019). Chemical Reactions in Pozzolanic Concrete. *Modern Approaches On Material Science*, *1*(4). https://doi.org/10.32474/mams.2019.01.000120
11. Kulasuriya, C., 2015. *Alkali Pozzolan Cement for Integral Sustainability*. Curtin University, Perth, 2015.
12. Cho, Y., Jung, S., & Choi, Y. (2019). Effects of chemical composition of fly ash on compressive strength of fly ash cement mortar. *Construction And Building Materials*, *204*, 255-264. https://doi.org/10.1016/j.conbuildmat.2019.01.208
13. Sri Lanka Standards SLS 107 Specification for Ordinary Portland Cement. Sri Lanka Standards Institution, Colombo 08, Sri Lanka.
14. British Standards Institution (2015) BS EN 196-6:2018 – TC Methods of testing cement - Determination of fineness.
15. American Society for Testing and Materials, ASTM C 109/C109 Standard Test Method for Compressive Strength of Hydraulic Cement Mortars.
16. Jung, C., Siang, T., Kwong, T., & Boon, K. (2019). Compressive Strength and Water Absorption of Mortar Incorporating Silica Fume. *International Journal Of Civil Engineering*, *6*(8), 39-43. https://doi.org/10.14445/23488352/ijce-v6i8p106

17. Uddin, M., Jameel, M., Sobuz, H., Hasan, N., Islam, M., & Amanat, K. (2012). The Effect of Curing Time on Compressive Strength of Composite Cement Concrete. *Applied Mechanics And Materials*, *204-208*, 4105-4109. https://doi.org/10.4028/www.scientific.net/amm.204-208.4105
18. Kulasuriya, C., Dias, W., & Vimonsatit, V. (2019). Durability properties of alkali pozzolan cement (APC). *Journal Of The National Science Foundation Of Sri Lanka*, *47*(1), 121. https://doi.org/10.4038/jnsfsr.v47i1.8929
19. Hatungimana, D., Taşköprü, C., İçhedef, M., Saç, M., & Yazıcı, Ş. (2019). Compressive strength, water absorption, water sorptivity and surface radon exhalation rate of silica fume and fly ash based mortar. *Journal Of Building Engineering*, *23*, 369-376. https://doi.org/10.1016/j.jobe.2019.01.011

Entrepreneurial Orientation on Talent Acquisition and Retention in Construction SMEs

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Abstract

This study investigates how Entrepreneurial Orientation (EO) influences talent acquisition and retention strategies in Small and Medium Enterprises (SME). Construction SMEs often face limitations in attracting and retaining skilled employees. Therefore, this study examines the role of EO dimensions (innovativeness, autonomy, and proactiveness) in offering a strategic approach to address these challenges and enhance HR practices. The author adopted a mixed-method research approach for this study, collecting data through semi-structured interviews with SME managerial-level professionals and administering a questionnaire survey among professionals in the construction sector. The data were analysed using correlation techniques and thematic analysis to identify the strategic alignment between EO practices and talent management efforts. The findings revealed that internships and employee referrals are the most used and effective talent acquisition strategies. In terms of talent retention approaches, performance-based incentives and career development programs were identified as dominant approaches. Moreover, the study found that the EO dimensions of autonomy and proactiveness significantly impact the adoption and success of these talent retention and acquisition strategies. The results offer a framework for construction SMEs to improve talent-related outcomes by integrating EO into their HR planning.

Keywords: *Entrepreneirial Orientation, Talent Acquisition, Talent Retention, Construction SMEs, HR Strategies*

Introduction

The construction industry plays a vital role in national economic development and employment, encompassing a diverse network of actors dominated primarily by small and medium enterprises (SMEs) (Akdogan et al., 2012). However, this sector faces persistent challenges, such as low productivity, poor workforce management, and fluctuating employment conditions (Abioye et al., 2021). Given the industry's heavy dependence on skilled labour, talent acquisition and retention have become critical HR concerns for SMEs, especially during economic uncertainty (Alsharef et al., 2024). Effective talent acquisition involves building a strong employer brand, using digital platforms, university partnerships, and analytics to attract qualified candidates (Wungsnuopparat & Jiarui, 2022). Despite the importance of talent acquisition, employee retention in the construction industry remains a significant challenge due to project-based work cycles, financial limitations, and high competition (Hongal & Kinange, 2020). Non-financial factors such as training, development, and work-life balance are known to support retention, though they may also increase employee (Baharin & Hanafi, 2018).

To address these challenges, the concept of **EO** offers a strategic lens through which construction SMEs can manage talent effectively. EO comprises five dimensions: innovativeness, proactiveness, risk-taking, autonomy, and competitive aggressiveness, collectively representing a firm's strategic posture in pursuing opportunities and navigating uncertainty (Tat et al., 2007). Studies suggest EO supports flexibility, innovation, and firm-level resilience in construction SMEs (Othman, Saadon and Al, 2022). Innovativeness enables SMEs to adopt technologies like BIM and sustainable materials, enhancing efficiency and appeal to employees (Saka & Chan, 2020). Risk-taking facilitates entry into new markets and investment in emerging construction technologies despite financial uncertainty (Okangi, 2019). Proactiveness empowers firms to anticipate market needs and adapt early to change, while autonomy fosters internal decision-making and responsiveness (Chelliah et al., 2023). Competitive aggressiveness, although context-dependent, allows SMEs to confront competitors to maintain market strategically (Abdullahi et al., 2019).

Despite growing academic interest in EO, its relationship with HR strategies in construction SMEs, particularly regarding talent acquisition and retention, has been underexplored (Anzules-Falcones & Novillo-Villegas, 2023). Much of the existing literature focuses on EO's impact on innovation and

business performance rather than workforce stability (Mara, 2018). The study thus seeks to fill this gap by examining how EO influences recruitment and retention strategies in construction SMEs facing limited resources, workforce shortages, and competitive pressures (Abdullahi et al., 2019). Talent acquisition strategies include social media recruitment, employer branding, internships, and partnerships with educational institutions (Malesev & Cherry, 2021). On the other hand, effective retention strategies include flexible scheduling, employee development programs, and inclusive work cultures (Lamane-Harim, Cegarra-Leiva and Sánchez-Vidal, 2023).

Due to financial and infrastructure constraints, SMEs also face challenges in implementing digital recruitment and HR analytics tools (Wentzel et al., 2022). Nevertheless, developing a strategic approach to talent management, especially one informed by EO, can help construction SMEs create a competitive and resilient workforce. By aligning EO with HR practices, SMEs can address their recruitment and retention issues and enhance organisational innovation, responsiveness, and long-term sustainability.

Methodology

The author adopted a mixed-methods research design to address the research objectives, combining qualitative and quantitative approaches to ensure a comprehensive understanding of how Entrepreneurial Orientation (EO) influences talent acquisition and retention strategies in construction SMEs. Initially, a comprehensive literature review was conducted to identify the dimensions of EO and existing HR strategies commonly used in construction SMEs. Following this, semi-structured interviews were conducted with selected SME managers to explore the current practices and real-world challenges they face in implementing talent acquisition and retention strategies. Semi-structured interviews provided the flexibility to probe deeper into participants' experiences while maintaining a structured framework to guide the discussion. Due to logistical limitations and professional commitments of the participants, the interviews were conducted virtually using online platforms, which ensured accessibility and convenience. The data were then analysed using code-based content analysis using **code-based content analysis to identify recurring themes, patterns, and linkages between EO dimensions and HR practices.** As the second phase of the data collection process, a questionnaire was administered, incorporating the literature and semi-structured interview findings. Quantitative data were then gathered through a structured questionnaire survey distributed among construction professionals. Descriptive statistical tools (mean, weighted average, percentage counts, etc.) using Likert scales were used to analyse the gathered data. This helped examine the influence of EO on various HR practices, particularly the most commonly used strategies such as internships, referrals, and performance-based initiatives. Pearson correlation analysis was performed by the author to establish the nature of relationships between EO dimensions and talent strategies. The combined use of qualitative interviews and quantitative surveys ensured a balanced and comprehensive exploration of the topic, enabling the identification of patterns, relationships, and practical implications for HR strategy development in construction SMEs.

Table 3:Liket scale used in survey

	Value	Range
Strongly Disagree	1	1.00-1.80
Disagree	2	1.81-2.60
Moderate	3	2.61-3.40
Agree	4	3.41-4.20
Strongly Agree	5	4.21-5.00

	Value	Range
Very Rare	1	1.00-1.80
Rare	2	1.81-2.60
Moderate	3	2.61-3.40
Often	4	3.41-4.20
Very Often	5	4.21-5.00

Table 4: correlation scale

Scale of correlation coefficient	Value
$0 < r \leq 0.19$	Very Low Correlation
$0.2 \leq r \leq 0.39$	Low Correlation
$0.4 \leq r \leq 0.59$	Moderate Correlation
$0.6 \leq r \leq 0.79$	High Correlation
$0.8 \leq r \leq 1.0$	Very High Correlation

DATA COLLECTION AND ANALYSIS

Qualitative Data

Respondent Profile

The author collected qualitative data from seven senior professionals, including Chartered Quantity Surveyors and Civil Engineers. All interviewees held managerial roles within their respective SMEs, representing consultancy and contractor firms. In parallel, the quantitative survey yielded responses from professionals with varying years of experience and organisational positions, providing a representative view of the SME landscape.

Responses	Position	Experience in the industry	Experience as entrepreneur
Respondent 01 (R_1)	Charted QS	50+ Years	45 Years
Respondent 02 (R_2)	Charted QS	32 Years	25 Years
Respondent 03 (R_3)	Charted QS	30 Years	27 Years
Respondent 04 (R_4)	Charted QS	14 Years	9 Years
Respondent 05 (R_5)	Charted QS	52 Years	26 Years
Respondent 06 (R_6)	Civil Engineer	18 Years	12 Years
Respondent 07 (R_7)	Civil Engineer	25 Years	8 Years

All the respondents possess 14 years or more of experience in the industry, of which 71.43% have over 30 years of experience. Similarly, 100% of the respondents possess entrepreneurial expertise ranging from 8 to 45 years, with 42.86% having over 25 years of entrepreneurial experience. Regarding professional designations

- 71.43% were Charted Quantity Surveyors
- 28.57% were Civil Engineers

This participant mix demonstrates a strong representation of experienced senior professionals with extensive experience working in technical and entrepreneurial aspects of construction. Therefore, their views are of significant use for researching EO and its impact on talent acquisition and retention strategy.

Entrepreneurial Orientation Practices

The analysis of Entrepreneurial Orientation (EO) dimensions among participants reveals the following:

- **Innovativeness**: Most participants use modern software tools to enhance operations, though some, like R2 and R7, still rely on traditional or obligatory tools, indicating varied adoption of innovation.
- **Proactiveness**: All respondents demonstrate proactive behaviour, such as forecasting demand and monitoring trends (R1–R5), addressing shortages (R6), and informal planning (R7), showing that proactiveness is common across firms.
- **Risk-Taking**: All respondents reported engaging in risk-taking, such as entering new markets, adopting technologies, or investing in large-scale or unfamiliar projects, highlighting a willingness to explore growth opportunities.
- **Competitive Aggressiveness**: Most firms focus on internal competition to improve staff performance rather than external rivalry. Exceptions include competitive bidding (R6) and price-based competition (R7).
- **Autonomy**: Respondents support employee autonomy, especially in documentation and project decisions. However, R7 noted limited autonomy due to centralised decision-making by the director.

Talent Acquisition Strategies

Construction SMEs adopt various talent acquisition strategies that reflect their unique organisational structures, limited resources, and informal networks. The analysis identified four primary approaches: employee referrals, internship programs, social media recruitment, and collaborations with universities and training institutes.

Most Used Talent Acquisition Strategies

The most frequently used method across the surveyed SMEs was **employee referrals**, with six out of seven respondents identifying it as their primary approach. This method aligns with the network-oriented hiring culture prevalent in SMEs, where trusted recommendations are vital in reducing hiring risks. Respondents noted that referrals typically yield culturally compatible and reliable candidates who integrate quickly into the organisational environment.

Internship programs were also widely adopted, allowing firms to assess, mentor, and gradually transition individuals into full-time roles. As reported by R1, this method enhances the selection process by offering long-term observation and skill development.

Social media recruitment emerged as another practical strategy, particularly among firms seeking younger candidates. Platforms such as LinkedIn and Facebook enabled rapid outreach at a low cost, offering access to a broader talent pool. R4 emphasised that this approach is efficient when immediate hiring is required.

Most Effective Talent Acquisition Strategies

Employee referrals were the most used and perceived as the most **effective acquisition strategy**. Respondents emphasised that referrals expedite recruitment and yield high-quality hires with better alignment to organisational values. R4 highlighted the reduced hiring time, while R6 stressed the cultural fit and trust associated with referred candidates.

Internship programs were also highly effective for building a future talent pipeline. R3 noted that interns quickly adapt to company culture, while R7 emphasised the value of hands-on experience and loyalty development.

University partnerships were mentioned as a valuable avenue for identifying technically capable and trainable individuals. According to R3, these collaborations bring in candidates with the relevant academic background and potential for long-term development.

Target Groups and Application of Talent Acquisition Strategies

Each acquisition strategy tends to target specific demographic or skill-based segments:

- **Social Media Recruitment**: Primarily targets younger job seekers. Respondents R1, R4, R5, R6, and R7 noted its effectiveness in attracting entry-level or administrative candidates.

- **Employee Referrals**: Generally focus on experienced professionals such as quantity surveyors, site supervisors, and technical workers. This method builds on trust and minimises cultural mismatches.
- **University and Training Institute Partnerships**: These are geared towards recruiting fresh graduates with strong technical knowledge, allowing SMEs to align their values with new talent from the outset.
- **Internships**: Provide early career exposure to undergraduates, trainees, and diploma holders. This strategy enables firms to assess candidates over time, improving hiring accuracy and supporting skill development.

Talent Retention Strategies

The interview data analysis revealed various formal and informal strategies adopted by construction SMEs to retain employees. These practices were categorised into the most commonly used and the most effective by senior management.

Most Used Talent Retention Strategies

Training and development opportunities were the most frequently cited retention strategies. Respondents emphasised that these opportunities motivate employees by enhancing skills and fostering a sense of value and commitment. R1, R2, and R7 noted that such initiatives support continuous learning, while R3 added that training helps bridge skill gaps and reinforces employee loyalty. **Work-life balance** initiatives were also widely practised. Respondents highlighted efforts to manage stress and prevent burnout among employees working in demanding construction environments. R1 and R4 observed that flexible scheduling and supportive policies improved job satisfaction and retention. **Performance-based incentives** were mentioned as a key, albeit slightly less prevalent, strategy. R5 described them as a reward for loyalty and tenure, while R6 acknowledged their positive impact on productivity. However, it was also noted that financial limitations in SMEs may restrict the broad implementation of such schemes. Other, less frequently mentioned but relevant strategies included **employee recognition**, **feedback systems**, and **career path planning**. These were seen as supplementary tools that, while not uniformly applied, contributed positively to employee morale and engagement.

Most Effective Talent Retention Strategies

Among all strategies, **training and career development** were overwhelmingly considered the most effective for retaining talent. Respondents agreed that these programs demonstrated organisational commitment to growth and development, which fostered loyalty. R3 and R5 emphasised the direct correlation between access to development and improved performance and satisfaction. **Performance-based incentives** were highly regarded for their motivational effect, particularly in roles with measurable outcomes. R6 noted that such incentives directly enhanced productivity, while R7 highlighted their influence on employee morale. **Work-life balance** was cited as an essential, non-financial strategy contributing to job satisfaction. R4 reported that it helped reduce stress and absenteeism, while R5 pointed out its cost-effectiveness relative to financial rewards. Although not universally applied, **career progression opportunities** and **recognition programs** were acknowledged as beneficial. R4 and R6 observed that clearly defined growth paths and regular feedback contributed to employee retention, even without formal promotion structures.

Quantitaive Data

A structured questionnaire survey was conducted among professionals working in construction SMEs in Sri Lanka to validate and support the findings of the qualitative phase. Respondents represented various levels of seniority across both contractor and consultancy organizations. Data were analyzed using descriptive statistics and mean score rankings to identify the most practiced and most effective strategies in talent acquisition and retention.

1. Talent Acquisition Strategies

1.1 Most Used Talent Acquisition Strategies

Survey responses showed that **employee referrals** were the most widely used strategy, with a **mean score of 4.130** on a 5-point Likert scale. This was followed by **internships** (mean: **3.826**) and **university/training institute partnerships** (mean: **3.891**). **Social media recruitment** (mean: **3.630**) was also commonly used, though slightly less than traditional networking methods.

Level of usage of following Talent acquisition strategies within the organisational level.	Weighted Average
Social Media Recruitment	Often
Employee Referrals	Often
University/Training Institute Partnerships	Very often
Internships	Often
Job Fairs	Moderate

1.2 Most Effective Talent Acquisition Strategies

When evaluating effectiveness, **internships** ranked the highest with a **mean score of 4.217,** followed by **university/training institute partnerships** (mean: **4.130**) and **job fairs** (mean: **3.804**). While employee referrals remained highly used, their effectiveness received a slightly lower score (**3.717**), indicating they are not always the most strategic option in terms of long-term outcomes.

Effectiveness to acquire talent in construction organisation	Weighted Average
Social Media Recruitment	Often
Employee Referrals	Often
University/Training Institute Partnerships	Often
Internships	Very often
Job Fairs	Often

2. Talent Retention Strategies

Most Used Talent Retention Strategies

According to respondents, **performance-based incentives** were the most widely implemented retention strategy, with a **mean score of 4.152**. **Training and development programs** followed closely at **3.783**, while **work-life balance initiatives** scored **3.739**. Other methods such as **employee recognition, career development planning**, and **feedback systems** received moderate usage.

Level of usage of strategies within the organisational level.	Weighted Average
Performance based incentives	4.152
Training and career development	3.783
Clear career progression paths	3.543
Work life balance initiatives	3.739
Regular feedback and appraisal systems	3.761

Most Effective Talent Retention Strategies

Performance-based incentives were also considered the most effective retention strategy, receiving a **mean score of 4.326. Training and development** (mean: **4.217**) and **work-life balance** (mean: **4.196**) followed closely. These findings support the idea that a combination of financial and non-financial strategies is vital to effective retention in SMEs.

Effectiveness of Talent retention strategies within the organisational level.	Weighted Average
Performance based incentives	4.152
Training and career development	3.783
Clear career progression paths	3.543
Work life balance initiatives	3.739
Regular feedback and appraisal systems	3.761

Correlation Between EO and HR Strategies

Relationship Between Employee Referrals and EO Dimensions

Employee referrals were identified as the most commonly used talent acquisition strategy in construction SMEs. The correlation analysis reveals a significant association between the use of employee referrals and key EO dimensions. Table 1 presents the correlation coefficients for each EO construct.

Table 1: Correlation Coefficient Between EO Dimensions and Employee Referrals

EO Dimension	Correlation Coefficient (r)	Strength of Association
Innovativeness	0.408	Moderate
Proactiveness	0.664	High
Risk-Taking	0.593	Moderate
Competitive Aggressiveness	0.035	Very Low
Autonomy	0.647	High

The strongest positive correlations were observed with **proactiveness** (r = 0.664) and **autonomy** (r = 0.647), suggesting that firms that are forward-looking and encourage independent decision-making tend to rely more on employee referrals. **Risk-taking** (r = 0.593) and **innovativeness** (r = 0.408) also exhibited moderate positive correlations, indicating a link between entrepreneurial risk behaviour and network-based recruitment. **Competitive aggressiveness**, however, demonstrated negligible influence (r = 0.035), implying that internal dynamics rather than external market competition primarily drive the adoption of referral-based hiring strategies.Relationship Between Performance-Based Initiatives and EO Dimensions

Performance-based incentives were the most widely implemented talent retention strategy among the surveyed SMEs. Table 2 illustrates the correlation between this strategy and EO dimensions.

Table 2: Correlation Coefficient Between EO Dimensions and Performance-Based Initiatives

EO Dimension	Correlation Coefficient (r)	Strength of Association
Innovativeness	0.216	Low
Proactiveness	0.503	Moderate
Risk-Taking	0.529	Moderate
Competitive Aggressiveness	-0.127	Very Low (Negative)
Autonomy	0.639	High

The highest correlation was recorded between **autonomy** and performance-based incentives (r = 0.639), signifying that SMEs that empower their employees are more inclined to reward individual performance. Moderate correlations with risk-taking (r = 0.529) and proactiveness (r = 0.503) suggest that entrepreneurial firms align performance rewards with calculated risks and future-oriented strategies. On the other hand**, innovativeness** showed a weak correlation (r = 0.216), and **competitive aggressiveness** presented a slight negative relationship (r = -0.127), reinforcing the idea that internal organisational culture, rather than external competitiveness, plays a larger role in employee.

Conclusion

The research concludes that **EO** significantly influences Sri Lankan construction SMEs' talent acquisition and retention strategies. The five EO dimensions, **innovativeness, proactiveness, risk-taking, autonomy,** and **competitive aggressiveness**, were evaluated concerning HR practices.
The findings revealed that **employee referrals** and **internship programs** are the most commonly used and effective recruitment strategies. Referrals are preferred for attracting experienced and culturally compatible employees, while internships provide a cost-effective way to assess and develop future talent. Strategies such as **performance-based incentives, career development opportunities**, and **work-life balance initiatives** were identified as the most effective for retention, aligning with the SMEs' focus on relationship-based and resource-conscious approaches.
Among the EO dimensions, **autonomy** and **proactiveness** emerged as the most influential. Firms fostering employee independence and forward-thinking attitudes were likelier to adopt strategic, people-focused HR practices. **Risk-taking** and **innovativeness** also contributed, particularly in experimenting with new hiring approaches like internships. **Competitive aggressiveness**, however, had minimal impact on talent strategies.
Correlation analysis validated these relationships, showing strong positive links between EO dimensions (especially autonomy and proactiveness) and key HR practices such as employee referrals and performance-based incentives. It confirms that the internal entrepreneurial mindset of SMEs shapes how they attract, develop, and retain talent, making EO an essential strategic driver in HR planning.

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References

1. Abdullahi, U., Kunya, S. ., Bustani, S. ., & Usman, N. (2019). Impact of competitive aggressiveness on performance of small and medium construction firms in Nigeria. *FUTY Journal of the Environment*, *13*(1), 65–74.
2. Abioye, S. O., Oyedele, L. O., Akanbi, L., Ajayi, A., Davila Delgado, J. M., Bilal, M., Akinade, O. O., & Ahmed, A. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *Journal of Building Engineering*, *44*(October), 103299. https://doi.org/10.1016/j.jobe.2021.103299
3. Akdogan, M. S., Ozgener, S., Kaplan, M., & Coskun, A. (2012). the Effects of Consumer Ethnocentrism and Consumer Animosity on the Re-Purchase Intent: the Moderating Role of Consumer Loyalty. *EMAJ: Emerging Markets Journal*, *2*(1), 1–12. https://doi.org/10.5195/emaj.2012.15
4. Alsharef, A., Ovid, A., Jamil Uddin, S. M., & Albert, A. (2024). Biggest Challenges Facing the Construction Industry. *Construction Research Congress 2024, CRC 2024*, *3*(March), 652–660. https://doi.org/10.1061/9780784485286.065
5. Anzules-Falcones, W., & Novillo-Villegas, S. (2023). Innovation Capacity, Entrepreneurial Orientation, and Flexibility: An Analysis from Industrial SMEs in Ecuador. *Sustainability (Switzerland)*, *15*(13), 18–22. https://doi.org/10.3390/su151310321
6. Baharin, N., & Hanafi, W. (2018). Effects of talent management on employee retention: A case study of hospitality industry. *Global Business and Management Research: An International Journal*, *10*(3), 697–708.
7. Chelliah, M. K., Aravindan, K. L., & Muthaiyah, S. (2023). Entrepreneurial Orientation and Open Innovation Promote the Performance of Services SMEs: The Mediating Role of Cost Leadership. *Administrative Sciences*, *13*(1), 1–19. https://doi.org/10.3390/admsci13010001
8. Hongal, P., & Kinange, U. (2020). *A Study on Talent Management and its Impact on Organization Performance- An Empirical Review*. *1*(1), 64–71.

9. Lamane-Harim, J., Cegarra-Leiva, D., & Sánchez-Vidal, M. E. (2023). Work–life balance supportive culture: a way to retain employees in Spanish SMEs. *International Journal of Human Resource Management*, *34*(10), 2074–2106. https://doi.org/10.1080/09585192.2021.1878255
10. Malesev, S., & Cherry, M. (2021). Digital and social media marketing-growing market share for construction smes. *Construction Economics and Building*, *21*(1), 65–82. https://doi.org/10.5130/AJCEB.v21i1.7521
11. Okangi, F. P. (2019). *The impacts of entrepreneurial orientation on the profitability growth of construction firms in Tanzania*. *1*, 1–23.
12. Othman, M. R., Alleimoun, A., & Saadon, M. S. I. (2022). the Impact of Talent Management, Entrepreneurial Orientation and Organizational Learning on Organizational Performance Amid and Post- Covid-19 Pandemic: the Conceptual Framework for Mediating Role of Organizational Learning. *Journal of Maritime Logistics*, *2*(1), 30–41. https://doi.org/10.46754/jml.2022.08.002
13. Saka, A. B., & Chan, D. W. M. (2020). Adoption and implementation of building information modelling (BIM) in small and medium-sized enterprises (SMEs): a review and conceptualization. *Engineering, Construction and Architectural Management*, *28*(7), 1829–1862. https://doi.org/10.1108/ECAM-06-2019-0332
14. Tat, H., Tuyet, T., Nguyen, M., & Ping, H. (2007). *The effects of entrepreneurial orientation and marketing information on the performance of SMEs ☆*. *22*, 592–611. https://doi.org/10.1016/j.jbusvent.2006.05.003
15. Wentzel, L., Fapohunda, J. A., & Haldenwang, R. (2022). The Relationship between the Integration of CSR and Sustainable Business Performance: Perceptions of SMEs in the South African Construction Industry. *Sustainability (Switzerland)*, *14*(3). https://doi.org/10.3390/su14031049
16. Wungsnuopparat, S., & Jiarui, W. (2022). Factors Influencing Effective Talent Acquisition of the Small and Medium-Sized Enterprises in China. *Journal of Economics, Finance And Management Studies*, *05*(08), 2258–2275. https://doi.org/10.47191/jefms/v5-i8-18

Impact of Emotional Intelligence on Improving Labour Productivity In the Sri Lankan Construction Industry

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ABSTRACT

The construction industry plays a vital role in fostering economic growth globally, with labour productivity being a critical determinant of project success and industry competitiveness. Despite extensive research and strategic efforts, Sri Lankan construction companies continue to face significant challenges related to low labour productivity, often stemming from interpersonal, organizational, and technological issues. Recent studies highlight the potential of emotional intelligence (EI) as a pivotal non-technical factor that enhances individual and team performance in construction settings. This research investigates the impact of EI on labour productivity within the Sri Lankan construction sector. Employing a mixed-methods approach, data were collected through structured questionnaires from a diverse sample of 45 workers and open-ended interviews from interviewers, including project managers and HR professionals. Quantitative analysis using correlation techniques and qualitative thematic analysis revealed that the impact of EI positively influences communication, teamwork, conflict resolution, and motivation among workers. Furthermore,5 key strategies and practical actions were identified as effective measures to enhance labour performance. The study underscores the importance of integrating EI development initiatives into industry practices to mitigate common productivity barriers and promote a more cohesive, efficient, and motivated workforce. The findings contribute to the theoretical understanding of non-technical skills in construction productivity and propose practical frameworks for industry stakeholders to implement EI-enhanced management practices, ultimately leading to higher efficiency, safety, and project success in Sri Lanka's evolving construction landscape.

KEYWORDS: *Construction industry, Emotional Intelligence, Labour productivity*

INTRODUCTION

The construction industry, essential to modern economies, increasingly drives economic growth through innovation, with its impact amplifying as innovation advances (Kubjana et al., 2024). Boosting productivity in the construction industry can significantly elevate a nation's gross domestic product, making a powerful contribution to its economic growth (Mistri et al., 2019; Pathirana, 2021; Manoharan et al., 2023a). Low productivity is one of the most significant challenges faced by the construction industry (Hamza et al., 2022; Premakumara and Siriwardana, 2025). Premakumara and Siriwardana, (2025) stated that the challenging nature of the construction industry has drawn the attention of scholars and practitioners aiming to improve productivity, yet despite extensive research, a universally applicable and robust approach has not yet been developed.

The economy is becoming more productive, more innovative, and more competitive due to the existing human potential (Mistri et al., 2019). Productivity is defined as maximising output while optimising input. It measures the ratio between the value of output, such as products or services, and the input, which includes materials, labour, capital, and energy (Hamza et al., 2022). Premakumara and Siriwardana (2025) stated labour and capital productivity are key factors that require multi-factor analysis for accurate results, as labour efforts are essential to construction operations.

Labour is a vital and flexible resource in construction, with productivity closely linked to human effort, efficiency, and performance. Given the large number of workers hired for projects, manpower is the dominant productive resource in this field (Hamza et al., 2022). Manoharan et al., (2021) research

studies stated that labour efforts are the lifeblood of construction operations. Consequently, the effectiveness of labour operations has a significant impact on the outcomes of construction processes in terms of efficiency, quality, productivity, physical progress and safety, specially in developing countries (Mistri et al., 2019; Manoharan et al., 2023, 2024). Also Manoharan et al., (2023) stated low performance of labourers has been seen to be a major factor that contributes to inefficient productivity in construction firms in developing countries

In a typical construction project, labour cost is significant and represents between 30% and 50% of the total project cost (Manoharan et al., 2021). Measuring labour productivity in the context of "Production by a worker" is the simplest method to do so in construction (Premakumara and Siriwardana, 2025). Occupational stress is a significant issue that results in over 15.4 million lost working days and incurs an estimated cost of $5.2 billion to industries, individuals, and governments (Tennakoon and Ariyaratne, 2021).

Research on labour productivity in the construction industry has identified several factors that affect productivity, such as project management practices, worker skill levels, safety regulations, and technology adoption (Ghoddousi et al., 2015). Some studies have also examined the impact of non-technical factors such as worker motivation, job satisfaction, and emotional intelligence on productivity (Grassetti et al., 2018).Additionally, more research is needed on the impact of non-technical factors such as emotional intelligence(EI) and worker motivation on productivity, as these factors may be just as important as technical factors in determining productivity levels (Doloi, 2008).

EI is linked to improved employee performance, innovation, and adaptability in dynamic work environments like Construction (Kubjana et al., 2024). Conversely, leaders with lower EI struggle with impulse control and are susceptible to emotional fluctuations, which impede effective decision-making (Kubjana et al., 2024).

EI, evolving from the concept of social intelligence, is essential for managing challenges, enhancing communication, and fostering a positive organisational culture. It comprises four key dimensions: self-awareness, understanding others' emotions, emotional regulation, and using emotions to improve performance (Kubjana et al., 2024). EI leads to fear and anxiety, while high EI promotes trust, open communication, and employee confidence. In light of disruptions such as the COVID-19 pandemic and technological shifts, enhancing EI is crucial for workforce adaptability and organisational success in modern construction settings.(Kubjana et al., 2024)

The cognitive, manual, and emotional abilities of employees have a direct impact on the components of the employment role, process, and duties (Manoharan et al., 2024). In light of the aforementioned facts, recent investigations, as well as consultations with skill development authorities and industry experts, have revealed that numerous construction firms in numerous developing countries like Sri Lanka lack suitable methods and procedures to evaluate the skills of site supervisory workers in labour management, performance assessments, and productivity measurements in construction tasks (Manoharan et al., 2024).

The Sri Lankan construction sector was undertaken. However, the focus of this evaluation was limited to labour-related aspects when assessing construction productivity (Premakumara and Siriwardana, 2025). Manoharan et al., (2023) strongly recommends that future studies should have more focus on various improving practices on labour performance in the Sri Lankan construction sector. Despite its importance, EI remains under-researched in construction (Kukah et al., 2023). Kubjana et al., (2024) stated research. findings indicated that emotional intelligence emerged as a crucial transformation factor. Despite the proven importance of EI in workplace performance, its role in improving labour productivity remains underexplored in the Sri Lankan construction industry. Existing studies mainly focus on technical and managerial aspects, overlooking how EI can enhance worker performance, motivation, and team dynamics. There is a clear need for research that examines how EI can be assessed, developed, and integrated into construction practices to boost productivity

This research aims to identify the impacts of emotional intelligence on enhancing labour productivity in the Sri Lankan construction industry and identify a solution to improve labour productivity. To achieve this aim, the study will first identify the challenges faced by the construction industry and examine existing strategies. It will then explore how Emotional Intelligence impacts employee productivity in Sri Lanka's construction sector. Finally, the research will propose strategies to enhance EI among workers to improve productivity and engagement in construction environments.

LITERATURE REVIEW

Labour Productivity

Premakumara and Siriwardana, (2025) identified 13% of labour-related factors contribute to 87% of productivity, while 30% of underlying reasons may solve 70% of industry problems. Understanding the critical factors that affect construction labour productivity is therefore essential for developing targeted strategies to reduce inefficiencies and manage construction workforces more effectively (Hamza et al., 2022; Premakumara and Siriwardana, 2025). Such improvements not only enhance project performance for construction companies but also strengthen their competitiveness, ultimately increasing their chances of survival in this highly competitive sector (Hamza et al., 2022; Manoharan et al., 2023).
Key findings from the literature review highlight significant challenges to labour productivity, labour-related issues affecting productivity, and current strategies implemented to enhance labour productivity, as represented in Figure 1.

Factor	References										
	1	2	3	4	5	6	7	8	9	10	11
Challenges / Labour-Related Issues											
Skills shortage	✓			✓						✓	
Personal conflicts among labourers	✓				✓					✓	
Lack of working experience	✓			✓		✓				✓	✓
Lack of knowledge in construction work					✓					✓	✓
Negative attitude of labourers	✓						✓			✓	
Lack of labour management				✓							✓
Low wages and incentives				✓							✓
Poor site safety/working environment	✓										✓
Excessive workload											✓
Lack of job security/high labour mobility											✓
Low motivation and morale	✓			✓			✓				
Strategies											
Workforce management	✓	✓	✓	✓							
Job planning	✓	✓			✓	✓					
Workers' motivation	✓				✓		✓				
Material availability	✓	✓									
Education and training					✓	✓		✓	✓	✓	
Health facilities					✓						✓
Increase labour benefits		✓									
Social skills development programmes									✓		

Figure 11. Challenges and Existing strategies for labor productivity

1. (Manoharan et al., 2023)
2. (Hamza et al., 2022)
3. (Kubjana et al., 2024)
4. (Premakumara and Siriwardana, 2025)
5. (Manoharan et al., 2021)
6. (Rajapaksha and Sakura, 2024)
7. (Lakshan et al., 2023)
8. (Pathirana, 2021)
9. (Alsulami et al., 2023)
10. (Manoharan et al., 2022)

The findings of the current research lay a new theoretical approach that helps the management of the construction industry to establish a safe climate for their workers. Although much progress has been made, there are still too many workplace problems that demand keen consideration (Alsulami et al., 2023). One significant challenge is low labour productivity, which can be linked to various factors, including a lack of emotional intelligence among workers (Lam and Kirby, 2002). The absence of emotional intelligence among team leaders exposes them to various challenges, including team dynamics, operational inefficiencies, and reduced job satisfaction (Kubjana et al., 2024).

Emotional Intelligence

The term emotional intelligence (EI) is "the ability to perceive emotions, to access and generate emotions in such a way as to support thinking, to understand emotions and their meaning and to effectively regulate emotionality, to determine the improvement of emotional and intellectual development" (Naeem, Saif and Khalil, 2011).
Salovey and Mayer, (1990) defined emotional intelligence (EI) as a type of social intelligence that comprises the capacity to oversee your own emotions and those of others, to differentiate among them, and to use the information to manage your thinking and behavior. EI is categorized into three models: ability, trait, and emotional systems, with Nelson and Low's model highlighted for its focus on personal growth and balanced thinking (Kukah et al., 2023).

Emotional Intelligence to Tackle Challenges in Labour Productivity

EI increases personal and project performance, inspires leadership, builds capacity against stress, improves communication skills and ensures greater confidence within project managers and construction workers (Kukah et al., 2022). Self-control and self-direction, awareness of one's own strengths and shortcomings, self-worth, the capacity to understand one's own potential, stress tolerance, and impulse control are all aspects of emotional intelligence. It also entails audacity. These points can be changed in a way that increases worker productivity. (Shehata and El-Gohary, 2011).
The following Table 1 shows how EI addresses challenges based on the findings from the literature.

Table 5. Impact from EI

Factor	Impact from EI
Risk Management	• Construction managers and employees will better appreciate the role of EI in enhancing project success and minimizing risks in the construction industry (Kukah *et al.*, 2022; Kukah *et al.*, 2023).
Workplace Culture	• EI can potentially help in conflict resolution, build a collaborative culture, motivate other workers, and help create psychological safety within working teams (Lawani *et al.*, 2024). • Introducing EI-based training programs can significantly enhance soft skills, stress management, and workplace ethics. These improvements help labourers manage emotional demands, reduce conflicts, and stay focused on their tasks, ultimately increasing output and job quality (Tennakoon & Ariyaratne, 2021). • Conflicts in the construction industry can impact productivity. EI aids in resolving these conflicts by promoting empathy and understanding, enabling individuals to manage emotions and maintain positive relationships (Hughes and Thorpe, 2014).
Job Satisfaction and Motivation	• Existing study indicates that construction project workers with higher emotional intelligence tend to display higher satisfaction, greater commitment towards their job, and lower turnover intentions in relation to their roles (Tennakoon and Ariyaratne, 2021; Lawani *et al.*, 2024) • Leaders who possess high EI are better able to communicate with their teams, understand their needs and concerns, and motivate them to achieve goals (Hooper, 2016). • Workers who possess high EI are more likely to be satisfied with their jobs and have lower turnover rates. This can result in significant cost savings for construction companies, as they do not have to spend time and resources recruiting and training new employees. (Yoon and Suh, 2003).
Experienced workers	• Demographic factors such as age and experience contribute to higher EI levels. More experienced and emotionally mature workers

	tend to manage pressure more effectively, sustain better working relationships, and maintain steady performance, positively influencing overall team productivity (Lawani *et al.*, 2024)
Construction Site Safety	• In environments with high safety risks in construction sites. Emotionally intelligent workers are more likely to comply with safety regulations and manage stress effectively. This reduces accidents, downtime, and emotional burnout, contributing to a safer and more productive workforce (Alsulami *et al.*, 2023) • In the construction business, emotional intelligence (EI) has become a tool for enhancing efficiency and safety. (El-Gohary and Aziz, 2014). • Safety is crucial in construction, and workers with high EI are more likely to adhere to safety protocols. Promoting EI can enhance safety and reduce accidents and fatalities on job sites (Lam and Kirby, 2002).
Enhances Output	• Assertiveness and emotional control traits of high EI help workers stay calm under pressure and make clear decisions. This leads to fewer mistakes, better coordination, and higher-quality work, all of which boost productivity at both the individual and organizational levels (Alsulami *et al.*, 2023).
Project success	• As emphasized by Goleman, EI accounts for 80% of individual success, compared to only 20% by IQ. Construction managers and workers who prioritize EI create environments where productivity thrives through trust, cooperation, and clear emotional understanding (Perera, 2021) • Supporting strategies like two-way communication, team targets, safety assurance, and skill development further increase cost-efficiency and labour productivity (Lakshan *et al.*, 2023). • According to the correlation between EI and life skills, a higher level is associated with stronger problem-solving abilities, greater adaptability, and less anxiety. (Amiri et al., 2015). • Leaders who understand their team members' emotions and motivations foster a cohesive group that works better together to achieve goals (Kaming *et al.*, 1997).

According to the correlation between EI and life skills, higher levels of EI are associated with stronger problem-solving abilities, greater adaptability, and reduced anxiety (Amiri et al., 2015). Furthermore, by enhancing workplace safety and job satisfaction, emotionally intelligent practices help employees remain more focused and engaged in their tasks, ultimately leading to increased productivity in the construction sector (Yi & Chan, 2014).

METHODOLOGY

Research Process

The data collection for this study was carried out using a mixed-methods approach, incorporating both qualitative and quantitative techniques to assess how Emotional Intelligence (EI) influences labour productivity in Sri Lanka's construction sector.

A comprehensive literature review was conducted to identify existing strategies for increasing labour productivity and to categorize the prevalent problems in the Sri Lankan construction industry. This review helped to conceptualize how Emotional Intelligence could be effectively integrated into existing strategies to enhance productivity.

Quantitative data were collected using a structured questionnaire survey. A sample of 45 construction workers across Sri Lanka participated in this survey. The questionnaire included both closed-ended and scaled questions designed to generate numerical data that could be statistically analyzed. This allowed for the measurement of EI levels and their potential impact on labour productivity. The standardized format of the questionnaire enabled structured data collection, facilitating both comparison and generalization.

Qualitative data were gathered through open-ended questionnaires administered to a smaller sample of 8 individuals, including project managers and HR managers. These surveys aimed to collect in-depth insights into how EI is perceived and practiced at the management level. The open-ended format encouraged detailed responses, which were later analyzed thematically to identify recurring themes and deeper meanings.

The insights obtained from eight project manager responses provided rich explanations of how EI contributes to productivity.

Data Analysis Process

Correlation Analysis

Correlation Analysis using SPSS was the primary statistical technique employed to examine the strength and direction of relationships between variables. The Pearson correlation coefficient, which ranges from -1 to +1, was used to quantify the linear relationship between continuous variables. A coefficient closer to +1 or -1 indicates a strong correlation, while a value near 0 suggests little to no linear relationship.

In this study, correlation analysis was used to assess the associations among Emotional Intelligence, labour productivity, personal life issues, conflict management IQ, flexibility of work environment, mental interaction with superiors, and site conditions. If a correlation coefficient greater than 0.9 was observed between any variable and labour productivity, it was considered a strong relationship.

Thematic Analysis

Thematic Analysis was used to interpret the qualitative data. This involved coding and categorizing the open-ended responses to identify recurring themes and key insights. Thematic analysis enabled the researcher to derive deeper meanings from the qualitative responses, providing context and depth to the quantitative findings.

RESULTS AND DISCUSSION

Quantitative data

Questionnaire survey demographic data analysis is as for the following figure 2 and 3.

What is your job here? (Profession/Specialty)

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Barbender	1	2.2	2.2	2.2
	Carpenter	1	2.2	2.2	4.4
	Carpentor	7	15.6	15.6	20.0
	Helper	2	4.4	4.4	24.4
	Machine Operator	3	6.7	6.7	31.1
	Mason	21	46.7	46.7	77.8
	Painter	10	22.2	22.2	100.0
	Total	45	100.0	100.0	

Figure 12 - Demographic data Analysis

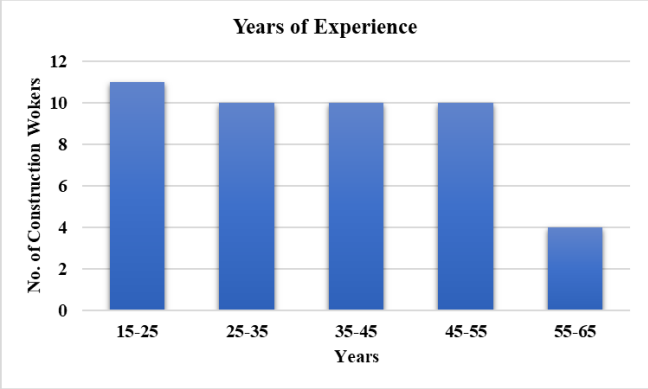

Figure 13-Years of Workers' (Demographic data)

Considered factors for assessing the impact of EI are represented in Table 2 and Figure 4 represents the correlation for Labour Productivity for the Construction Industry. To facilitate analysis, the Factors are divided into different parts, each representing various condition factors. These factors are related to determining the EI for labor productivity and overall labor productivity within the construction industry.

Table 6 - Factors for finding the impact of EI

Factor Group		EI for Labour Productivity		Labour Productivity for the Construction Industry	
A	**Site Condition Factor**	**A2**	Response to a conflict with a co-worker	**A1**	Site work conditions
		A3	How the complaint was managed	**A4**	Solution given for the conflict
B	**Overall Labour Condition Factor**	**B1**	Response to the supervisor in conflict	**B2**	Working relationship after conflict
		B3	B3 – Reaction to co-worker criticism	**B4**	Settlement after co-worker criticism
		B5	Reaction to supervisor criticism	**B6**	Settlement after the supervisor criticism
C	**Labour Interacting Condition Factor**	**C2**	Communication in problem-solving	**C1**	Cooperation with co-workers during teamwork
		C4	Managing personal/family life with a job	**C3**	Example of problem-solving skill
		C6	Informing the supervisor about the deadline extension	**C5**	Handling pressure during deadlines
D	**Personal Condition Factor**	**D2**	Ability to understand emotions	**D1**	Use of smartphone, YouTube, Facebook
		D3	Reasons for job satisfaction/dissatisfaction		

Correlations

		A2	A3	B1	B3	B5	C2	C4	C6	D2	D3
A2	Pearson Correlation	1	.953**	.285	.031	-.085	.209	-.449**	.199	-.516**	-.610**
	Sig. (2-tailed)		.000	.058	.837	.577	.168	.002	.190	.000	.000
	N	45	45	45	45	45	45	45	45	45	45
A3	Pearson Correlation	.953**	1	.214	-.009	-.185	.116	-.435**	.245	-.421**	-.588**
	Sig. (2-tailed)	.000		.158	.955	.225	.449	.003	.105	.004	.000
	N	45	45	45	45	45	45	45	45	45	45
B1	Pearson Correlation	.285	.214	1	-.075	.261	.429**	-.330*	.031	-.520**	-.195
	Sig. (2-tailed)	.058	.158		.625	.083	.003	.027	.839	.000	.199
	N	45	45	45	45	45	45	45	45	45	45
B3	Pearson Correlation	.031	-.009	-.075	1	.113	-.200	.405**	-.307*	.057	.041
	Sig. (2-tailed)	.837	.955	.625		.459	.188	.006	.040	.709	.788
	N	45	45	45	45	45	45	45	45	45	45
B5	Pearson Correlation	-.085	-.185	.261	.113	1	.014	.136	-.053	-.219	.038
	Sig. (2-tailed)	.577	.225	.083	.459		.928	.374	.728	.149	.806
	N	45	45	45	45	45	45	45	45	45	45
C2	Pearson Correlation	.209	.116	.429**	-.200	.014	1	-.027	-.175	-.205	.204
	Sig. (2-tailed)	.168	.449	.003	.188	.928		.862	.251	.176	.180
	N	45	45	45	45	45	45	45	45	45	45
C4	Pearson Correlation	-.449**	-.435**	-.330*	.405**	.136	-.027	1	-.423**	.554**	.491**
	Sig. (2-tailed)	.002	.003	.027	.006	.374	.862		.004	.000	.001
	N	45	45	45	45	45	45	45	45	45	45
C6	Pearson Correlation	.199	.245	.031	-.307*	-.053	-.175	-.423**	1	-.087	-.183
	Sig. (2-tailed)	.190	.105	.839	.040	.728	.251	.004		.568	.228
	N	45	45	45	45	45	45	45	45	45	45
D2	Pearson Correlation	-.516**	-.421**	-.520**	.057	-.219	-.205	.554**	-.087	1	.477**
	Sig. (2-tailed)	.000	.004	.000	.709	.149	.176	.000	.568		.001
	N	45	45	45	45	45	45	45	45	45	45
D3	Pearson Correlation	-.610**	-.588**	-.195	.041	.038	.204	.491**	-.183	.477**	1
	Sig. (2-tailed)	.000	.000	.199	.788	.806	.180	.001	.228	.001	
	N	45	45	45	45	45	45	45	45	45	45

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 14 - Correlation for Labour Productivity for the Construction Industry

The Pearson correlation analysis reveals several significant relationships between EI factors and labour productivity within the Sri Lankan construction industry. According to the correlation values, there is a clear indication of a positive impact of EI on labour productivity, which in turn contributes to the overall productivity of the construction industry. Specifically, the variables A2 and A3, which relate to site condition factors, show strong negative correlations with personal condition indicators D2 and D3. For instance, A2 demonstrates a significant negative correlation with both D2 ($r = -0.516$, $p = 0.000$) and D3 ($r = -0.610$, $p = 0.000$), while A3 is significantly negatively correlated with D3 ($r = -0.588$, $p = 0.000$). These findings suggest that poor site conditions can significantly reduce labour productivity.

In contrast, the variable C4, associated with labour interacting conditions, shows a strong positive correlation with both D2 ($r = 0.554$, $p = 0.000$) and D3 ($r = 0.491$, $p = 0.001$). This indicates that effective emotional interactions, teamwork, and communication among labour teams can positively influence productivity outcomes. These statistically significant relationships highlight the importance of managing both the physical environment (e.g., site conditions) and the emotional climate (e.g., interpersonal relationships) in construction settings.

Furthermore, personal life problems, conflict management skills, emotional intelligence, workplace flexibility, mental engagement with superiors, and site conditions are identified as critical factors affecting labour productivity in the construction industry. Therefore, fostering emotional intelligence, especially in terms of interpersonal communication and conflict resolution, is essential for enhancing productivity and ensuring better project performance.

Qualitative data

It was found through qualitative data analysis that EI has a significant impact on labour productivity in the construction industry. Based on the findings of the analysis, several key strategies are proposed to enhance critical components that contribute to improving labour productivity. These strategies aim to leverage emotional intelligence to foster better communication, teamwork, empowerment, and work environments within construction projects.
The proposed strategies are outlined in the following table 3 under the theme: "Improving Labour Productivity in the Sri Lankan Construction Industry by Using Emotional Intelligence."

Table 7 . Proposed Strategies, Actions & Applications

Key Strategy	Actions	Applications
Improve collaboration and communication	Encourage open, sincere communication- Regular team meetings	Use real-time project management tools
	Train staff on proper communication	Weekly team updates and planning
	Create a respectful work environment	Encourage a question-asking culture
Promote a supportive work environment	Show appreciation to the staff	Celebrate achievements (big or small)
	Provide learning opportunities- Encourage feedback and growth	Offer training & development programs
	Foster teamwork	Create a safe space for sharing concerns
	Promote work-life balance	
Empower workers	Involve workers in decisions	Give autonomy in task decisions
	Provide tools and guidance	Acknowledge achievements and lessons learned
	Encourage pride in work	
	Build trust and respect	
Develop EI skills among staff	Provide EI training	Conduct workshops on empathy, self-awareness
	Enable real-world EI practice	Promote an emotionally intelligent culture
	Encourage EI values in the workplace	
Additional Supporting Strategies	Invest in new technology and machinery	Reduce rework and increase efficiency
	Ensure safe and secure workspaces	Provide PPE and safety training
	Offer attractive benefits and compensation	Attract and retain top talent
	Implement strong training & development programs	

Interviewers explained how EI helped them build stronger relationships with workers, resolve conflicts effectively, and maintain team motivation. To address challenges in the industry, it suggests collaboration between the government and construction companies, emphasizing the need for investment in training and new technologies. Improved work practices and incentive schemes are also

recommended to boost productivity. Additionally, raising awareness of EI's benefits and implementing training programs can help strengthen workers' emotional intelligence. By focusing on these areas, the Sri Lankan construction sector can enhance productivity, competitiveness, and create a more positive work environment.

CONCLUSION

The Sri Lankan construction industry is currently grappling with persistent issues of low labour productivity, driven by factors such as ineffective communication, poor site conditions, lack of motivation, interpersonal conflicts, and limited emotional support for workers. Literature findings highlight that despite the industry's significant contribution to national development, existing productivity enhancement strategies have often overlooked the importance of non-technical skills like EI. Findings from this research indicate that emotional intelligence has a positive influence on several key aspects of labour performance, including teamwork, communication, conflict resolution, motivation, and job satisfaction. The correlation analysis revealed strong associations between emotional and interpersonal factors and overall labour productivity. Qualitative insights further supported the argument that emotionally intelligent leadership and workforce practices contribute to a more cohesive and efficient working environment.

To overcome the current productivity challenges, the research proposes targeted strategies such as enhancing emotional intelligence through training, fostering a supportive work culture, involving workers in decision-making, and creating safe and empowering work environments. Additional support through investment in safety, new technologies, and recognition systems can further improve employee engagement and performance. Addressing labour productivity through the development of emotional intelligence offers a practical and sustainable path to improving project outcomes, worker well-being, and the overall competitiveness of the Sri Lankan construction industry.

REFERENCE

1. Alsulami, H., Serbaya, S. H., Rizwan, A., Saleem, M., Maleh, Y., & Alamgir, Z. (2023). Impact of emotional intelligence on the stress and safety of construction workers' in Saudi Arabia. *Engineering, Construction and Architectural Management*, *30*(4), 1365–1378. https://doi.org/10.1108/ECAM-06-2021-0481
2. Amiri, S., Mousavi Rizi, S., & Safikhanlou, S. (2015). Emotional Intelligence Components in Alcohol Dependent and Mentally Healthy Individuals. *The Scientific World Journal*, *2015*, 1–6. https://doi.org/10.1155/2015/841039
3. Doloi, H. (2008). Application of AHP in improving construction productivity from a management perspective. *Construction Management and Economics*, *26*(8), 841–854. https://doi.org/10.1080/01446190802244789
4. El-Gohary, K. M., & Aziz, R. F. (2014). Factors Influencing Construction Labor Productivity in Egypt. *Journal of Management in Engineering*, *30*(1), 1–9. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000168
5. Ghoddousi, P., Poorafshar, O., Chileshe, N., & Hosseini, M. R. (2015). Labour productivity in Iranian construction projects: Perceptions of chief executive officers. *International Journal of Productivity and Performance Management*, *64*(6), 811–830. https://doi.org/10.1108/IJPPM-10-2013-0169
6. Grassetti, F., Mammana, C., & Michetti, E. (2018). On the Effect of Labour Productivity on Growth: Endogenous Fluctuations and Complex Dynamics. *Discrete Dynamics in Nature and Society*, *2018*, 1–9. https://doi.org/10.1155/2018/6831508
7. Hamza, M., Shahid, S., Bin Hainin, M. R., & Nashwan, M. S. (2022). Construction labour productivity: Review of factors identified. *International Journal of Construction Management*, *22*(3), 413–425. https://doi.org/10.1080/15623599.2019.1627503
8. Hooper, A. (Ed.). (2016). *Leadership perspectives*. Routledge, Taylor & Francis Group.

9. Hughes, R., & Thorpe, D. (2014). A review of enabling factors in construction industry productivity in an Australian environment. *Construction Innovation*, *14*(2), 210–228. https://doi.org/10.1108/CI-03-2013-0016
10. Kaming, P. F., Olomolaiye, P. O., Holt, G. D., & Harris, F. C. (1997). Factors influencing construction time and cost overruns on high-rise projects in Indonesia. *Construction Management and Economics*, *15*(1), 83–94. https://doi.org/10.1080/014461997373132
11. Kubjana, L., Adekunle, P., Aigbavboa, C., & Akinradewo, O. (2024). Analyzing the Impact of Emotional Intelligence on Leadership in Construction 4.0. In K. Arai (Ed.), *Proceedings of the Future Technologies Conference (FTC) 2024, Volume 4* (Vol. 1157, pp. 474–484). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-73128-0_30
12. Kukah, A. S., Akomea-Frimpong, I., Jin, X., & Osei-Kyei, R. (2022). Emotional intelligence (EI) research in the construction industry: A review and future directions. *Engineering, Construction and Architectural Management, 29*(10), 4267–4286. https://doi.org/10.1108/ECAM-05-2021-0414
13. Kukah, A. S. K., Owusu-Manu, D.-G., & Edwards, D. (2023). Critical review of emotional intelligence research studies in the construction industry. *Journal of Engineering, Design and Technology*, *21*(6), 1925–1947. https://doi.org/10.1108/JEDT-08-2021-0432
14. Lakshan, H. G. S., Wijesinghe, T., & Perera, B. K. C. (2023). *The Impact of Labour Motivation on Project Performance with an Insight into the Sri Lankan Construction Industry*. 57–66. https://doi.org/10.54389/LUJO3426
15. Lam, L. T., & Kirby, S. L. (2002). Is Emotional Intelligence an Advantage? An Exploration of the Impact of Emotional and General Intelligence on Individual Performance. *The Journal of Social Psychology*, *142*(1), 133–143. https://doi.org/10.1080/00224540209603891
16. Lawani, K., Arias Abad, L. A., Craig, N., Hare, B., & Cameron, I. (2024). Exploring emotional intelligence and conflict management styles in Dominican Republic construction industry. *Journal of Engineering, Design and Technology*, *22*(1), 89–119. https://doi.org/10.1108/JEDT-09-2021-0485
17. Manoharan, K., Dissanayake, P., Pathirana, C., Deegahawature, D., & Silva, R. (2021). COMPARISON OF SKILLS BETWEEN SRI LANKAN AND FOREIGN CONSTRUCTION LABOUR. *Proceedings of the 9th World Construction Symposium 2021 on Reshaping Construction: Strategic, Structural and Cultural Transformations towards the "Next Normal,"* 208–220. https://doi.org/10.31705/WCS.2021.18
18. Manoharan, K., Dissanayake, P., Pathirana, C., Deegahawature, D., & Silva, R. (2023a). Assessment of critical factors influencing the performance of labour in Sri Lankan construction industry. *International Journal of Construction Management*, *23*(1), 144–155. https://doi.org/10.1080/15623599.2020.1854042
19. Manoharan, K., Dissanayake, P., Pathirana, C., Deegahawature, D., & Silva, R. (2023b). The Influence of Labour Competencies on the Efficiency of Road Construction Operations in Sri Lanka. *Applied Bio-Systems Technology*, *3*(1), 13–23.
20. Manoharan, K., Dissanayake, P., Pathirana, C., Deegahawature, D., & Silva, R. (2024). A case study on the site supervisory attributes in construction labour management, performance assessment and productivity measurement practices. *Journal of Responsible Production and Consumption*, *1*(1), 37–61. https://doi.org/10.1108/JRPC-01-2024-0001
21. Mistri, A., Patel, C. G., & Pitroda, D. J. R. (2019). Analysis of Causes, Effects and Impacts of Skills Shortage for Sustainable Construction through Analytic Hierarchy Process. *International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES)*, *5*(05). https://www.researchgate.net/publication/354202419
22. Naeem, H., Saif, M. I., & Khalil, W. (2011). Emotional Intelligence And Its Impact On Service Quality Empirical Evidence From The Pakistani Banking Sector. *International Business & Economics Research Journal (IBER)*, *7*(12). https://doi.org/10.19030/iber.v7i12.3313
23. Pathirana, L. P. D. S. (2021). Construction Industry and Factor Condition Prospective Of Sri Lanka: A Special Reference to Skill Labour Shortage. *IOSR Journal of Business and Management (IOSR-JBM)*, *23*(2), 35–41. https://doi.org/10.9790/487X-2302073541

24. Perera, M. (2021). *The Effect of Emotional Intelligence on Work Outcomes in the Construction Industry*. Auckland University of Technology.
25. Premakumara, A., & Siriwardana, C. (2025). A comprehensive approach for assessing the causes of low productivity in the construction sector: A systematic categorization and ranking using Pareto and Fuzzy analysis. *Construction Management and Economics*, *43*(1), 40–58. https://doi.org/10.1080/01446193.2024.2377712
26. Salovey, P., & Mayer, J. D. (1990). Emotional Intelligence. *Imagination, Cognition and Personality*, *9*(3). https://doi.org/10.2190/DUGG-P24E-52WK-6CDG
27. Shehata, M. E., & El-Gohary, K. M. (2011). Towards improving construction labor productivity and projects' performance. *Alexandria Engineering Journal*, *50*(4), 321–330. https://doi.org/10.1016/j.aej.2012.02.001
28. Tennakoon, W. D. N. S. M., & Ariyaratne, W. K. D. (2021). EMOTIONAL INTELLIGENCE AS A MODERATOR ON THE STRESSPERFORMANCE RELATIONSHIP. *Proceeding of the Open University Research Sessions (OURS)*, 6.
29. Yoon, M. H., & Suh, J. (2003). Organizational citizenship behaviors and service quality as external effectiveness of contact employees. *Journal of Business Research*, *56*(8), 597–611. https://doi.org/10.1016/S0148-2963(01)00290-9

An Investigation of Effective Document Management Strategies for Post-Contract Period Used by Consultant Quantity Surveyors in Sri Lanka

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ABSTRACT

In the construction industry, efficient document management is crucial for ensuring the successful completion of projects, compliance with regulations, and the delivery of high-quality results. The importance of proper document management becomes even more apparent during the post-contract period, as it governs essential processes such as project handover, maintenance, and future reference. Most studies have examined document management issues from the contractor's perspective, leaving a gap in understanding how consultant Quantity Surveyors, who manage extensive documentation during the post-contract period, handle these challenges. This gap is critical, as poor practices cause disputes, delays, and weak claim administration, yet little research addresses it. This research aims to explore effective strategies for managing construction documents during the post-contract period by consultant quantity surveyors in Sri Lanka. An extensive literature review was conducted to identify existing document management strategies and assess their effectiveness. Mixed-methodology approach was adopted in this study. Data were collected through preliminary interviews, a comprehensive questionnaire survey, and semi-structured interviews with professionals in the construction industry. The questionnaire survey yielded 50 responses from industry professionals, which were analyzed using the Relative Importance Index (RII) analysis. Qualitative data were obtained from preliminary interviews with five industry experts and semi-structured interviews with an additional five experts, which were evaluated using thematic analysis. The research proposes current best practices for implementing document management systems (DMS) to support construction projects. Key aspects such as the evaluation of existing DMSs, identification of writing strategies, strategy implementation, challenges encountered, recommended solutions, and the effectiveness of document management strategies and standards are highlighted. The findings reveal a strong preference for physical records, driven by concerns over digital durability, security, and familiarity. The study identified for integrate digital DMS to enhance efficiency, security, and long-term accessibility, encouraging a gradual shift towards more sustainable, technology-driven practices in the industry.

KEYWORDS: *Construction industry, digital methods, document management, physical methods, post-contract, Sri Lanka*

INTRODUCTION

The construction industry is highly information-dependent, with project success significantly relying on effective data access and document management (Sun et al., 2020; Ahmad et al., 2017). The complexity of construction projects arises from multiple stakeholders and the diverse nature of information involved (Chen & Kamara, 2011; Gamage et al., 2025). Key issues in current document management practices include delays in document flow, incomplete records, and inefficient communication (Zarebidaki et al., 2012). Although electronic document management systems (EDMS) offer solutions, challenges such as high costs, software usability, and interoperability issues persist (Forcada et al., 2007; Zarebidaki et al., 2012). Poor record-keeping has been linked to delays in claims, increased rework, and general inefficiencies (Kumaraswamy & Yogeswaran, 2003). Despite the availability of digital tools, traditional manual systems like Microsoft Excel are still widely used due to convenience, though they are ineffective for complex project needs (Nycyk, 2008). Effective document management is thus essential

to improving communication, reducing costs, and enhancing the overall success of construction projects (Ahmad et al., 2015).

While EDMS usage is growing, a significant portion of construction data remains unstructured and hard to retrieve (Caldas et al., 2002; Martínez-Rojas et al., 2016). Effective and efficient management of documents is essential to ensure the successful completion of a construction project (Rathnayaka et al., 2023).

Ghosh and Karmakar (2024) demonstrate that the escalating complexity of conventional construction claims document management systems (CDMSs) results in improper documentation, ineffective claim generation processes, and inadequate resources. This undeniably heightens the risk of disputes and conflicting interpretations within the industry. Construction projects with multi-stakeholder interactions need decentralized management to reduce disputes (Mahmudnia et al., 2022). Also, the Ekanayake et al. (2025) study indicated that while many ISO 9001:2015 elements meet the documentation requirements of quantity surveyors in construction projects, some fall short.

A Quantity Surveyor ensures accurate organization and management of project documents, facilitating clear communication and preventing disputes. Their role in document management enhances transparency, efficiency, and smooth project execution in heavy engineering projects (Akorah et al., 2025). Many studies have explored document management issues, challenges, and tools from the contractor's perspective (Ahmad et al., 2017; Bakhary et al., 2015; Senaratne & Mayuran, 2015), yet limited research focuses on consultant Quantity Surveyors, especially regarding the post-contract period. Effective documentation management by consultant Quantity Surveyors is essential to ensure traceability, accuracy, and compliance with contract requirements, minimizing disputes and delays during the post-contract stage (Karmakar, 2024; Senaratne & Mayuran, 2015).

Therefore, this research aims to identify and assess effective document management strategies for handling construction documents during the post-contract period by consultant Quantity Surveyors in Sri Lankan construction projects. To achieve this, the study will identify current strategies used in managing post-contract documents in Sri Lanka and analyze and compare their effectiveness in local context. Ultimately, the research will develop practical recommendations and guidelines for implementing the most effective document management strategies during the post-contract period in Sri Lanka.

LITERATURE REVIEW

Document management in construction refers to organizing, regulating, storing, sharing, and editing drawings, specifications, estimates, and other construction-related documents. (Kulatunga, 2023) DMS refers to the repository that stores documents and allows end-users to retrieve required information (Ahmad et al., 2017). A DMS makes it easy to have access to the information at any time and from any place (Akakandelwa, 2020).

Existing Document Management Strategies in the Post-Contract Phase

Traditional Paper-Based Methods

Historically, Sri Lankan construction consultants, particularly Quantity Surveyors, have relied on conventional document handling methods such as physical filing systems, printed drawings, handwritten logbooks, and hardcopy bills of quantities. These paper-based systems, while once effective, are increasingly criticized for their inefficiencies. Akakandelwa (2020) and Ahmad et al. (2017) emphasize that these systems require substantial physical storage, are vulnerable to damage, and are labor-intensive when it comes to searching and retrieving information. In addition, Löwnertz (1998) notes that the lack of metadata, search capabilities, and structured indexing in paper systems makes long-term storage and version control nearly impossible.

Emergence of Digital DMS

In response to the limitations, the industry has witnessed a shift toward digital platforms. DMS, such as EDMS cloud-based repositories and web-based project platforms, are now used to improve document

accessibility and control. These systems store electronic versions of construction documents, including CAD files, spreadsheets, BOQs, and technical reports, while enabling features like version control, user authentication, and structured retrieval (Rathnayaka et al, 2023; Löwnertz, 1998; Abdulkadir, 2020). The EDMS also allows project participants to upload, track, and access documents in real time through a centralized server, ensuring improved communication and collaboration.

Effectiveness of Current Strategies

The transition to digital systems has brought several improvements. EDMS platforms have enabled better document control, increased transparency, and reduced project delays due to faster information access (Rathnayaka et al., 2023). The EDMS is more appropriate for mega projects than traditional documentation methods due to its functionality, neutrality, interoperability, space efficiency, reversibility, and delivery speed (Rathnayaka et al., 2024). According to Ahmad et al. (2017), electronic systems improve operational efficiency by reducing paper usage, storage costs, and the time required for document sharing. Web-based systems also support remote collaboration, cutting down the need for physical meetings and transportation of files (Abdulkadir, 2020). Despite these benefits, Löwnertz (1998) highlights that only 20–40% of construction documentation is currently exchanged digitally, indicating that traditional systems still dominate in many firms.

Current Needs and Gaps in Practice

Despite increased awareness and availability of technology, many small and medium-sized construction firms in Sri Lanka continue to rely on manual documentation methods. This is largely due to limited technical infrastructure, a lack of formal training, resistance to change, and insufficient government support for digital transformation (Rathnayaka et al, 2023; Ahmad et al., 2017). Fernando et al. (2019) also observed that the absence of clearly defined document management responsibilities within teams leads to inconsistent implementation of digital systems. Experts suggest that effective transition requires strong leadership, formal guidelines, and ongoing training programs to build confidence among users and ensure widespread adoption. Ghosh and Karmakar (2024) study revealed that the manual nature of inputting, retrieving, analyzing, and disseminating claim results consumes valuable time and resources. Many claim requests are disapproved due to insufficient evidence. Additionally, manual and improper approaches to CDMSs result in cost overruns, conflicts, and disputes, which are common in construction projects. This highlights the urgent need for a streamlined and efficient CDMS to address the industry's challenges.

Technical Aspects of Document Management During Post-Contract Period

During the post-contract phase, which spans from the commencement of construction to final handover, documentation plays a vital role in verifying progress, processing payments, managing variations, preparing claims, and generating final accounts (Abobakr, 2017.; Gunarathna & Fernando, 2013). The need for accurate, timely, and secure document handling is especially critical at this stage. Hassan and Le (2020) emphasize that contract documents act as legal references for all stakeholders, making it essential that they are well-maintained and easily retrievable. Tools like cloud storage, BIM-integrated document systems, and encryption-enhanced digital files have therefore become increasingly relevant. Technologies such as blockchain and digital signatures are also being explored to ensure traceability, prevent unauthorized access, and maintain document integrity (Kulatunga, 2023).

Barriers to Implementation and Suggested Solutions

A major challenge in adopting EDMS solutions is the initial cost, security, and complexity of implementation. Security concerns in DMSs, particularly regarding data integrity, can severely impact a project's finances and the reputations of its participants(Das et al., 2022). However, Rathnayaka et al. (2024) emphasized that developing low-cost Sri Lankan software for document management is the most viable solution. Ahmad et al. (2017) and Fernando et al. (2019) report that many construction companies are hesitant to invest due to uncertain returns and a lack of immediate visible benefits. Furthermore, staff may resist transitioning to digital systems due to unfamiliarity with the technology. To address these

challenges, Hernad and Gaya (2013) recommend clearly defining document management roles, setting up feedback mechanisms, following ISO-based quality standards, and motivating staff through recognition and incentives. Additional training and departmental support are also essential to overcome technical and psychological barriers to adoption.

The evolving nature of construction technology suggests that the future of document management will be highly integrated, intelligent, and secure. Emerging tools such as BIM, cloud computing, AI-based document search, and real-time collaboration platforms are reshaping how data is created, accessed, and used. As noted by Kulatunga (2023), the effective implementation of digital document management can significantly reduce errors, cut costs, enhance project transparency, and improve legal compliance. Akakandelwa (2020) adds that advanced DMS platforms also contribute to sustainability by minimizing paper consumption and waste. However, achieving this future state requires a clear national strategy, standardization of systems, and coordinated efforts among public and private sector stakeholders.

RESEARCH METHODOLOGY

This study adopted a mixed-method approach combining quantitative and qualitative data. Mixed methods research involves collecting and integrating quantitative and qualitative data; therefore, may result in a more comprehensive understanding of the phenomenon under investigation. Mixed methods design value both quantitative and qualitative approaches to research (Leavy, 2022). The interpretivism paradigm and inductive reasoning supported the research framework.

Data Analysis Process

A preliminary interview was conducted with five professionals from the local construction industry to explore the existing document management strategies employed during the post-contract period in Sri Lanka. The objective of this initial stage was to gain foundational insights and identify common themes related to documentation practices. The collected qualitative data were analyzed using thematic analysis, and the key themes identified were used to design a structured questionnaire.

The questionnaire survey responses were obtained from a total of 50 participants. The RII method was used to evaluate and compare the effectiveness of various document management strategies. RII is a statistical measure often used in construction research to determine the relative ranking of the factors. In addition, qualitative data were gathered to triangulate the analyzed results (Senaratne and Mayuran, 2015). Kinemo (2024) studies have stated that RII is a statistical tool used to rank different factors based on their level of importance or impact. Researchers commonly use it to prioritize items according to respondents' ratings. To further develop practical recommendations and guidelines for implementing the most effective practices, a semi-structured interview was conducted with another five industry experts. The data from these interviews were also subjected to thematic analysis to enrich and validate the findings.

The questionnaire survey used a non-probability sampling method. Non-probability sampling suits exploratory studies and hard-to-reach groups where full population access is impractical (Ahmed, 2024). To select participants for the interviews, the data saturation method was used. Data saturation is a key concept in qualitative research, marking the point at which no new information or themes emerge from the data. Achieving this indicates that the researcher has thoroughly explored the phenomenon, allowing data collection to stop without missing important insights (Ahmed, 2025)

Expertise Core Data Analysis

Table 1 represents the demographic data analysis of the preliminary interviews, questionnaire survey, and semi-structured interviews.

Table 8.Demographic Data Analysis

Data Collection Method	Profession	Years of experience	No. of Experts
Preliminary Interview	Assistant Quantity Surveyor	Less than 5 years	1
	Quantity Surveyor	5-10 years	1

Data Collection Method	Profession	Years of experience	No. of Experts
	Senior Quantity Surveyor	10-15 years	3
Questionnaire Survey	Assistant Quantity Surveyor	Less than 5 years	17
	Quantity Surveyor		17
	Senior Quantity Surveyor	5-10 years	9
	Lead Quantity Surveyor	10-15 years	4
	Managing Quantity Surveyor	More than 15 years	3
Semi-structured interview	Senior Quantity Surveyor	10-15 years	2
		15-20 years	2
		Above 20 years	1

RESULTS AND DISCUSSION

Existing document management methods

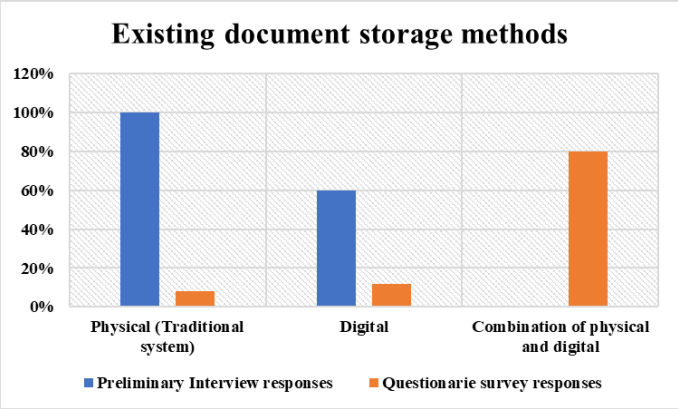
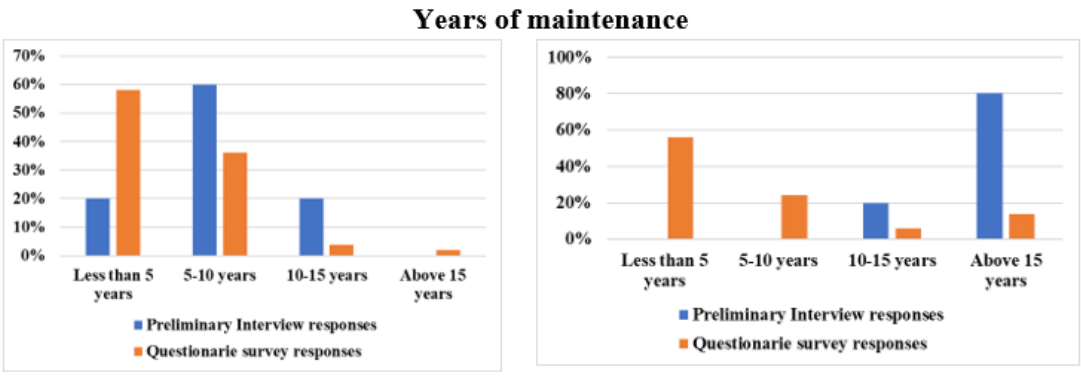


Figure 15. Existing document management methods

Figure 1 shows the distribution of document storage methods based on preliminary interviews and a questionnaire survey. All interview respondents noted that traditional physical systems are still dominant. However, few survey respondents use physical systems exclusively, indicating a shift in industry practices. While some interviewees recognized digital methods, about 80% of survey respondents reported using a mix of physical and digital storage. This reflects a trend towards hybrid solutions that combine traditional and modern approaches for better efficiency, accessibility, and security in document management.

Existing document management maintenance



Physical **Digital**

Figure 16. Document management maintenance

For physical document storage, the majority of questionnaire respondents prefer short-term maintenance, typically less than five years, mainly due to storage limitations, cost, and the deterioration of physical records over time. However, experienced professionals interviewed in the study indicated a tendency to retain physical documents for a longer period, particularly five to ten years, suggesting a deeper awareness of contractual obligations and potential dispute resolutions that may arise post-completion.

In contrast, digital document storage reflects a growing recognition of its long-term value. The interviewees strongly favored maintaining digital records for more than fifteen years, demonstrating confidence in the durability, retrievability, and security of digital systems. Encouraging long-term digital document retention would ultimately enhance record accessibility, legal protection, and operational continuity in quantity surveying practices.

Challenges and solutions for existing document management methods

Table 2. Existing Challenges

No	Challenges	Preliminary interview						Questionnaire Survey	
		I_1	I_2	I_3	I_4	I_5	%	Responses	%
1	Technical Challenges	✓	✓	✓	✓	✓	100%	42	84%
2	Budget Constraints	✓		✓			40%	39	78%
3	Storage Or Space Constraint	✓	✓	✓	✓	✓	100%	38	76%
4	Compliance and Regulatory Issues		✓	✓	✓		60%	34	68%
5	Cultural Resistance	✓		✓		✓	60%	26	52%
6	Paper Sheet may be discolored.	✓	✓	✓	✓	✓	100%		
7	Lack of Knowledge strategies.	✓	✓	✓	✓	✓	100%		
8	Searching Issues	✓	✓			✓	60%		
9	Transfer information	✓	✓		✓		60%		
10	Damage can be caused by rodents.	✓		✓		✓	60%		
11	Access Control Issues	✓	✓				40%		
12	Communication Challenges	✓				✓	40%		

Table 2 reveals the challenges faced in existing document management practices. The data indicate that technical issues were universally acknowledged by all interviewees and were confirmed by 84% of survey participants. Similarly, storage and space constraints, along with a lack of awareness about digital documentation methods, were also highlighted by 100% of the preliminary interviewees. Budget constraints, compliance and regulatory issues, cultural resistance, and difficulties in accessing and transferring information also emerged as significant concerns. These findings highlight that the barriers are both technological and organizational, underscoring the complexity of implementing effective DMSs in the Sri Lankan construction industry.

Table 3. Solutions Implemented

No	Solutions	Preliminary interview					
		I_1	I_2	I_3	I_4	I_5	%
1	Proper maintenance of a file system and log notes.	✓	✓	✓	✓	✓	100%
2	Storing files properly	✓	✓	✓	✓	✓	100%
3	Improving the digital system.	✓	✓	✓	✓	✓	100%
4	Introducing the paperless concept	✓	✓	✓		✓	80%

5	Reducing the Cultural Resistance	✓		✓		✓	60%
6	Regulatory Compliance		✓	✓	✓		60%
7	Managing and operating a proper search system	✓	✓		✓		60%
8	Maintaining systems to reduce the use of paper.	✓	✓				40%
9	Using budget control methods	✓				✓	40%
10	Proper management of access control system	✓			✓		40%
11	Using a one platform to transfer information related to documents	✓		✓			40%
12	Improving communication knowledge	✓					20%

In response to these challenges, Table 3 outlines a range of practical solutions during the preliminary interviews. All five interviewees emphasized the importance of maintaining proper file systems and log notes, storing files securely, and improving the existing digital systems. The introduction of a paperless concept also received strong support, along with strategies to overcome cultural resistance and improve search systems. These solutions suggest a strong awareness of the potential for digital transformation, although implementation varies across organizations.

Effectiveness of existing document management methods

Physical document management method

Table 6 presents the RII analysis of physical document strategies.

Table 4. Effectiveness of strategies (Physical method)

No	Strategies	Current Implementation		Effectiveness	
		RII	Ranks	RII	Ranks
1	Keep File as Videos	0.556	6	0.588	6
2	Keep File as Images	0.676	5	0.624	5
3	Keep Text documents	0.724	4	0.696	4
4	Keep Spreadsheets	0.796	1	0.744	3
5	Keep as Drawings	0.792	2	0.748	2
6	Keep document according to 5's Method	0.732	3	0.78	1

Among the methods analyzed, maintaining documents according to the 5S methodology was ranked as the most effective strategy, with an RII score of 0.78. However, spreadsheets were the most commonly implemented, scoring the highest in current usage with an RII of 0.796. Drawings and text documents were also commonly used, though perceived as less effective. This suggests that while traditional physical documentation methods remain widespread, there is recognition of the greater efficiency offered by systematic approaches like the 5S method.

Digital document management method

Below table 5 presents a similar analysis for digital documentation strategies.

Table 5. Effectiveness of strategies (Digital method)

No	Strategies	Current Implementation		Effectiveness	
		RII	Ranks	RII	Ranks
1	Maintain workflow automation	0.684	6	0.716	6
2	Maintain document version control	0.716	4	0.724	5
3	Maintain a records management system	0.732	3	0.744	4
4	Maintain as BIM files	0.656	7	0.744	4
5	Maintain document scanning and digitization	0.752	2	0.748	3
6	Maintain a cloud-based document storage	0.708	5	0.756	2
7	Maintaining digital documents as repositories	0.78	1	0.76	1

The highest effectiveness ratings were attributed to maintaining digital document repositories and using cloud-based storage, with RII scores of 0.76 and 0.756, respectively. Document scanning and digitization also ranked highly, reflecting a growing preference for digital storage solutions. Although strategies like workflow automation and the use of BIM files were implemented to a lesser extent, their perceived effectiveness indicates potential for broader future adoption. Overall, the data reflect a shift towards digital platforms and underscore the importance of infrastructure and training in facilitating this transition.

Document access and security are managed within the organization

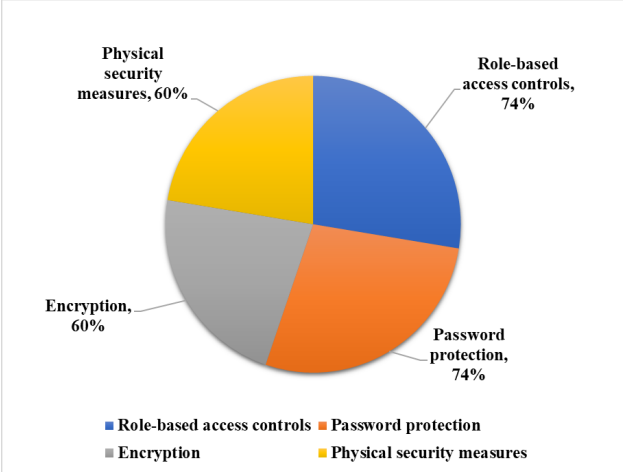


Figure 3. Document Security

Table 9 explores how document access and security are managed within organizations. All 50 participants in the questionnaire survey agreed on the importance of maintaining cloud-based backups, while a majority supported using encryption, password protection, and access control systems. The responses demonstrate growing awareness of the need for data security in document management. However, the relatively lower endorsement of advanced security features such as selective access systems and physical document lockers points to inconsistencies in current practices and the need for more standardized approaches across the industry.

Proposed recommendations and guidelines for implementing the most effective document management strategies

Table 6. Proposed guidelines

No	Proposed guidelines	Semi-structured Interviewers					%
		I_1	I_2	I_3	I_4	I_5	
1	The method adopted should be practicable	ü	ü	ü			60%
2	Maintaining a secure digital store			ü	ü		40%
3	It should be practical to do it through the cloud-based system		ü			ü	40%
4	Refer to using cloud backup		ü		ü		40%
5	Limiting Access and Control for Important Documents			ü	ü		40%
6	Maintaining a check and balance System	ü					20%
7	Entry for the syllabus of the Quantity Surveying degree	ü					20%
8	Generate and store physical documents as a digital version, and maintain					ü	20%
9	Maintaining correct and properly standardized document management strategies			ü			20%
10	Awareness about the cybersecurity of document management and how to manage					ü	20%

Table 6 outlines proposed guidelines from expert interviews aimed at enhancing document management during the post-contract phase. Of the five industry professionals interviewed, 60% stressed the need for practical and usable document management methods for daily operations. Furthermore, 40% recommended secure digital storage and favored cloud-based platforms for centralized access. Another 40% highlighted the importance of cloud backups for data preservation and continuity. Access restrictions for sensitive documents were also emphasized by 40% of respondents. Additional, albeit less common, suggestions (20%) included implementing a check-and-balance system, integrating document management practices into quantity surveying education, and digitizing physical documents for efficiency. The guidelines underscore the importance of modernizing DMSs with secure and effective strategies.

Table 7. Proposed practical methods

No	Proposed methods	Semi-structured Interviewers					%
		I_1	I_2	I_3	I_4	I_5	
1	Maintain as soft copy.	ü	ü	ü	ü	ü	100%
2	Complying with local construction rules and regulations	ü	ü	ü		ü	80%
3	Using a system like Aconex.	ü	ü				40%
4	Using a cloud-based system.	ü			ü	ü	40%
5	Using the 5's system.	ü					20%
6	Drivers, maintaining the server properly		ü				20%
7	Maintaining important or sensitive documents properly			ü			20%
8	Using digital signatures				ü		20%
9	Using a system like master build.	ü					20%
10	Using spreadsheets				ü		20%

In Table 7, the participants proposed various methods currently in use or recommended for adoption. All five experts emphasized maintaining soft copies of documents and complying with Sri Lankan

construction regulations. Systems like Aconex and Master Build were mentioned as beneficial tools for document tracking and control. The use of spreadsheets, digital signatures, and server maintenance were also discussed, though these were less commonly implemented. These insights reinforce the direction of digital transformation and highlight areas where practical application can be improved.

Table 8. Proposed document security systems

No	Proposed document security and confidentiality systems	Interviewers					%
		I_1	I_2	I_3	I_4	I_5	
1	Maintaining Cloud base backup	ü	ü	ü	ü	ü	100%
2	Use encryption	ü		ü		ü	60%
3	Using Password System	ü		ü	ü		60%
4	Access limited		ü	ü		ü	60%
5	A digital security system should be used	ü		ü			40%
6	Providing access control		ü		ü		40%
7	Level of authorities should be given for paper-based system	ü					20%
8	Traditional system is not practical		ü				20%
9	Providing a separate locker or a separate key		ü				20%
10	Using a selective access system		ü				20%
11	Internet threats are difficult to avoid		ü				20%
12	Deleting access control		ü				20%

The research highlights the critical need for secure DMSs among consultant quantity surveyors in Sri Lanka. All five interviewed experts emphasized the importance of cloud-based backups for data preservation and remote access. They also noted the necessity of encryption and password protection to safeguard sensitive information. Access control mechanisms, which limit user privileges, were recommended to prevent unauthorized access to critical documents. Although advanced security measures like selective access and hierarchical permissions were discussed, their implementation is limited. Traditional security methods, such as locked cabinets, are seen as impractical in today's digital landscape, underscoring the need for technology-driven solutions. Additionally, the research reveals a lack of systematic procedures to combat internet threats, suggesting that a standardized security framework with encrypted storage, layered access rights, and cloud redundancy could significantly improve the security of post-contract documentation in the construction industry.

Table 9. Proposed technologies

No	Proposed emerging technologies & how organizations should prepare	Interviewers					%
		I_1	I_2	I_3	I_4	I_5	
1	Using Cloud based DMS			ü	ü	ü	60%
2	Using block chain technology and can ensuring the details security.	ü		ü			40%
3	Using BIM Technology		ü			ü	40%
4	AI technology		ü	ü			40%
5	Introduction of smart contract	ü					20%
6	Retyping and printing the format made by CIDA	ü					20%
7	Taking photos and videos with the help of drone technology and processing them with the date	ü					20%
8	Using digital Signature system				ü		20%

Emerging technologies are set to transform document management practices in the construction industry. Expert interviews highlighted cloud-based systems as the most practical solution, offering easy

access and improved collaboration. Blockchain was identified for its potential to enhance document security and transparency, while BIM technology supports centralized digital coordination. Artificial intelligence was also noted for its ability to automate and optimize document workflows. Despite these benefits, adoption remains low due to limited resources and resistance to change. To prepare, organizations should invest in digital tools, train staff, and integrate flexible systems that support these technologies. Embracing these advancements will ensure more efficient, secure, and future-ready document management practices.

Developed Framework for Proposed Guidelines to Implement Effective Document Management Strategies in the Post-Contract Period in Sri Lanka

Figure 4 outlines a framework for effective document management in the post-contract phase of construction projects in Sri Lanka. The framework defines six key guidelines (1–6) for effective document management. Guidelines 1.1–1.9 outline practical methods, supported by technological integration with eight proposed technologies (1A.1–1A.8). Guidelines 1, 2, and 3 emphasize the need to combine these methods with security system plans, detailed in twelve proposed security systems (6.1–6.12). The strategies are categorized into two main areas: managing physical documents (3.1) and managing digital documents (3.2), ensuring a comprehensive and secure approach to document management.

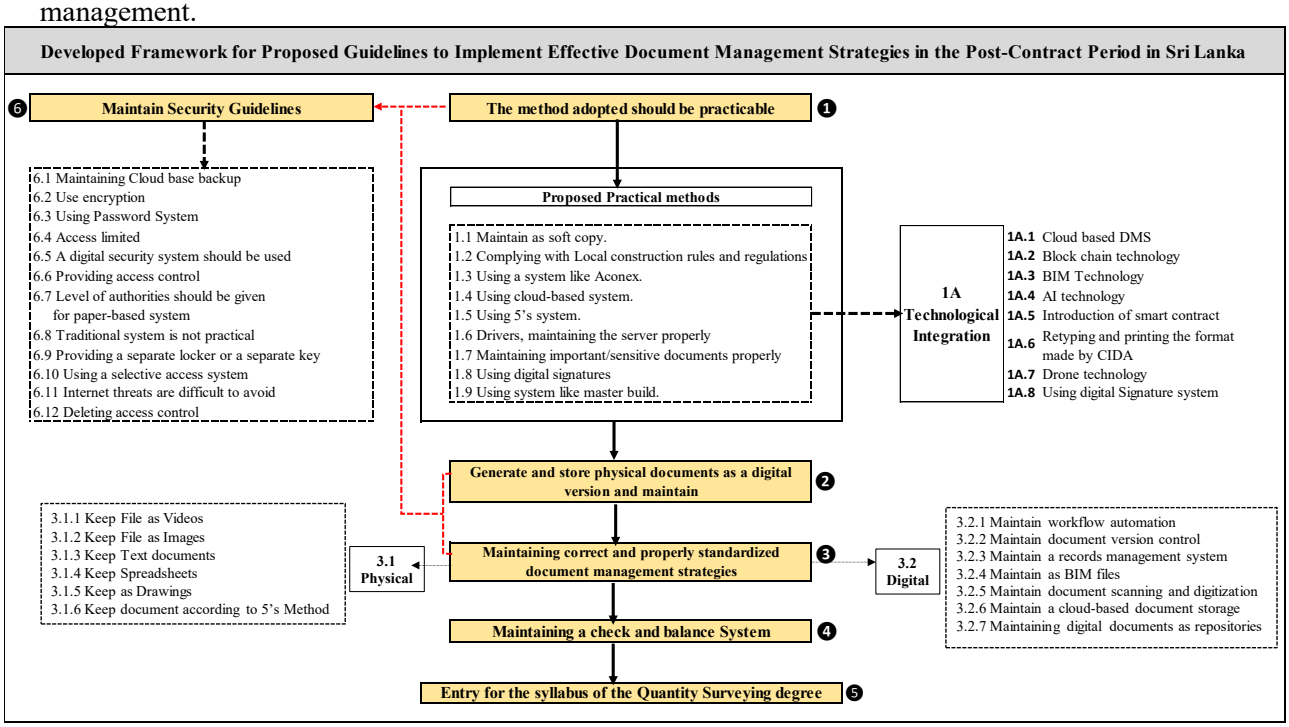


Figure 4. Developed Framework

Together, these elements form a comprehensive framework that balances practicality, security, and technology to enhance post-contract document management used by consultant quantity surveyors in Sri Lanka.

CONCLUSION

The research underscores the significance of adopting effective document management strategies during the post-contract phase in Sri Lanka's construction industry. While traditional manual methods remain prevalent due to familiarity and resource limitations, the emergence of digital systems such as cloud-based platforms and electronic tracking tools offers notable advantages in security, accessibility, and operational efficiency. Challenges such as space constraints, high costs, and resistance to change impede progress; however, with targeted training, organizational commitment, and regulatory support, these

barriers can be mitigated. The study advocates for a hybrid approach that combines the strengths of manual and digital practices, emphasizing the need for organizations to invest in staff training, develop standardized procedures, and prioritize secure storage solutions. Implementing these strategies can lead to improved document control, reduced project delays, and enhanced collaboration among stakeholders. Future research should focus on quantifying the benefits of digital adoption and exploring industry-specific customization of management practices. The findings highlight that maintaining documents according to the 5S methodology emerged as the most effective strategy for physical document management, while maintaining digital repositories and adopting cloud-based storage ranked highest in digital document management practices. Furthermore, the results underscored the universal agreement among participants on the importance of cloud-based backups, alongside strong support for encryption, password protection, and access control systems to ensure secure and reliable document access. Ultimately, a systematic and well-managed post-contract documentation process is essential for driving project success and sustaining growth in Sri Lanka's construction sector.

REFERENCES

1. Abdulkadir, S. (2020). Adoption of web-based project management system for construction project delivery. *International Journal of Information Processing and Communication (IJIPC), 8*(1), 79–91.
2. Abobakr, A. T. (2017). *Necessity of cost control process (pre- & post-contract stage) in construction projects* [Bachelor's thesis, Helsinki Metropolia University of Applied Sciences].
3. Ahmad, H., Ayoush, M., & Bazlamit, S. (2015). Document management systems in small and medium size construction companies in Jordan. In *Proceedings of the 6th International Conference on Engineering, Project, and Production Management* (pp. 273–281). https://doi.org/10.32738/CEPPM.201509.0028
4. Ahmed, S. K. (2024). How to choose a sampling technique and determine sample size for research: A simplified guide for researchers. *Oral Oncology Reports*, *12*, 100662. https://doi.org/10.1016/j.oor.2024.100662
5. Ahmed, S. K. (2025). Sample size for saturation in qualitative research: Debates, definitions, and strategies. *Journal of Medicine, Surgery, and Public Health*, *5*, 100171. https://doi.org/10.1016/j.glmedi.2024.100171
6. Ahmad, H. S., Bazlamit, I. M., & Ayoush, M. D. (2017). Investigation of document management systems in small size construction companies in Jordan. *Procedia Engineering, 182*, 3–9. https://doi.org/10.1016/j.proeng.2017.03.101
7. Akakandelwa, M. (2020). *Development & implementation of a web-based document management system* (Doctoral dissertation, Cavendish University).
8. Akorah, C., Agu, N. N., Ajator, U. O., & Nwoyiri, C. S. (2025). *Optimizing Construction Performance: The Essential Role of Quantity Surveyors and their Involvement in Heavy Engineering Projects*. https://doi.org/10.5281/ZENODO.14860060
9. Bakhary, N. A., Adnan, H., & Ibrahim, A. (2015). A study of construction claim management problems in Malaysia. *Procedia Economics and Finance, 23*, 63–70. https://doi.org/10.1016/S2212-5671(15)00327-5
10. Caldas, C. H., Soibelman, L., & Han, J. (2002). Automated classification of construction project documents. *Journal of Computing in Civil Engineering, 16*(4), 234–243. https://doi.org/10.1061/(ASCE)0887-3801(2002)16:4(234)
11. Chen, Y., & Kamara, J. M. (2011). A framework for using mobile computing for information management on construction sites. *Automation in Construction, 20*(7), 776–788. https://doi.org/10.1016/j.autcon.2011.01.002
12. Das, M., Tao, X., Liu, Y., & Cheng, J. C. P. (2022). A blockchain-based integrated document management framework for construction applications. *Automation in Construction, 133*, 104001. https://doi.org/10.1016/j.autcon.2021.104001
13. Ekanayake, G. B. E. M. A. S., Disaratna, P. A. P. V. D. S., Ilangakoon, I. W. M. A. D., & Perera, B. A. K. S. (2025). Adequacy of document management systems for postcontract quantity

surveying roles: A qualitative Delphi study. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 17*(2). https://doi.org/10.1061/jladah.ladr-1243

14. Fernando, H., Hewavitharana, T., & Perera, A. (2019). Evaluation of electronic document management (EDM) systems for construction organizations. In *2019 Moratuwa Engineering Research Conference (MERCon)* (pp. 273–278). https://doi.org/10.1109/MERCon.2019.8818768
15. Forcada, N., Casals, M., Roca, X., & Gangolells, M. (2007). Adoption of web databases for document management in SMEs of the construction sector in Spain. *Automation in Construction, 16*(4), 411–424. https://doi.org/10.1016/j.autcon.2006.07.011
16. Gamage, N., Ambagala, A. P. K. K., Nanayakkara, S., & Perera, S. (2025). Towards a framework for implementing blockchain technology in the construction industry of Sri Lanka. *Built Environment Project and Asset Management, 15*(3), 612–628. https://doi.org/10.1108/BEPAM-12-2023-0222
17. Ghosh, B., & Karmakar, S. (2024). Digitalized document management system for construction claims and disputes to enhance the smoothness of advanced construction projects using the building information modeling integrated framework. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 17*(1). https://doi.org/10.1061/JLADAH.LADR-1203
18. Gunarathna, M. A. C. L., & Fernando, N. G. (2014). Stakeholders' preference towards the use of conflict management styles in dual concern theory in post contract stage. In *International Conference on Construction in a Changing World* (pp. 4–7).
19. Hassan, F. U., & Le, T. (2020). Automated requirements identification from construction contract documents using natural language processing. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 12*(2), 04520009. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000379
20. Hernad, J. M. C., & Gaya, C. G. (2013). Methodology for implementing document management systems to support ISO 9001:2008 quality management systems. *Procedia Engineering, 63*, 29–35. https://doi.org/10.1016/j.proeng.2013.08.225
21. Karmakar, S. (2024). Third-party quality control concept, methodology, and implementation in the building and housing construction industry in India. *International Journal of Construction Management*, *25*, 1–11. https://doi.org/10.1080/15623599.2024.2397227
22. Kinemo, S. (2024). Relative Importance Index in Ranking Performance Management Practices Towards Organizational Performance. *NG Journal of Social Development*, *13*(2), 54–60. https://doi.org/10.4314/ngjsd.v13i2.4
23. Kumaraswamy, M. M., & Yogeswaran, K. (2003). Substantiation and assessment of claims for extensions of time. *International Journal of Project Management, 21*(1), 27–38. https://doi.org/10.1016/S0263-7863(01)00052-7
24. Leavy, P. (2017). *Research design: Quantitative, qualitative, mixed methods, arts-based, and community-based participatory research approaches*. The Guilford Press.
25. Löwnertz, K. (1998). *Change and exchange: Electronic document management in building design* [Licentiate thesis, Royal Institute of Technology Stockholm, Sweden].
26. Mahmudnia, D., Arashpour, M., & Yang, R. (2022). Blockchain in construction management: Applications, advantages and limitations. *Automation in Construction, 140*, 104379. https://doi.org/10.1016/j.autcon.2022.104379
27. Nycyk, M. (2008). Records management practices in construction industries: Australian perspectives. *Records Management Journal, 18*(2), 140–149. https://doi.org/10.1108/09565690810882995
28. Rathnayaka, L. S. D., Malsha Nadeetharu, B. K., & Kulatunga, U. (2024). Applicability of electronic document management system (EDMS) for the cost management of mega construction projects in Sri Lanka. *Journal of Financial Management of Property and Construction, 29*(2), 314–330. https://doi.org/10.1108/JFMPC-01-2023-0005
29. Rathnayaka, L. S. D., Nadeetharu, B. K. M., & Kulatunga, U. (2023). Quantity surveyor's perspective on document management in construction projects: An exploratory study in Sri Lanka. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, T. Ramachandra, & K. A. T. O.

Ranadewa (Eds.), *Proceedings of the 11th World Construction Symposium, 21–22 July 2023, Sri Lanka* (pp. 909–919). https://doi.org/10.31705/WCS.2023.73

30. Senaratne, S., & Mayuran, J. (2015). Documentation management based on ISO for construction industries in developing countries. *Journal of Construction in Developing Countries, 20*(2), 81–95.
31. Sun, J., Lei, K., Cao, L., Zhong, B., Wei, Y., Li, J., & Yang, Z. (2020). Text visualization for construction document information management. *Automation in Construction, 111*, 103048. https://doi.org/10.1016/j.autcon.2019.103048
32. Zarebidaki, A., Nikakhtar, A., & Wong, K. Y. (2013). Document management in construction for shorter project lead time using web-based software. In *ICSDEC 2012* (pp. 687–694). https://doi.org/10.1061/9780784412688.082

Smart Irrigation System Using Arduino and LabVIEW for Real-Time Monitoring and Efficient Water Management

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Abstract

Efficient water management is a critical challenge in agriculture, particularly in regions experiencing water scarcity and climate variability. Conventional irrigation systems, typically based on fixed schedules or manual practices, often result in over- irrigation or under-irrigation, leading to resource wastage and reduced crop performance. This paper presents the design and implementation of a Smart Irrigation System that integrates Arduino-based embedded hardware with a LabVIEW graphical interface to achieve real-time monitoring, automation, and user-driven control of irrigation. The system continuously measures soil moisture, temperature, and humidity, enabling dynamic threshold-based irrigation supported by a manual override option. Experimental validation confirmed that the system operates reliably, responds accurately to changing soil conditions, and prevents unnecessary irrigation by activating the water pump only when required. Unlike existing solutions, the proposed system provides dual operating modes, interactive threshold adjustment, and intuitive real-time visualization through LabVIEW, making it both scalable and cost-effective for small- to medium-scale farming applications. This work contributes to sustainable agricultural practices by combining affordability, adaptability, and improved water-use efficiency.

Keywords: Arduino Uno; automation; DHT22; LabVIEW; real time monitoring; smart irrigation; soil moisture sensor; water conservation

1. Introduction

Agriculture consumes nearly 70% of the world's freshwater resources, and with increasing population growth and climate variability, efficient water management has become an urgent necessity. Irrigation, being one of the most critical processes in crop cultivation, often suffers from inefficiencies when carried out using traditional time- based or manual methods. Such approaches fail to respond to real-time soil and environmental conditions, frequently leading to water wastage through over-irrigation or yield losses caused by under-irrigation. This has created a strong demand for automated and intelligent irrigation solutions capable of adapting to dynamic agricultural environments.

In recent years, researchers have explored the integration of sensors, microcontrollers, and software platforms to enhance irrigation efficiency. Aswale et al. [1] demonstrated an Arduino–LabVIEW interfaced irrigation controller, but the system was primarily restricted to basic soil moisture feedback without comprehensive environmental monitoring. Barkunan et al. [2] proposed a drip irrigation system for paddy cultivation using smart sensors, yet its effectiveness across different crop types and field conditions was not fully examined. Gogoi [4] introduced a LabVIEW-monitored irrigation framework, but it lacked scalability and did not provide adaptive control strategies. More recently, Montesano et al. [5] highlighted the potential of IoT-based irrigation monitoring with cloud integration, although the higher cost and complexity of such systems limit their feasibility for small and medium-scale farms. These studies illustrate significant progress in the field, but they also reveal persistent limitations in terms of adaptability, user interaction, and affordability.

The present work aims to address these gaps by developing a cost-effective and scalable smart irrigation system that integrates real-time monitoring of multiple parameters with an intuitive decision-support interface. The proposed system is designed to continuously measure soil moisture, temperature, and humidity using low-cost sensors interfaced with an Arduino microcontroller, while a LabVIEW-based graphical user interface provides real-time data visualization, threshold configuration, and manual override features. Unlike conventional systems that operate solely on preset schedules, this solution enables automatic irrigation based on dynamic soil conditions while still allowing user control when necessary.

Through this combination of embedded hardware and virtual instrumentation, the system offers an affordable and user-friendly approach to precision irrigation. Its ability to adapt irrigation decisions to actual field conditions improves water efficiency, reduces resource wastage, and enhances crop health. Moreover, by validating the system under controlled conditions, the study demonstrates the potential of this approach to serve as a practical and sustainable solution for small and medium-scale agricultural operations.

2. System architecture

The proposed smart irrigation system is structured into three major functional components: environmental data acquisition, control and decision-making, and irrigation execution with user feedback. These components work together in a closed-loop cycle that begins with environmental sensing, proceeds through processing and decision- making, and culminates in actuation and feedback to the user. Figure [1] illustrates the overall flow of operations, showing how soil and climate parameters are continuously monitored, evaluated against thresholds, and translated into irrigation actions.

2.1 Environmental Data Acquisition

The first stage of the architecture focuses on capturing real-time environmental parameters that govern irrigation requirements. A soil moisture sensor forms the core of this layer by measuring volumetric water content in the soil. Its analog output is calibrated between two extreme conditions: completely dry soil and fully saturated soil. The calibrated output is then mapped to a percentage scale between 0% and 100%, ensuring accuracy in determining the irrigation need [3]. Since soil moisture directly influences plant growth, this parameter is prioritized in the decision-making process [2].

In addition to soil conditions, ambient temperature and relative humidity are continuously recorded using a DHT22 sensor. With a resolution of 0.1 °C and ±0.5 °C accuracy for temperature, and ±2–5% for humidity, this sensor provides reliable information on environmental dynamics that affect evapotranspiration and crop water demand [7]. Incorporating temperature and humidity ensures that

irrigation control is not solely dependent on soil moisture but also considers broader climatic influences.

All sensor data are acquired by the Arduino Uno microcontroller, which acts as the central collection point. The Arduino performs analog-to-digital conversion (ADC) for the soil moisture sensor and aggregates the readings into structured packets. These packets are transmitted to the LabVIEW interface via serial communication at regular intervals, enabling continuous monitoring while balancing communication efficiency [1]. The combination of multi-parameter sensing and reliable transmission provides a strong foundation for intelligent irrigation decisions.

2.2 Control and Decision-Making Unit

At the core of the system lies the integration of the Arduino Uno with a LabVIEW-based graphical user interface, forming the control and decision-making unit. The Arduino receives and preprocesses data from the sensing layer before transmitting it to LabVIEW. Within LabVIEW, a custom Virtual Instrument (VI) interprets the incoming data stream, displaying soil moisture, temperature, and humidity in both numerical and graphical formats for real- time monitoring [4].

The system allows users to set a soil moisture threshold through a slider interface in LabVIEW. This threshold is critical for determining irrigation cycles. When the soil moisture value falls below the threshold, LabVIEW recognizes the condition as "dry" and transmits a binary signal ('1') back to the Arduino. The Arduino then activates the relay module to switch on the water pump. Conversely, if the soil moisture value is equal to or above the threshold, LabVIEW sends a '0', ensuring that the pump remains inactive [5]. This simple yet effective binary communication scheme reduces latency, conserves bandwidth, and ensures rapid responsiveness, which is vital for real-time agricultural applications.

A significant advantage of this architecture is the inclusion of a manual override function. Farmers or users can bypass the automatic control by directly commanding the pump through the LabVIEW interface. This feature is particularly useful during system calibration, maintenance, or exceptional conditions such as sudden weather changes. The dual-mode operation—automatic and manual—provides both flexibility and reliability, addressing a limitation observed in several prior works that relied solely on automatic scheduling without user intervention [2,6].

2.3 Irrigation Execution and Feedback

The final component of the system is responsible for executing irrigation commands and providing immediate feedback to the user. The Arduino drives a single-channel relay module, which serves as an electronic switch to control the submersible water pump. When the soil is identified as dry, the relay energizes, activating the pump and initiating irrigation. Once the soil moisture level reaches or exceeds the threshold, the pump is automatically switched off, conserving water resources while maintaining optimal soil conditions [2].

To improve usability, the system incorporates visual indicators through red and green LEDs. The red LED illuminates when the soil is dry and irrigation is in progress, while the green LED signals sufficient soil moisture and an inactive pump. This provides farmers with an immediate, low-complexity means of interpreting system behavior, even without the LabVIEW interface.

This stage effectively closes the system's control loop. Real-time sensing drives decision-making, which in turn governs actuation, while feedback ensures transparency and user trust in the system's operation. The architecture demonstrates how embedded systems and virtual instrumentation can be integrated into a cost-effective and scalable irrigation solution, supporting the broader goals of sustainable agriculture and precision farming [5,6].

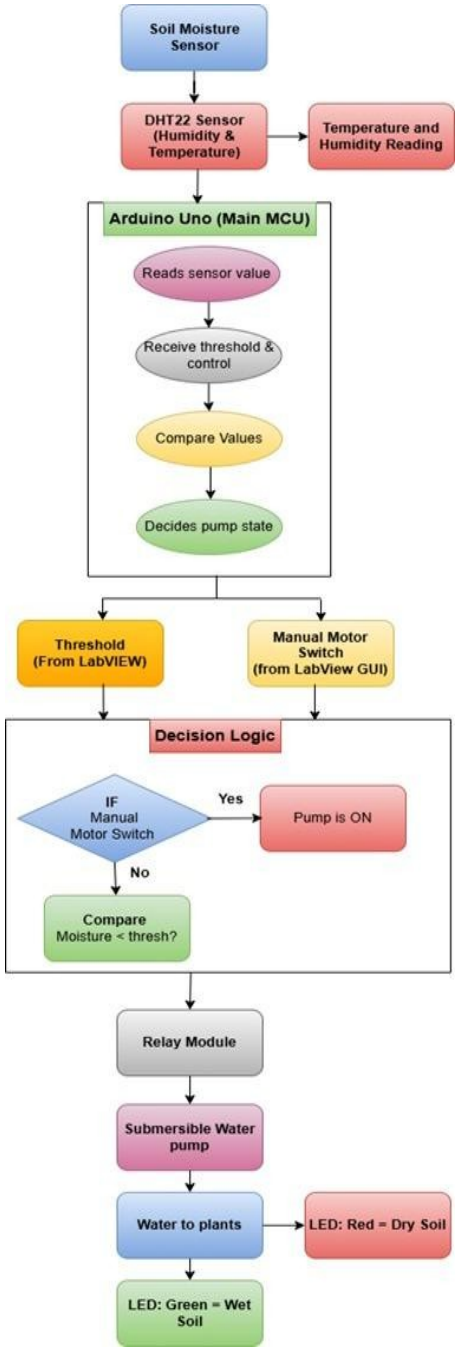

Figure 1: Flow diagram of the smart irrigation system architecture, illustrating the closed-loop process of environmental data acquisition, control and decision-making, and irrigation execution with feedback. Sensor inputs (soil moisture, temperature, and humidity) are processed by the Arduino and LabVIEW interface to determine irrigation needs, which are executed through a relay-controlled water pump with visual feedback to the user.

3. Hardware Components and Experimental Setup

The prototype comprises an Arduino Uno as the central controller, a DHT22 sensor for ambient temperature and relative humidity, an analog soil-moisture probe for substrate water status, a single-channel relay to switch a DC submersible pump, and red/green LEDs for user feedback. The Arduino is powered via USB, which also serves as the serial link to the LabVIEW host for data exchange and user interaction. The relay drives the pump according to the irrigation decision logic, while the LEDs indicate

"dry/irrigate" versus "wet/hold" states to enable at-a- glance status checking in the field [1], [4], [7].

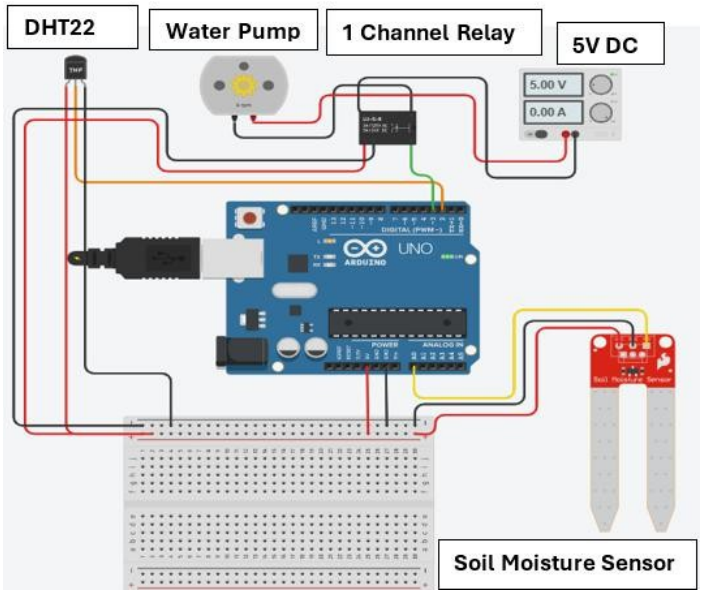

Figure 2: Complete wiring of the Arduino Uno, DHT22, soil-moisture sensor, active-low relay, indicator LEDs, and submersible pump. The schematic reflects the USB power/serial link used in bench testing.

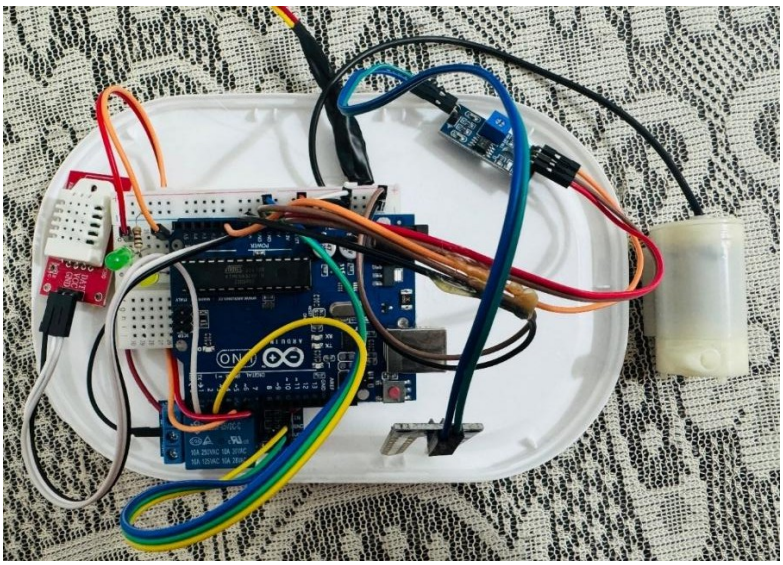

Figure 3: *implementation showing sensor placement, relay–pump connection, and visual indicators used during evaluation.*

Table 1: The materials with roles and rationale for each device used in the prototype.

Component	Description	Justification
Arduino Uno	Microcontroller	Central control unit for data acquisition
DHT22 Temperature/Humidity sensor		Provides accurate environmental data for analysis
Soil Moisture Sensor	Analog sensor	Determines soil dryness and irrigation need
Relay Module	1-channel relay	Electrically isolates and switches water pump
Water Pump	Submersible DC pump	Delivers irrigation water to crops
Red/Green LEDs	Visual indicators	Indicate dry or wet soil status
USB Cable	Communication link	Connects Arduino to PC for serial communication

4. Operating Principle and Control Logic

The system supports automatic and manual irrigation modes. In automatic operation, the Arduino continuously samples the soil-moisture sensor and DHT22, computes a moisture percentage from calibrated dry/wet references, and transmits the current humidity, temperature, and moisture values to LabVIEW. The LabVIEW front panel exposes a user-defined moisture threshold; when the real-time moisture drops below this threshold, a command is sent to the Arduino to energize the relay and run the pump until the threshold is met. Manual override allows the operator to force pump state regardless of the measured moisture, which is useful for maintenance and calibration [1], [4], [6], [7].

4.1 Equation

$$M = \frac{V_{raw} - V_{dry}}{V_{wet} - V_{dey}} \times 100 \quad (1)$$

The system determines the soil moisture percentage by processing the current sensor reading (V_{raw}), the dry calibration value (V_{dry}, such as 740), and the wet calibration value (V_{wet}, such as 330). This calculation is mapped so that the output always falls between 0% and 100%, ensuring valid and reliable data for further processing [3]. At the same time, the DHT22 sensor measures the ambient temperature (T) and humidity (H), and all three values humidity, temperature, and soil moisture percentage are transmitted as a comma-separated string from the Arduino to the LabVIEW interface via the serial port. Within LabVIEW, users can view real-time numeric indicators and graphical plots of these sensor readings. A slider control on the interface allows the user to set a desired soil moisture threshold (M_{thresh}). The system continuously compares the current soil moisture (M) to this threshold. If the measured soil moisture is less than the threshold ($M < M_{\text{thresh}}$), the soil is considered dry, and LabVIEW sends a command to the Arduino to activate the pump (relay ON). If the soil moisture meets or exceeds the threshold ($M \geq M_{\text{thresh}}$), the soil is considered sufficiently moist, and the pump remains off (relay OFF). Additionally, LabVIEW provides a manual override through a toggle button. When this button is activated, it sends a command to the Arduino to force the pump ON or OFF, regardless of the soil moisture reading. This manual feature is particularly useful for maintenance or special irrigation needs.

The Arduino receives these control commands from LabVIEW as single-character inputs: '1' signals a dry condition (pump ON), and '0' indicates a wet condition.

(pump OFF). Based on the received command, the Arduino updates the relay state and the LED indicators accordingly. When the soil is dry and the pump is running, the red LED illuminates; when the soil is adequately moist and the pump is off, the green LED is lit. This integrated approach ensures both automated and user- controlled irrigation, providing clear feedback and efficient water management [2], [7].

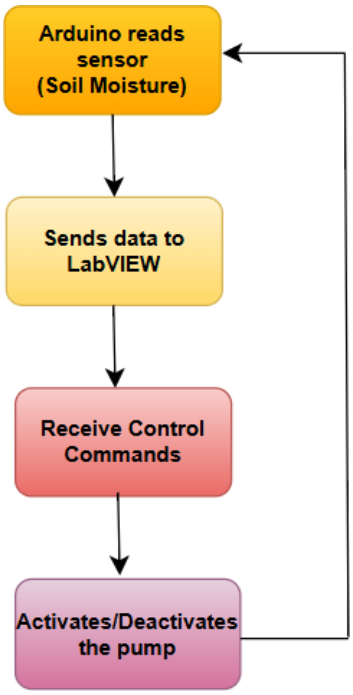

Figure 4: Serial data flow for sensing, threshold comparison, command generation, and relay actuation enabling autonomous irrigation with manual override.

5. Software Implementation

The software stack consists of (i) Arduino firmware for data acquisition, decision execution, and serial I/O, and

(ii) a LabVIEW Virtual Instrument (VI) that provides visualization, thresholding, override control, and bidirectional communication using VISA blocks [1], [4].

5.1 Arduino Firmware

The firmware initializes the DHT library and I/O pins, sets **Serial** at 9600 baud, and defaults the relay to a safe **OFF** state (logic HIGH on an active-low module). In the main loop, it samples humidity and temperature (DHT22) alongside the raw analog moisture value, converts moisture to a percentage using the calibrated endpoints, and streams a comma-separated record ⟨H, T, M⟩ to LabVIEW once per cycle. Concurrently, it listens for the one- byte LabVIEW command and updates the relay and LEDs accordingly [1], [7].

1.1 LabVIEW Virtual Instrument

The LabVIEW 2020 VI displays real-time numeric indicators and trend plots for humidity, temperature, and moisture, and exposes a “Soil Thresh” slider to configure the decision boundary without reflashing firmware. VISA Read parses the CSV stream; Boolean logic compares moisture to the threshold and drives status indicators and the outgoing command via VISA Write. A manual toggle supersedes the automatic branch to force pump state when needed [1], [4], [6].

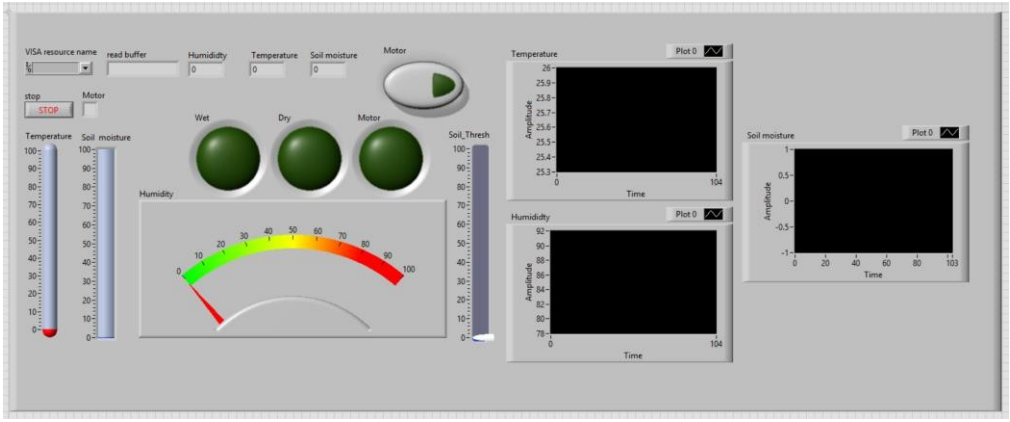

Figure 5: This figure displays the graphical user interface (GUI) of the automated plant watering system, developed using LabVIEW. The interface provides a comprehensive dashboard for monitoring and controlling the system.

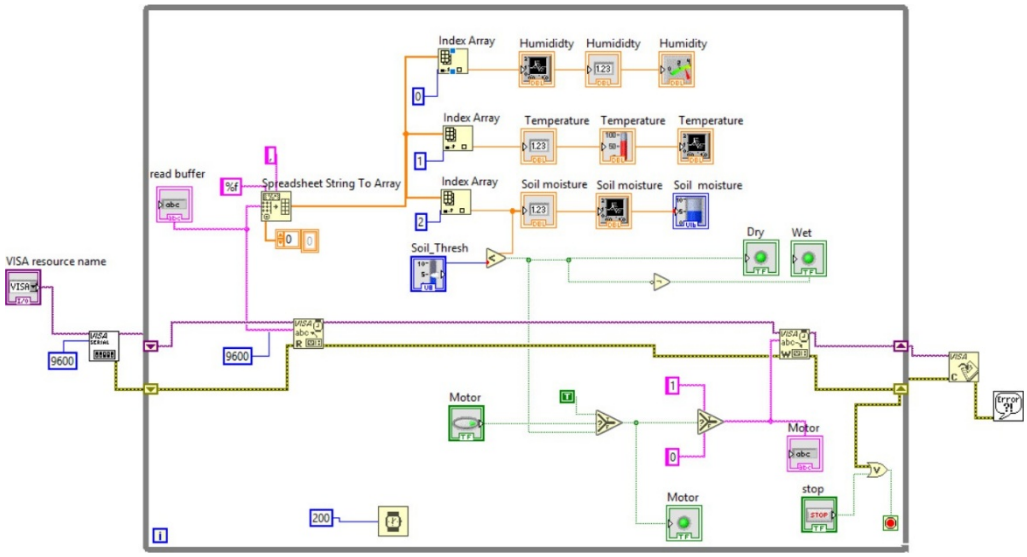

Figure 6: This figure shows the LabVIEW block diagram, which represents the programmatic logic behind the automated plant watering system. The diagram is a visual representation of the code, demonstrating how data flows through the system.

Figure 6 illustrates the LabVIEW control panel (block diagram) that governs the logic and communication flow of the smart irrigation system. This back-end representation outlines how sensor data is received from the Arduino, processed within LabVIEW, and how user inputs influence the control decisions. It also shows how commands are transmitted back to the Arduino to activate or deactivate the irrigation pump. On the left side of the diagram, the VISA resource name and VISA Read blocks initiate and maintain serial communication with the Arduino. Incoming data formatted as comma-separated values representing humidity, temperature, and soil moisture is acquired through the serial buffer. This raw string is converted into an array using the "Spreadsheet String to Array" function, after which individual sensor values are extracted using "Index Array" blocks. These sensor values are routed to both numeric indicators for visualization and logical decision blocks. The "Soil Thresh" slider enables the user to set a desired soil moisture threshold. This threshold is then compared against the real-time soil moisture reading using a comparator. If the current moisture level is below the threshold, the system logic activates the red "Dry" LED and sets the yellow "Motor" indicator ON, triggering irrigation. Conversely, if the moisture level is above the threshold, the green "Wet" LED is illuminated and the motor remains OFF. In addition to automatic control, a manual override switch allows the user to bypass the automated logic and directly control the pump's state. The final command determined either by automatic comparison or manual input is formatted as a single-character string ('1' for pump ON, '0' for pump OFF) and transmitted back to the Arduino via the VISA Write block. The processed sensor readings are also routed to graphical and numeric displays on the LabVIEW front panel, offering real-time environmental monitoring. This block diagram serves as the core engine of the smart irrigation system, enabling closed-loop control that is both autonomous and user-adjustable, thereby enhancing precision and efficiency in agricultural water management.

2. Experimental Results

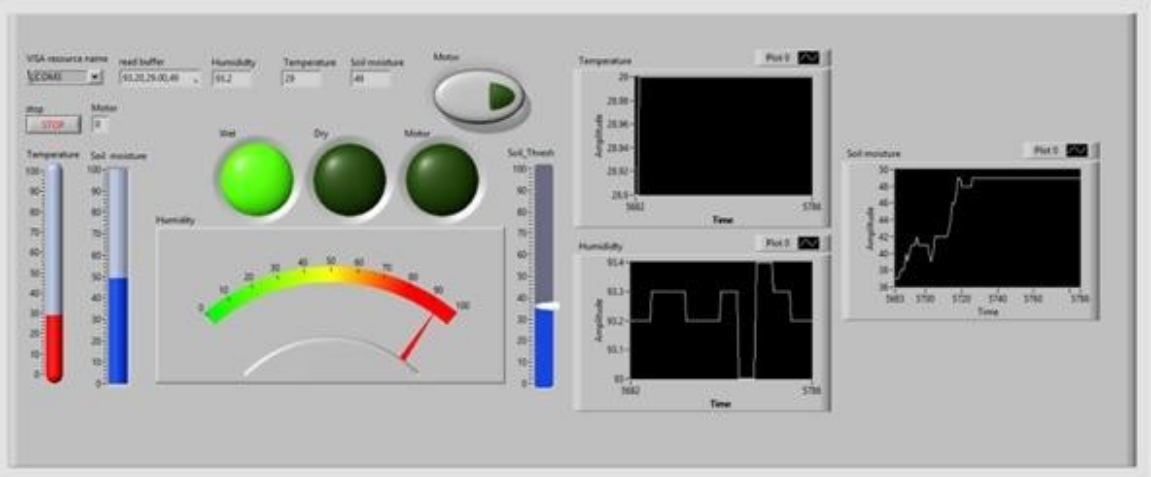

Figure 7: This figure shows the LabVIEW front panel in a live monitoring state, capturing a specific moment during the automated watering process. The interface displays real-time data and system status, demonstrating the functionality of the user interface. (Interface of LabVIEW when the threshold of the moisture is less than the moisture)

In the Figure 5, the current soil moisture percentage displayed both numerically and on the semicircular gauge exceeds the user-defined threshold set using the "Soil Thresh" slider. As a result, the system identifies the soil as adequately moist, and irrigation is not required. The green LED labeled "Wet" is illuminated, while the "Dry" and "Motor" indicators remain off, confirming that the pump is inactive. The interface includes numeric indicators for live temperature, humidity, and soil moisture readings. A semicircular gauge provides a visual representation of the soil moisture level, with the needle positioned in the green (wet) zone. The manual threshold slider allows users to dynamically adjust the moisture threshold. Additionally, real-time plots on the right-hand side of the GUI display trends in temperature, humidity, and soil moisture, supporting data-driven decision-making. The top left section displays VISA

communication status, confirming active data exchange between LabVIEW and Arduino.

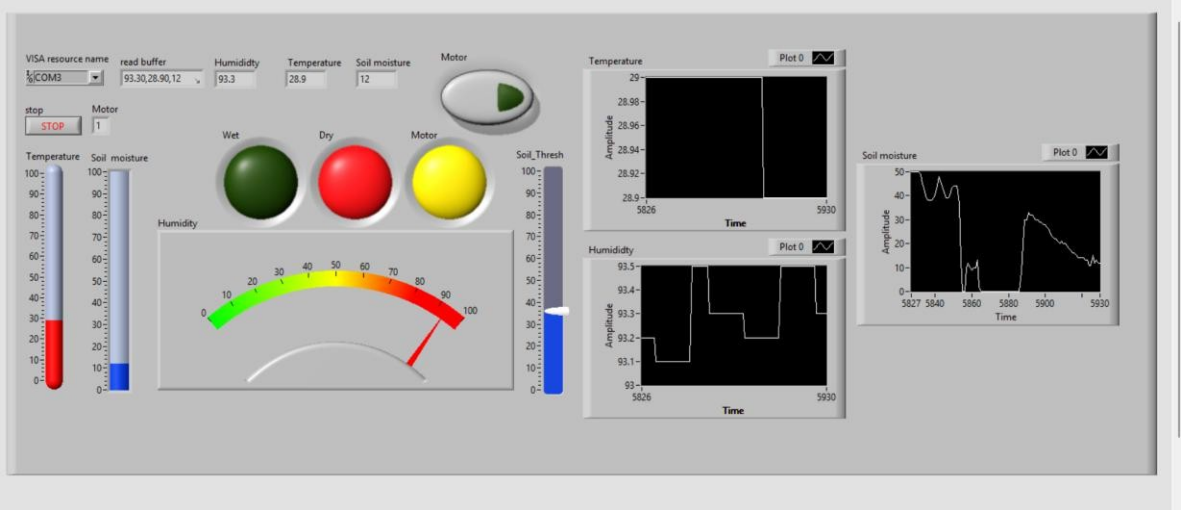

Figure 8: This figure shows a critical moment on the LabVIEW front panel where the automated system has activated the pump.

Figure 8 presents the LabVIEW graphical user interface (GUI) of the smart irrigation system operating in a scenario where the soil moisture level has fallen below the user-defined threshold. In response, the system has automatically identified the soil as dry and activated the irrigation pump to initiate watering. The interface highlights this condition through multiple visual indicators. The red LED labeled "Dry" is illuminated, indicating that the soil moisture is insufficient. Simultaneously, the "Motor" LED (yellow) is on, confirming that the pump has been triggered to irrigate the soil. The green "Wet" LED remains off, signifying that the soil has not yet reached adequate moisture levels. The semicircular soil moisture gauge shows the needle positioned in the red (dry) zone, visually reinforcing the low soil moisture condition. Numeric indicators display the real-time values of temperature, humidity, and soil moisture, with the moisture reading clearly below the threshold set by the "Soil Thresh" slider. The slider's position above the current soil moisture reading confirms the trigger condition for automatic irrigation. To the right, real-time plots of temperature, humidity, and soil moisture allow the user to observe recent environmental trends and system behavior. Additionally, the motor status indicator at the top right confirms that the pump is actively running. This figure effectively demonstrates the system's automatic control capability: when soil moisture falls below the defined threshold, the system autonomously activates irrigation. The GUI provides clear and immediate feedback, ensuring efficient and responsive water management without the need for manual intervention.

The implemented smart irrigation system was rigorously tested under controlled environmental conditions to evaluate its functionality, reliability, and performance [1], [4]. During the testing phase, the system consistently responded to real-time soil moisture readings. When the soil moisture percentage fell below the user-defined threshold, configured via the LabVIEW interface, the Arduino successfully activated the relay to turn on the water pump [1], [4]. Once the soil moisture reached an adequate level, the system automatically deactivated the pump, demonstrating precise and repeatable control [2], [6].

The manual override feature, accessible through LabVIEW, functioned as intended, allowing the user to bypass automatic control and directly operate the pump [1], [4]. This feature proved valuable during calibration or in response to unexpected environmental changes [6].

Real-time serial communication between the Arduino Uno and the LabVIEW GUI was stable and highly responsive. Sensor data, including temperature, humidity, and soil moisture percentage, were continuously transmitted and displayed on the LabVIEW front panel through numeric indicators and

graphical plots [7]. The moisture threshold could be adjusted dynamically via slider control, and the system promptly adapted its irrigation behavior according to the updated settings [1], [4].

Visual feedback through LED indicators provided clear operational status: the red LED illuminated when soil moisture was low and irrigation was active, while the green LED indicated sufficient moisture levels and that the pump was off [1], [4].

Compared to conventional time-based irrigation methods, the smart irrigation system demonstrated a substantial reduction in water usage [2], [5]. By irrigating only when necessary, based on real-time soil conditions, the system maintained optimal moisture levels, promoting healthier plant growth and improving overall resource efficiency [3], [5].

The setup operated reliably throughout testing and shows strong potential for scalability. Future extensions may include multi-zone irrigation, integration with additional environmental sensors, cloud-based data logging, and remote system access [1], [4], [6].

3. Discussion

The implementation of the smart irrigation system in this project clearly demonstrates the benefits of integrating embedded systems with virtual instrumentation to automate and optimize agricultural water management. Using the Arduino Uno as the core processing unit for environmental data acquisition and actuator control ensures real- time responsiveness and straightforward deployment [1], [4]. The LabVIEW-based graphical user interface (GUI) enhances user experience by enabling intuitive interaction, real-time visualization of sensor data, threshold configuration, and manual pump control [1], [4]. This combination of hardware and software provides a flexible,

user-configurable platform that bridges the gap between traditional irrigation practices and modern precision agriculture [2], [6].

A key achievement of the system is its ability to autonomously regulate irrigation based on soil moisture levels, ensuring water is used only when necessary. This prevents over-irrigation, which can lead to nutrient leaching and root diseases, as well as under-irrigation, which can cause plant stress and reduced yields [3], [5]. The LabVIEW interface allows users to dynamically set and adjust soil moisture thresholds, adapting the irrigation response to varying crop types, soil conditions, and climatic variations [1], [4]. This adaptability makes the system suitable for small and medium-scale farms where resource optimization is critical [6].

The system features dual operating modes: automatic mode, which minimizes user intervention while maintaining efficient irrigation, and manual mode, which provides flexibility for field testing, calibration, or specific user preferences [1], [4]. LED indicators offer immediate status feedback, allowing non-technical users to interpret system behavior easily. Additionally, the modular design facilitates future expansion, such as integrating additional sensors or supporting multi-zone irrigation [2], [5].

However, several limitations were observed during practical testing. The current implementation relies on wired serial communication between the Arduino and LabVIEW interface, which restricts deployment in large or remote fields where wireless access is preferable [1], [4]. Moreover, the system lacks data logging and historical analysis capabilities, limiting long-term environmental monitoring and irrigation optimization [5], [7]. There is also no fault notification mechanism for sensor errors or pump failures, potentially affecting reliability [7].

Despite these constraints, the system provides a robust and scalable solution that can serve as a foundation for advanced smart farming applications. Its affordability and ease of implementation make it particularly relevant for developing regions with limited access to high-end commercial systems [6].

Future enhancements can significantly increase system effectiveness, scalability, and real-world applicability. Integration of wireless communication modules such as Wi-Fi (ESP8266/ESP32), GSM (SIM800L), or LoRa would remove physical tethering and enable remote monitoring and control via smartphones or web dashboards [1], [4]. Cloud-based data storage and visualization platforms (e.g., ThingsBoard, Firebase, or Blynk) could archive sensor data, track trends, and support predictive irrigation models using machine learning algorithms [2], [5]. Multi-zone irrigation support, additional environmental sensors (pH, light, rain), and AI-based decision- making would allow more precise, automated water management [3], [6]. Finally, implementing error detection and notification systems, such as SMS alerts or LED fault indicators, would enhance reliability by alerting users to sensor malfunctions, communication failures, or pump issues [7]. These improvements would help evolve the system toward an industry-grade solution suitable for varying environmental conditions.

4. Conclusion

This paper presented the design and development of a smart irrigation system that effectively combines Arduino- based hardware with a LabVIEW-based user interface to automate and optimize irrigation processes. The system monitors real-time soil moisture, temperature, and humidity data to intelligently control a relay-operated water
pump, reducing water wastage while maintaining optimal soil conditions. User-defined thresholds and manual override controls enhance flexibility and usability, empowering farmers to make informed irrigation decisions. Experimental validation confirmed the system's reliability, responsiveness, and positive impact on water conservation and plant health. With its modular and scalable architecture, the proposed solution offers strong potential for adaptation in various agricultural settings. Future enhancements such as wireless connectivity and cloud integration could further evolve the system into a comprehensive smart agriculture platform, contributing to sustainable and precision farming practices.

References

[1] P. S. Aswale, S. Sali, S. Zarole, and P. Patil, "Automatic irrigation control system based on LabVIEW Arduino interfacing," *Int. J. Innovative Res. Technol.*, vol. 4, no. 3, pp. 261–264, 2018. [Online]. Available: https://ijirt.org/publishedpaper/IJIRT143549_PAPER.pdf

[2] S. Barkunan, V. Bhanumathi, and R. Sethuram, "Smart sensor for automatic drip irrigation system for paddy cultivation," *Comput. Electron. Agric.*, vol. 165, p. 104968, 2019. [Online]. Available: https://doi.org/10.1016/j.compag.2019.104968

[3] G. J. Gaskin and J. D. Miller, "Measurement of soil water content using a simplified impedance measuring technique," *J. Agric. Eng. Res.*, vol. 63, no. 2, pp. 153–160, 1996. [Online]. Available: https://doi.org/10.1006/jaer.1996.0016

[4] M. N. Gogoi, "An automated garden irrigation system: Controlled and monitored via Arduino and LabVIEW," *Int. J. Comput. Sci. Eng.*, vol. 6, no. 5, pp. 982–987, 2018. [Online]. Available: https://ijcseonline.isroset.org/pub_paper/195-IJCSE-03599.pdf

[5] M. Montesano, A. Parisi, P. Santamaria, and F. Serio, "Development of a smart irrigation monitoring system employing the Internet of Things," *J. Hydroinform.*, vol. 26, no. 12, pp. 3224–3240, 2024. [Online]. Available: https://doi.org/10.2166/hydro.2024.123

[6] S. Rathika, T. Ramesh, V. Priyadharshini, A. Suriya Prasanth, and P. Shanmugapriya, "Automation in irrigation – A review," *Int. J. Curr. Microbiol. Appl. Sci.*, vol. 9, no. 12, pp. 2974–2982, 2020. [Online]. Available: https://doi.org/10.20546/ijcmas.2020.912.352

[7] W. Whisnumurti Adhiwibowo, A. Firman Daru, and A. Maulana Hirzan, "Temperature and humidity monitoring using DHT22 sensor and Cayenne API," *Transformatika*, vol. 17, no. 2, pp. 209–214, 2020. [Online]. Available: https://journals.usm.ac.id/index.php/transformatika/article/viewFile/1820/1348

Circular Economy Practices and Challenges in the Industries of Bangladesh: A Case Study

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ABSTRACT

Circular economy (CE) is a concept that represents a paradigm shift from the conventional linear economic model—characterized by the "take-make-dispose" approach—toward a more sustainable framework grounded in the principles of "reduce-reuse-recycle." This transition emphasizes enhanced resource efficiency and the minimization of waste generation. While regions such as Europe and North America have made significant progress in integrating circular economy principles, Bangladesh continues to operate largely within a linear economic framework, exhibiting low levels of recycling and substantial waste accumulation. Circular economy awareness and implementation remain limited across most industrial sectors in Bangladesh, with only a few industries demonstrating preliminary engagement. Nonetheless, the country possesses considerable untapped potential for CE adoption. To investigate the current status and practices of the circular economy in Bangladesh, this study employed semi-structured interviews with key stakeholders across relevant sectors. Additionally, secondary data sources, including annual reports and industry publications, were analyzed to complement and triangulate the primary findings. In this paper, circular economy practices and challenges in a large home appliance manufacturing company of Bangladesh are explored and beneficial guidelines are suggested.

KEYWORDS: *Circular Economy, Home Appliance Industry, Sustainability.*

INTRODUCTION

The circular economy (CE) has emerged as a transformative framework for advancing the United Nations Sustainable Development Goals (SDGs). At its core, the CE emphasizes resource efficiency, waste minimization, and the reintegration of materials into production cycles. The global shift from the traditional linear economic model—characterized by the "take-make-dispose" paradigm—to a circular one has garnered widespread attention due to its potential to reduce environmental degradation and foster economic resilience [1–5]. In regions such as Europe and North America, circular economy principles have been increasingly embedded within industrial operations, particularly in the manufacturing and consumer goods sectors, where notable progress has been observed. However, despite growing international momentum, the implementation of CE practices in Bangladesh remains limited and underexplored [6].

Bangladesh continues to follow a predominantly linear economic model, with limited recycling initiatives and a high rate of waste generation. This prevailing approach exacerbates pressure on the country's already constrained natural resources and contributes to escalating environmental challenges. The relatively low engagement with CE frameworks within the national context contrasts with foreign developments and highlights the necessity of evaluating CE's potential applicability and benefits within Bangladesh.

This paper explores the current state of circular economy practices in a a large home appliance manufacturing company of Bangladesh, namely Walton. It seeks to assess the extent to which CE

principles have been integrated into their operational models, and propose potential circular practices that could be adopted to enhance sustainability outcomes.

A mixed-methods approach was adopted to address these research questions, combining quantitative analysis with qualitative insights gathered through semi-structured interviews with industry stakeholders and experts. This methodological design facilitates a comprehensive understanding of the operational, economic, and environmental dimensions of CE implementation within the selected industries, offering a holistic overview of Bangladesh's current positioning in the circular economy discourse.

LITERATURE REVIEW

Circular Economy (CE) practices in Bangladesh are currently limited in scope and are predominantly interpreted as recycling activities within a few sectors. The broader adoption of CE principles faces several critical challenges, including technological constraints, inadequate policy frameworks, and low levels of public awareness and participation. Nonetheless, the implementation of CE strategies holds the potential to yield substantial environmental benefits—such as improved waste management and reduced pollution—as well as economic gains through enhanced resource efficiency and job creation [6].

The shipbreaking industry in Bangladesh plays a significant role in the national economy by supplying essential raw materials such as steel and iron, which support local construction and manufacturing sectors. This industry contributes to reducing reliance on costly imports and sustains a large number of jobs across the supply chain. Emerging technologies, such as Deep Neural Networks (DNN), are being explored to enhance efficiency in estimating recoverable materials from dismantled ships, thereby reducing processing time and improving profitability. Despite these economic advantages, the sector has drawn substantial criticism due to its adverse environmental impacts and poor labor conditions. Ahasan et al. [7] highlight the need to strike a balance between economic imperatives and the environmental and social responsibilities inherent to CE frameworks.

Understanding and leveraging the key drivers of CE adoption can inform more effective strategic planning and operational decision-making. Moreover, investment in advanced technologies and circular processes is crucial for aligning industrial practices with sustainability goals [8].

To date, research on circular economy practices in Bangladesh remains scarce, particularly in comparison to the extensive body of literature produced in Western contexts. This study seeks to address this research gap by investigating CE practices and potentials within the Bangladeshi industrial context with special focus on home appliance industry, thereby contributing to the growing discourse on sustainable economic development in the Global South.

METHODOLOGY

This study employs semi-structured interviews and secondary data analysis to examine Circular Economy (CE) practices The integration of qualitative and analytical methods allows for a comprehensive assessment of both the current state and future potential of CE implementation in Bangladesh.

Primary data were collected through semi-structured interviews conducted with key executives from Walton. The number of such interviews was two and duration of each session was half an hour. The semi-structured interview format was deliberately chosen for its flexibility, allowing for open-ended responses and enabling interviewees to elaborate on their experiences, challenges, and strategic insights related to sustainability and CE. Interviewees were selected based on their direct involvement in sustainability or operational initiatives within their respective organizations. While a common thematic structure guided all interviews, industry-specific questionnaires were developed to capture sectoral nuances, with substantial overlap in core questions to ensure consistency and comparability.

In addition to primary data, secondary sources—including company reports, industry publications, and policy documents—were analyzed to contextualize findings and triangulate data obtained through interviews. These sources offered valuable insights into organizational performance, sustainability reporting, and existing CE-related initiatives, where available.

FINDINGS

Following the completion of the semi-structured interviews, the findings were systematically organized and presented in a tabulated format for clarity and comparative analysis. Table 1 summarizes the key insights obtained from the questionnaire-based interviews conducted with Walton.

Table 1. Key Finding from Walton

Material	**Waste Stream**	**Circular Economy Practice**	**Outcome**
Aluminum	100%	Melts and reuses aluminum for LED bulb parts	Reduced reliance on virgin aluminum, energy savings
Packaging and shield material	Sheet metal safety guards	Recycles materials, reduces landfill waste	Resource recovery, promotes a closed- loop system
Plastic	100%	Recycles for various applications	Eliminates plastic waste, creates new products from recycled material
Dining system	Waste	Biogas plant for electricity production	Generates renewable energy from organic waste, reduces reliance on fossil fuels
Burnable materials		Incineration boiler	Energy recovery from waste, avoids landfill disposal
Copper	100%	Makes Walton cable	Reduced copper mining need, minimizes environmental impact
Metal plate wastage		Makes lift counterweight	Utilizes waste material for new application, avoids additional production
Machine making section		Makes their machines	Increases self-reliance, reduces external resource dependence

From the interviews and secondary data analysis, it is found that Walton is one of the leading electronics and appliance manufacturing companies in Bangladesh, with a strategic focus on waste reduction and the integration of sustainability into its operational framework. Table 1 provides a concise overview of Walton's operational practices, based on data obtained through semi-structured interviews. In addition to material recycling, Walton has adopted several innovative waste management strategies. Notably, organic waste generated from the company's dining facilities is processed to produce biogas, which serves as a source of renewable energy and helps reduce dependence on fossil fuels. The company operates through a vertically integrated supply chain, which facilitates greater control over resource use and waste minimization. In instances where machine components become non-functional, Walton prioritizes the reuse of parts from obsolete equipment. Furthermore, the company engages in systematic repair and upgrading of machinery and components to maximize resource efficiency and extend the lifespan of its products. However, as a leading company in Bangladesh, it has

the potential to take further initiatives. These may include establishing electronic waste collection facilities through its own retail outlets and increasing investment in public awareness campaigns, among other measures.

CONCLUSION

The research mentioned in the paper demonstrates that, although awareness and implementation of Circular Economy (CE) practices in Bangladesh remain limited, the country holds considerable potential for CE adoption. Despite facing several challenges—including a lack of advanced technological infrastructure, inadequate policy support, and low levels of public awareness—Bangladesh has the opportunity to improve resource efficiency and mitigate environmental degradation. These improvements can, in turn, generate long-term economic benefits and support the nation's broader sustainability goals. This study highlights the urgent need for governmental support, strategic investment in technology, and public engagement to facilitate the transition toward a more circular economic model. The findings underscore the critical role that CE adoption can play in aligning Bangladesh with the United Nations Sustainable Development Goals (SDGs) and enhancing national economic resilience. However, this study is not without limitations. The most significant constraint was the limited sample size. Future research should aim to expand the scope of inquiry by including small and medium-sized enterprises (SMEs), which constitute a large segment of the Bangladeshi economy. Moreover, the development of a policy-oriented research framework would be beneficial for identifying practical interventions and regulatory mechanisms to support CE implementation. Continued research in this area will offer deeper insights and guide the formulation of effective, context-specific strategies for mainstreaming circular economy practices in Bangladesh, especially in home appliance sector.

REFERENCES

1. Ciccullo, F., Cagliano, R., Bartezzaghi, G., & Perego, A. (2021). Implementing the circular economy paradigm in the agri-food supply chain: The role of food waste prevention technologies. *Resources, Conservation and Recycling, 164*, 105114. https://doi.org/10.1016/j.resconrec.2020.105114
2. Esposito, B., Sessa, M. R., Sica, D., & Malandrino, O. (2020). Towards circular economy in the agri-food sector: A systematic literature review. *Sustainability, 12*(18), 7401. https://doi.org/10.3390/su12187401
3. Chiaraluce, G., Bentivoglio, D., & Finco, A. (2021). Circular economy for a sustainable agri-food supply chain: A review for current trends and future pathways. *Sustainability, 13*(16), 9294. https://doi.org/10.3390/su13169294
4. Opferkuch, K., Walker, A. M., Roos Lindgreen, E., Caeiro, S., Salomone, R., & Ramos, T. B. (2023). Towards a framework for corporate disclosure of circular economy: Company perspectives and recommendations. *Corporate Social Responsibility and Environmental Management, 30*(6), 2457–2474. https://doi.org/10.1002/csr.2453
5. Krstić, M., Elia, V., Agnusdei, G. P., De Leo, F., Tadić, S., & Miglietta, P. P. (2024). Evaluation of the agri-food supply chain risks: The circular economy context. *British Food Journal, 126*(1), 113–133. https://doi.org/10.1108/BFJ-01-2023-0024
6. Ahmed, Z., Mahmud, S., & Acet, H. (2022). Circular economy model for developing countries: Evidence from Bangladesh. *Heliyon, 8*(5), e09446. https://doi.org/10.1016/j.heliyon.2022.e09446
7. Ahasan, S., Zaman, F. N., & Ahmed, T. (2021, August 2). Perspective of circular economy in Bangladesh: A comprehensive review towards ship demolition industry. In *Proceedings of the 4th European International Conference on Industrial Engineering and Operations Management (IEOM 2021)* (pp. 2375–2385).

8. Mehmood, A., Ahmed, S., Viza, E., Bogush, A., & Ayyub, R. M. (2021). Drivers and barriers towards circular economy in agri-food supply chain: A review. *Business Strategy and Development, 4*(4), 465–481. https://doi.org/10.1002/bsd2.168
9. Saaty, T. L., & Vargas, L. G. (1991). *Prediction, projection and forecasting*. Springer. https://doi.org/10.1007/978-94-015-7952-0
10. Bartholomew, D. J. (1984). Scaling binary data using a factor model. *Journal of the Royal Statistical Society: Series B (Methodological), 46*(1), 120–123. https://doi.org/10.1111/j.2517-6161.1984.tb01284.x