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EDITORIAL NOTE

The Evolving Role of Science, Engineering and Technology in an AI-Driven World

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Artificial Intelligence (AI) has become a powerful factor that changes the course of development in science, engineering, and technology. The emergence and rapid growth of the field of AI have resulted in significant modifications in the tools and technologies used by scientists, engineers, and technicians in the industry. Moreover, AI is a driving factor that alters how researchers approach challenges, process information and find solutions to them, thus becoming a crucial part of modern innovations and achievements in different industries.

As far as the field of science is concerned, AI helps to process increasingly complex amounts of data much more efficiently than was possible before [1]. Nowadays, scientists collect an enormous amount of data during their experiments, observations and even simulations that cannot be analyzed with the help of traditional methods. As a result, the involvement of AI allows researchers to analyze these datasets, find specific patterns and make predictions based on the information collected. Therefore, there is no doubt that AI significantly contributes to the advancements across a wide range of fields, including medicine, environmental research, climatology, agriculture, material science, engineering, transportation, education, manufacturing and many other scientific and technological domains [2].

It is crucial to understand that AI should not be seen as an alternative to established scientific methods. AI is a technological instrument that augments the effectiveness and applicability of conventional scientific methodologies by adding a data-driven dimension to research. Thus, scientific reasoning, human knowledge and analytical thinking are still indispensable aspects of any scientific endeavor.

The purpose of AI is to facilitate the process of scientific inquiry by improving its effectiveness, scale and rigor, allowing researchers to obtain novel findings and insights.

From an engineering perspective, AI contributes to the ongoing shift from traditional engineering designs towards more intelligent, flexible and autonomous systems [3]. In modern engineering applications, there is an increased demand for systems capable of functioning in unpredictable circumstances, where continuous decision-making, real-time learning and adaptation become vital factors. Similar developments can be observed in robotics, autonomous transportation, industrial automation, intelligent manufacturing and cyber-physical systems. Here, in addition to applying advanced engineering practices, system designers need to consider the ability of engineering systems to acquire knowledge and behave intelligently within dynamically changing environments.

On the other hand, the convergence of AI with new technologies including internet of things (IoT), cloud computing, edge computing, and advanced communication systems is giving rise to intelligent and highly inter-connected ecosystems [4]. This can be seen in the form of applications like smart cities, intelligent transportation systems, digital health care platforms and smart grids. Such a combination has the ability to significantly enhance productivity, sustainability, efficiency and quality of life. However, at the same time, it poses many challenges relating to security, privacy, dependability, accountability and ethics of the use of advanced technologies.

It is important to appreciate in this regard that the responsibilities of the science, engineering, and technology community go well beyond the purely technical aspects involved here.

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Not only do we need researchers and engineers who can build state-of-the-art technologies, we also require professionals with the expertise to accomplish the tasks ethically and responsibly. This will involve not only technical skills, but also inter-disciplinary thinking and critical perspectives. Therefore, universities and research communities can play a pivotal role in shaping future professionals equipped with such skills.

The Journal of Emerging Science, Engineering and Technology (JESET) provides an important platform to support this direction. With its encouragement of high-quality and multidisciplinary research, the platform can provide avenues for fruitful scholarly discussion that could result in beneficial innovation for both industry and society. In a world that is becoming more and more AI-driven, platforms like JESET should play a critical role in ensuring that research in technology takes an ethical turn towards benefiting humanity.

As the first edition of the Journal of Emerging Science, Engineering and Technology (JESET), this edition represents a significant landmark in the effort by the journal to serve as an excellent multi-disciplinary forum for the sharing of scientific, engineering, and technological information. This journal seeks to encourage academic discussions, stimulate innovation, and facilitate the creation of knowledge that is beneficial to industry, society, and humankind.

The articles presented in this edition feature a varied array of emerging topics in science, engineering, and technology. This edition features articles that capture the modern-day trends and innovations being practiced in different fields of study. The current edition features sixteen research papers, one editorial paper, and one correspondence paper.

The Editorial Board would like to take this opportunity to express its gratitude to all who made the publication of this issue possible. Our gratitude goes out to the authors for entrusting their scholarly contributions to JESET, the reviewers for the time, effort, and expertise they have invested in ensuring the quality of published articles, and members of the Editorial Board and Advisory Board for their advice and guidance during the preparation of this issue. The contribution of the typesetting team and the administrative team deserves special mention here for their dedication and professionalism which made the publication of this issue possible. Finally, we gratefully acknowledge the encouragement and support provided by the institutional leadership of Sri Lanka Technology Campus (SLTC), whose vision and commitment to research excellence have been fundamental to the establishment of JESET.

It is our expectation that the contributions made in this issue will help initiate future research and interdisciplinary studies towards the advancement of science, engineering, and technology.

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CORRESPONDANCE

“Harvest Now, Decrypt Later”

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Abstract: Due to the increased threat of “Harvest Now, Decrypt Later” attacks, Post-Quantum Cryptography (PQC) is moving from theoretical research to real-world implementations. By 2024, the National Institute of Standards and Technology (NIST) finalized the first set of quantum safe cryptographic algorithms. At present, governments across the world are developing plans for mandatory PQC migration, typically targeting timelines between 2030 and 2035. This letter investigates key challenges in transition to PQC, ongoing standardization efforts by NIST and other organizations, and national policies of proposed migration strategies.

Keywords: PQC, NIST, ML-KEM, ML-DSA, FIPS

INTRODUCTION

The advent of quantum computing poses a significant threat to traditional cryptographic algorithms, including RSA, Diffie-Hellman, and Elliptic Curve Cryptography, due to the capabilities of quantum algorithms like Shor’s algorithm. PQC has emerged to address these challenges. Lattice-based cryptography (LBC) has emerged as a prominent candidate for PQC [1].

LBC, underpinned by hard mathematical problems like Learning with Errors (LWE) and Ring-LWE (RLWE), offers robust security against quantum and classical adversaries. LBC-based PQC can be used for access control in addition to the encapsulation and signature schemes. Ciphertext-Policy Attribute-Based Encryption (CPABE) has become a critical tool for enabling fine-grained access control in data-sharing scenarios, such as secure cloud storage and IoT. While existing CP-ABE implementations rely on bilinear pairings vulnerable to quantum attacks, lattice-based CPABE schemes provide a quantum-resistant alternative. Despite their potential, these schemes face challenge in Computational efficiency, collusion resistance, and implementation correctness.

Recent work by the author and collaborators [2] presents a detailed mathematical breakdown of one of the states of the art (SOTA) lattice-based CP-ABE schemes and a novel correctness proof for the same scheme.

This letter discusses the key challenges associated with transition to PQC algorithms, standardization efforts and migration strategies of selected countries.

KEY CHALLENGES IN PQC TRANSITION

There are several challenges in the transition to PQC including incompatibility with legacy systems to performance and resource demands of proposed PQC algorithms. This section summarizes key challenges faced by the researchers, developers, service providers and policy makers.

"Harvest Now, Decrypt Later" Threat: The urgency of a fast-tracked transition to PQC is driven by the risk that adversaries may harvest encrypted data today, with the aim to decrypt them later using quantum computers when they are widely available. Some researchers have also suggested that nation-state actors could possess more advanced quantum capabilities than publicly disclosed, although such claims remain unverified. In February 2025, Microsoft announced a major quantum computing breakthrough with the introduction of Majorana 1, the world’s first Quantum Processing Unit (QPU) powered by a topological core. According to the announcement, this new chip uses a novel state of matter to create smaller, stable, and highly resilient qubits, aiming for a million-qubit system within 10 years. These developments reinforce the need for a timely transition to PQC, with researchers, standardization bodies, and different governments across the world actively working toward secure and scalable solutions [3].

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RESOURCE CONSTRAINTS AND PERFORMANCE LIMITATIONS

The proposed PQC algorithms generate large key sizes, signatures and cipher texts in comparison to traditional algorithms such as RSA or ECC. This results in increased computational requirements, memory usage, network latency and storage overhead. Tables 1, 2 and 3 present the key sizes of the proposed PQC algorithms. In contrast, traditional cryptographic algorithms generate significantly smaller keys and cipher texts (e.g., public key sizes for RSA-3072 and ECDSA P-256 are approximately 384 bytes and 32 bytes respectively) which are considerably smaller than those shown in the Tables. Consequently, PQC algorithms introduce additional constraints when deployed in resource constrained environments such as IoT and sensor networks. These differences may also create compatibility challenges with legacy systems, where some IoT or Industry Control Systems (ICSs) may require hardware upgrades to support PQC.

Table 1: Cryztals-Kyser Key Sizes ML-KEM (Module Lative Based Key Encapsulation Mechanism)

Algorithm	Encapsulation Key size	Decapsulation key size	Ciphertext size
ML-KEM 512	800	1632	768
ML-KEM 768	1184	2400	1088
ML-KEM 1024	1568	3168	1568

Table 2: Crystals- Dilithium Key Sizes - ML-DSA (Module-Lattice-Based Digital Signature Standard)

Algorithm	Private Key size	Public key size	Signature size
ML-DSA-44	2560	1312	2420
ML-DSA-65	4032	1952	3309
ML-DSA-87	4896	2592	4627

Crypto Agility Requirement and validation bottlenecks:

Similar to Shor's algorithm, new quantum threats will emerge in the future. Therefore, organizations and standardization bodies should design processes and systems that enable rapid evaluation, standardization, validation and deployment of new algorithms if current PQC options are compromised. At present, validation of proposed PQC algorithms takes considerable time, which further delays their deployment in real-world applications.

Table 3: Sphincs+ - Slh-Dsa (Stateless Hash-Based Signature Standard)

Algorithm	Security Category	Public Key size	Signature Size
SLH-DSA-SHA2-128s SLH-DSA-SHAKE-128s	1	32	7856
SLH-DSA-SHA2-192s SLH-DSA-SHAKE-192s	3	48	16224
SLH-DSA-SHA2-256s SLH-DSA-SHAKE-256s	5	64	29792

Standardization Efforts (NIST & International)

NIST has led the standardization efforts of quantum safe cryptographic algorithms. The effort began in November 2017 and resulted in the first set of standards finalized in 2024: FIPS 203 (ML-KEM/Kyber for general encryption), FIPS 204 (ML-DSA/Dilithium for signatures), and FIPS 205 (SLH-DSA/SPHINCS+ for signatures) towards end of 2024 [4]. NIST continues to evaluate the security and performance of additional algorithms. To this end it has selected the Hamming Quasi-Cyclic key encapsulation mechanism (HQC) for encryption and is working on FALCON digital signature scheme (FIPS 206) as alternatives to the primary lattice-based methods. The focus has now shifted toward implementing these standardized algorithms in sectors such as cloud services, telecommunications and finance. While NIST leading the PQC standardization activities other international bodies/organizations (IETF, ISO/IEC, ETSI, ITU-T) and national agencies (e.g., NCSC-UK) are actively working to facilitate the migration by finalizing guidelines, protocols and standards. For instance, Internet Engineering Task Force (IETF) is working on updating the internet protocols such as TLS and IKEv2 to accommodate PQC algorithms.

Policies of Different Countries

Many governments across the world are moving beyond awareness and advisory stages towards PQC implementations, auditing and compliance. For instance, the United States is working to adopt PQC algorithms standardized by the NIST across critical systems and services with migration targets extending into the early 2030s. To this end, several policy documents and guidelines have been published, including the executive

orders EO-14144, EO-14306, and the memorandum by the Department of War on "Preparing for Migration to Post-Quantum Cryptography", Nov 2025. In contrast, China is pursuing the development and adoption of its own PQC algorithms and has recently issued a call for submissions of new PQC candidates, with a timeline from 10 Oct 2025 to 30 June 2026. Within the European Union (EU), member states are evaluating both NIST and other alternative PQC algorithms. For instance, countries including Germany and Netherland have shown interest in schemes such as FrodoKEM alongside NIST selected algorithms. The EU is also working toward establishing a coordinated PQC roadmap for member states by 2026.

Sri Lanka's PQC Transition

Following the urgent need to address the threats faced by emerging quantum computers, many countries including Sri Lanka are in the process of evaluating and implementing PQC algorithms across critical platforms and service sectors. The Sri Lanka Computer Emergency Response Team (SLCERT) has launched a PQC initiative aimed at safeguarding Sri Lanka's Digital Public Infrastructure (DPI) from potential quantum enabled threats [5]. The completion of migration targets by 2035 is mandatory to ensure long-term security and interoperability. The global systems (e.g., TLS) are gradually cooperating PQC algorithms and lack of adoption may lead to security vulnerabilities and potential compatibility challenges.

Migration Strategy

Migration is being urged now, with a target of 2030 for deprecating legacy systems and 2035 for full transition. The migration strategy can be implemented through the following steps:

- Inventory & Discovery: Identify all systems that rely on vulnerable public-key cryptography (e.g., RSA/ECC).
- Hybrid Deployment: Use both classical and quantum-safe algorithms together to guard against unforeseen weaknesses in newly developed PQC algorithms.
- PKI Upgrades: Prioritizing upgrading of Public Key Infrastructure (PKI), including code-signing and digital certificates, to support PQC.

CONCLUSION

The letter discusses the challenges associated with the transition to PQC including migration strategies, standardization efforts and the policies adopted by different governments to implement quantum safe cryptographic algorithms. The standardisation efforts are now shifting towards implementing the selected algorithms along with auditing and compliance. Many technologists and policy makers aim to complete this migration as early as possible, with the latest target being 2035.

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RESEARCH ARTICLE

A Remote Sensing and MCDA-Based Assessment of Sustainable Water Availability in Sri Lanka

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Abstract: In Sri Lanka, uneven distribution of water poses significant challenges to the agriculture, environment, and ecosystem stability. Diverse climatic zones, topographical variations, and anthropogenic factors are the main causes of disparities in water availability. Accurate spatial assessments will help to locate these disparities. Therefore, this study proposes a framework that combines Geographic Information Systems (GIS), Remote Sensing, and Multi-Criteria Decision Analysis (MCDA) to produce a Surface Water Availability Index (SWI) across Sri Lanka. For this analysis, four key factors such as rainfall, drainage density, evapotranspiration, and surface water extent were selected, compared, and systematically weighted through the Analytic Hierarchy Process (AHP), with an acceptable Consistency Ratio (1.7%), to generate an SWI for Sri Lanka. District-wise SWI analysis indicates that water availability is limited in some parts of the country, especially in the Northern Province, highlighting the need for targeted interventions. Correlation analysis shows that a moderate negative correlation ($r = -0.44$) can be observed between SWI and LST, which reflects the cooler conditions in water-rich regions. Conversely, SWI exhibited weak correlations with NDWI ($r = -0.21$) and NDVI ($r = 0.25$), which show the complex hydrological and ecological dynamics. Despite some data limitations, this framework will support water conservation, drought mitigation, and efficient environment management. The accuracy of this method can further be improved with the use of higher-resolution, accurate data and relevant environmental and hydrological variables. It provides direct value for policy and planning in support of sustainable agriculture and environmental stewardship.

Keywords: Analytical Hierarchy Process, Decision Support, Environmental Monitoring, Geographic Information Systems, Normalised Difference Indices

INTRODUCTION

Water scarcity and uneven distribution of freshwater sources have become a serious issue nowadays globally due to the rapid development and population growth. This is threatening food security, public health, ecosystem stability, and many more [1], [2]. To address such challenges, there is a need to have tools and technologies, which are capable of mapping, monitoring, and managing water resources at finer spatial and temporal scales. Accurately mapping the water availability is critical in resource planning, irrigation management, and ensuring sustainable land and ecosystem use. In recent years Geographic Information Systems (GIS) and Remote Sensing techniques have been increasingly used, providing tools to assess, monitor, and visualize the spatial variability of water-related parameters at various scales [3].

Sri Lanka is a tropical island country located in South Asia, and it has been experiencing severe challenges in water resources due to its highly variable rainfall patterns and diverse topography. Significant spatial disparities in water availability can be observed due to three major climate zones: wet, intermediate, and dry zones [4]. Droughts and seasonal water shortages are a serious threat to agriculture, which remains the backbone of rural livelihoods and national food security.

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In Sri Lanka, most existing water management strategies rely mainly on coarse regional assessments. High-resolution, spatially explicit assessments that can capture regional disparities and support more targeted, sustainable water management strategies [5].

The integration of GIS, Remote Sensing, and multi-criteria decision analysis (MCDA) gives an effective, simple way for water resources evaluation and management practices. While Remote Sensing provides timely, wide-area coverage of many parameters including hydrological environmental variables, GIS enables synthesis and spatial analysis [6].

Analytic Hierarchy Process (AHP) is a widely used pairwise comparison-based technique, where multiple factors can be systematically incorporated and weighted to produce composite maps for decision support [7] [8]. Many studies have demonstrated that GIS-MCDA frameworks are successful in generating accurate, policy-relevant water availability maps and drought risk assessments across various scales. Thus, this study aims to develop and validate a composite Surface Water Availability Index (SWI) for Sri Lanka by considering various factors, and the output validated using some Remote Sensing Indices. This integrative approach offers a practical framework for sustainable water planning and spatial prioritization under climate variability.

METHODOLOGY

A. Study Area

Figure 1: Study Area

Figure 1 shows Sri Lanka (study area), which is one of the tropical islands in South Asia, located between 5.91 to 9.83 degrees north latitude and 79.52 to 81.87 degrees east longitude. Administratively, the country is divided into 25 districts, 331 Divisional Secretariats (DS), and 14,022 Grama Niladhari Divisions (GNDs). According to the Asian Development Bank (2024), the country has a total extent of 65,610 km², a population of over 23.1 million, and a population density of about 368 people per km². Approximately the island contains 2,020 km² of water bodies and 20,258 km length of streams, indicating its significant hydrological infrastructure. According to UNESCO, in 2021, around 80.1% of the population had access to improved drinking water resources. It shows clearly that some areas have limited water availability, and therefore spatial-based assessments of water availability are essential to support more sustainable and equitable water management practices across the country.

B. Factor Identification & Data Collection

Various factors were identified under different criteria based on the literature and availability of the data for assessing water availability. Openly available data were used, which were obtained from satellite imagery and Open Street Map (OSM). Table 1 shows the factors and their data sources.

Table 1: Factors and data sources for water availability

Factor	Data Source
Rainfall	CHRS PERSIANN-CDR
Drainage Density	OSM
Surface Water Area	OSM
Evapotranspiration	MODIS MOD16A2

C. Data Processing & Normalisation

Through Google Earth Engine, rainfall and evapotranspiration data were downloaded for October 2024. Then, proper cloud masking and downscaling techniques were applied. Stream networks were obtained from OSM, and their lengths were calculated in kilometers. A drainage density raster was created by the line density tool in ArcGIS Pro. Similarly, tanks data were obtained from OSM, and their areas were calculated in square kilometers. Then, the kriging interpolation method was used to create a continuous surface water area raster.

Finally, all layers were projected to the Sri Lanka Kandawala coordinate system (EPSG: 5234) and resampled to a common resolution of 50 × 50 meters. Normalisation brings input variables with different units and scales into a common comparable range. Thus, min-max normalisation was applied to each layer to make it suitable for MCDA. Output layer values vary between 0 and 1 [6].

The min-max normalisation formula used in this study is:

$$X' = \frac{(\mathrm{X} - \mathrm{Xmin})}{(\mathrm{Xmax} - \mathrm{Xmin})}$$

Where X is the original value, Xmin and Xmax are the minimum and maximum values of the dataset, and X' is the normalized value.

D. Analytical Hierarchy Process (AHP)

AHP was used to identify the significance of each factor to find the water availability. It involves pairwise comparisons between criteria to assess their relative importance in finding the availability of water through the systematic decision-making process. A pairwise comparison matrix was created with respect to Saaty's 1 to 9 scale, with the larger number demonstrating the stronger importance of one criterion over another. The sum of all the weightage values must be equal to 100. The Consistency Ratio (CR) is calculated in AHP to assess the consistency of the pairwise comparisons; a CR value below 10% (0.1) indicates an acceptable level of consistency [7], [8]. In this case, the calculated CR was 1.7% (0.017), demonstrating a high level of consistency in the judgments used for deriving the weights. Table 2 shows the weightage of factors derived from AHP.

Table 2: Weightage of factors (from AHP)

Factor	Weightage
Rainfall	63.21 %
Drainage Density	20.09 %
Surface Water Area	10.70 %
Evapotranspiration	6 %

E. Surface Water Availability Index and Zonal Analysis

The Surface Water Availability Index (SWI) was produced by multiplying each normalised raster with the respective weight derived during the AHP process. The outcome raster is the merged influence of all factors in which higher values indicate greater water availability. This raster was further reclassified into five classes using the natural breaks method. The extent of each class was calculated. Additionally, the district-wise sum of water availability was computed to assess spatial variations and to identify districts with relatively high or low water availability. A high-accuracy land use/land cover layer was obtained from the ESRI Living Atlas and reclassified into five main classes. The mean water availability value was then calculated for each land use class to assess how the water availability varies by land use.

E. Remote Sensing Indices and Validation

Remote Sensing Indices provide quantitative measures of key environmental properties such as surface water extent, vegetation health, built-up areas, and land surface temperature, all of which are critical for understanding spatial water dynamics. In the research, three main indices were calculated using Landsat 8 data in October 2024: Normalised Difference Water Index (NDWI) [9], Normalised Difference Vegetation Index (NDVI), and Land Surface Temperature (LST) [10]. Table 3 shows the indices and their equation, used in this study.

Table 3: Used Remote Sensing Indices and their formula

Factor	Equation
NDWI	(Green- NIR) (Green+ NIR)
NDVI	(NIR - Red) (NIR+ Red)
LST	Derived from Modelling of Thermal Infrared (TIRS) band

In the case of Landsat 8 (OLI/TIRS) imagery, Band 3 is green, Band 4 is red, Band 5 is near infrared (NIR), and Band 10 is thermal infrared (TIRS). Pearson correlation analysis was used to assess the correlations between water availability and the selected Remote Sensing Indices. Pearson's r measures the strength and direction of the linear relationships between different variables, and values close to +1 or -1 indicate strong correlation, while values near 0 indicate weak correlation [11]. 500 random points were generated across Sri Lanka to assess the correlation between these indices.

The main aim of the correlation between the Surface Water Availability Index (SWI) with NDWI, NDVI, and LST is to validate the reliability and physical relevance

of the SWI by comparing it with independently derived Remote Sensing proxies for water, vegetation, and surface temperature. Moreover, the correlation between NDWI and the rest of the indices (NDVI and LST) were also calculated to analyse the interactions among surface water, land cover, and thermal characteristics better. Five correlations were tested altogether: SWI against NDWI, NDVI, and LST, as well as NDWI against NDVI and LST, to better understand the influencing factors and spatial variability of water availability.

RESULTS

A. Surface Water Availability Index

Figure 2 presents the MCDA output, illustrating the spatial variation of water availability across Sri Lanka. This was categorized into five zones based on water availability levels, and this shows the area values of each zone.

Table 4: Extent of water availability Zones

Water Availability Zone	Class Area (Sq. Km)	Percentage (%)
Very Low	12946.33	19.73 %
Low	12919.53	19.69 %
Moderate	12928.68	19.71 %
High	13784.85	21.01 %
Very High	13028.83	19.86 %

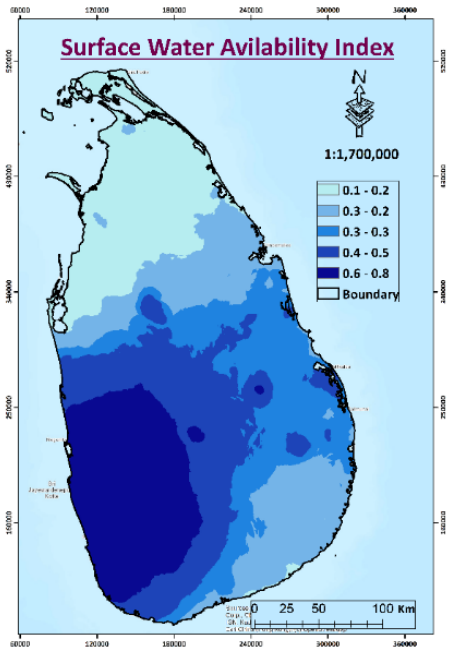

Figure 2: Surface water availability map

Surface water availability by Land use classes

Table 5: SWI by Land use

Land use	Mean value of WAI
Built-up Area	0.2752
Vegetation	0.3230
Agriculture	0.2693
Water	0.3868
Barren/ other land	0.2587

Analysis of mean SWI values across major land use classes illustrates significant variations (Table 5). Water bodies, with a mean SWI value of 0.3868, show the greatest water availability, as expected. The relatively high mean SWI value (0.3230) is observed in vegetation areas, indicating the association between natural water retention and healthy ecosystems. On the other hand, the means of SWI values for agricultural lands (0.2693), built-up lands (0.2752), and barren or other land categories (0.2587) are lower, indicating the limitation of water availability.

B. Water availability by districts

The district-wise analysis of the Surface Water Availability Index (SWI) demonstrates considerable spatial variability across Sri Lanka (Figure 3). The cumulative water availability is highest in Kurunegala, with a total sum of SWI of about 795,482, followed by Ratnapura (735,586) and Anuradhapura (577,812). Other districts like Monaragala (564,611), Ampara (470,736), and Kegalle (436,948) have also shown a significant amount of water availability, which are in the moderate-to-high trend. Conversely, in the northern districts, the values are very low, with the SWI sum in Jaffna being the lowest (52,243), followed by Mannar (92,173) and Kilinochchi (69,003), which indicates limited water resources and the highest exposure to a shortage. Most other districts, such as Colombo (177,076) and Matara (197,582), are at a moderate level.

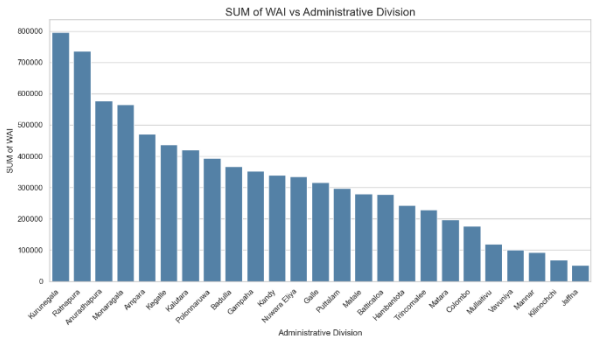

Figure 3: The total surface water availability by district.

A. Remote Sensing Indices and Correlation with SWI

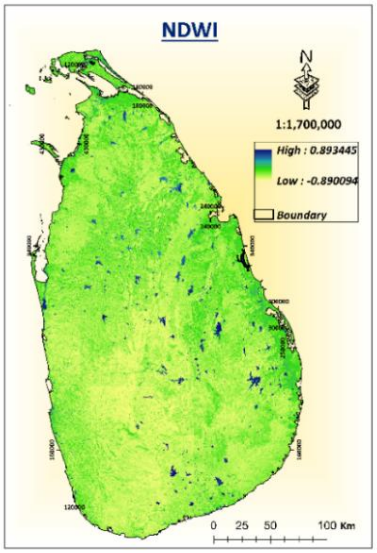

Figure 4: NDWI Map of Sri Lanka

Correlation analysis (Figure 7 to 11) demonstrates that various relationships were found between the Surface Water Availability Index (SWI) and the chosen Remote Sensing Indices (Figure 4 to 6). SWI showed a poor negative correlation with NDWI (r = -0.21). The correlation between SWI and NDVI was weak and positive (r = 0.25). Land Surface Temperature (LST) and SWI showed a moderate negative linear correlation with a Pearson r of -0.44. Looking at its relationships with other indices, it has been found that the correlation between NDWI and NDVI was strong but negative (r = -0.96), and the correlation between NDWI and LST was weak but positive (r = 0.18).

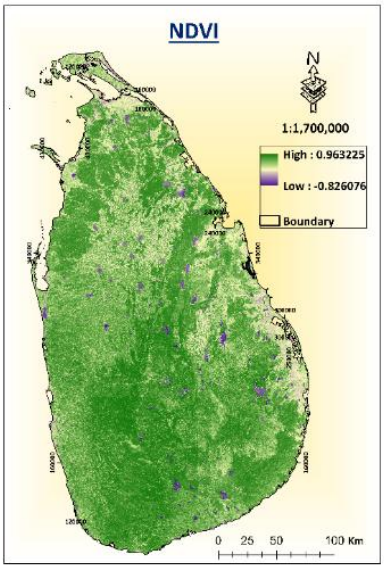

Figure 5: NDVI Map of Sri Lanka

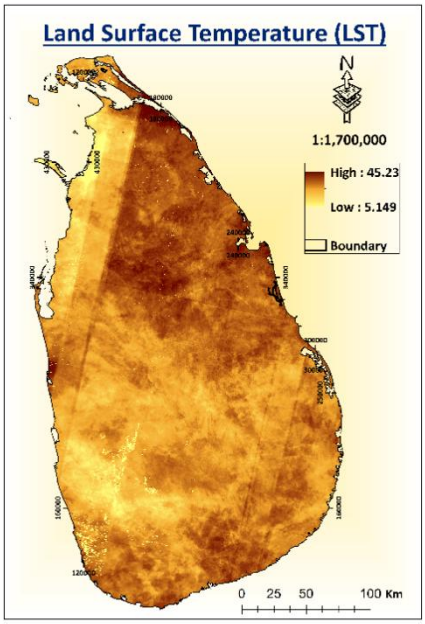

Figure 6: LST Map of Sri Lanka

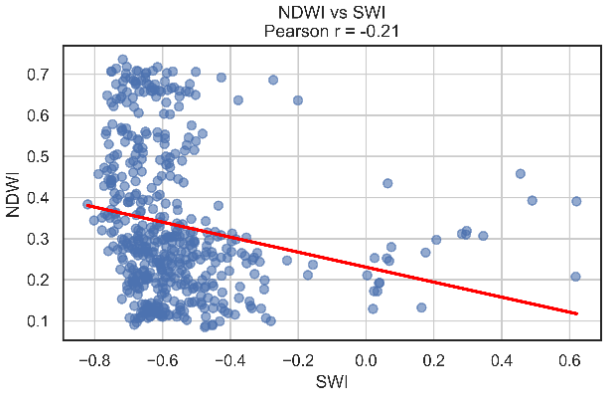

Figure 7: Correlation between SWI and NDWI

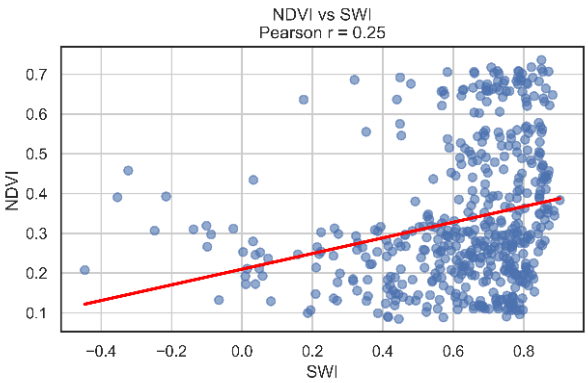

Figure 8: Correlation between SWI and NDVI

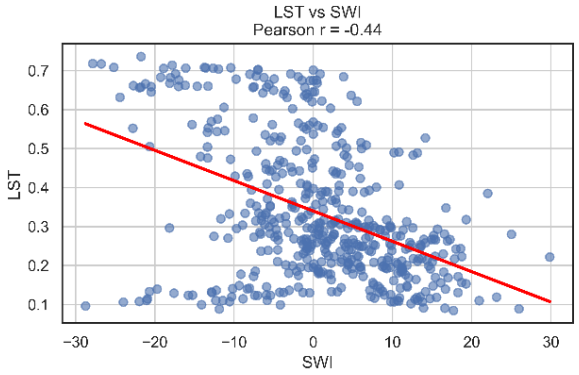

Figure 9: Correlation between SWI and LST

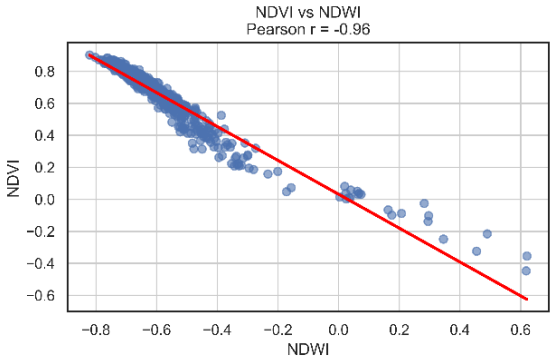

Figure 10: Correlation between NDWI and NDVI

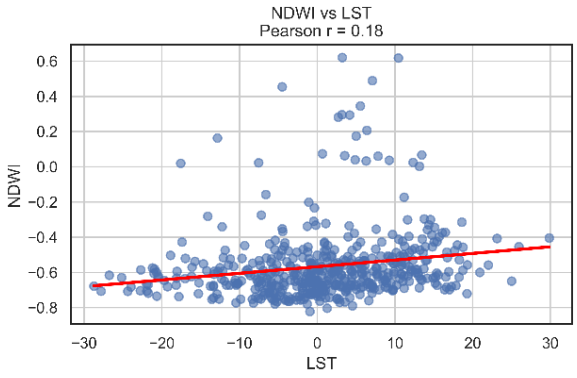

Figure 11: Correlation between NDWI and LST

DISCUSSION

Sri Lanka's varied climate zones, topography, and land use classes create significant spatial disparities in water availability. To address this, the study selected the entire country of Sri Lanka as the study area. For accurate spatial analysis, proper cloud masking and downscaling techniques were applied to enhance the quality and reliability of satellite data. To bring diverse input parameters to a uniform scale, normalisation techniques were used. Among them, min-max normalisation was used for its simplicity and effectiveness, allowing meaningful integration within the MCDA framework while preserving original data patterns. The AHP was used to derive the weight systematically and scientifically through an expert judgment decision-making process. The consistency and reliability of these judgments are confirmed by the achieved CR (1.7%). Here, rainfall was the most influencing factor with 63.21%, while evapotranspiration is the least influential factor with 6% to find the water availability index. Remote Sensing Indices NDWI, NDVI, and LST were chosen as independent validation measures because they have proven relevance to surface water, the health of the vegetation, and temperature changes. To ensure spatial representativeness, 500 sample points were used for assessing the correlations.

The SWI map classified nearly 20% of the area as high-water availability zones, while approximately 39% of the area was categorized as very low or low water availability zones. The dominant factor, rainfall, directly affects the variation in water availability, as proved by district-wise analysis. Since this analysis was conducted in the month of October 2024, the districts such as Kurunegala, Ratnapura, and Anuradhapura received higher rainfall, resulting in high total water availability values. This was further supported by dense drainage networks and large surface water bodies. On the other hand, the northern provinces show lower water availability. This may be due to limited rainfall, sparse drainage, higher evapotranspiration rates, and drought conditions. The results of the land use-based analysis demonstrated that the SWI of water bodies were to be expected, with the built-up lands, as well as agricultural and barren lands, having a lower water availability, which also suggests a possible water scarcity problem because of anthropogenic influence. The correlation analysis showed that SWI is moderately and negatively correlated with LST and has a weak relation with both NDVI and NDWI, and NDWI is strongly and inversely correlated with NDVI. These results confirm the spatial complexity of water, vegetation, and temperature interactions, which support the significance of planning integrated, spatially explicit water management in Sri Lanka.

CONCLUSION

This research uses a combination of MCDA, AHP, GIS and Remote Sensing to assess the spatial variation of water availability across districts and different types of land use associated with climatic, topographic and anthropogenic factors. District-level analysis highlighted

the vulnerable regions, particularly in the Northern Province, emphasizing urgent needs for targeted sustainable water resource management and agricultural interventions. Correlation of SWI with Remote Sensing Indices such as NDVI, NDWI, and LST enhances the reliability of the derived SWI, demonstrating its potential as a robust tool for environmental monitoring. Although certain limitations exist, particularly in the datasets, this methodology provides a scalable and practical framework for national and regional-level water resource planning. By incorporating high-resolution satellite images, relevant hydrological variables such as permeability, soil moisture, groundwater distribution with additional socio-economic variables into the MCDA framework, these results can be further enhanced. It will support the implementation of sustainable environment and agriculture policies by identifying priority areas for water conservation, drought mitigation, and sustainable land-use planning.

Finally, this research offers a replicable geospatial methodology that can support informed decision-making in water-scarce regions beyond Sri Lanka.

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RESEARCH ARTICLE

Automated Packed Cell Volume Analyzer

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Abstract: Packed Cell Volume (PCV), or hematocrit, is a crucial indicator of red blood cell concentration in blood, essential for clinical diagnostics. Traditional PCV measurement methods are manual, require significant blood volumes, and are unsuitable for remote or resource-limited areas. This project presents the development of a fully automated, portable PCV analyzer that minimizes blood sample volume while delivering accurate results. The system consists of a compact centrifuge driven by a 12V DC brushless motor and controlled by a Raspberry Pi. After centrifugation, a Raspberry Pi Camera Module 2 captures high-resolution images of the separated blood layers. These images are processed using a custom-trained YOLO machine learning model hosted on a Flask API to identify and measure the red cell and plasma layers. The PCV value is calculated from the proportional heights of these layers and automatically uploaded to a Firebase database. A React Native mobile application enables real-time access to the results. The system achieved an average accuracy of 97.67 % compared to commercial hematology analyzers (Sysmex), confirming its clinical reliability. Key technical challenges, such as image clarity and sample holder stability, were overcome using high-definition imaging. This project demonstrates the potential of cost-effective, automated PCV measurement solutions to improve healthcare access in decentralized and resource constrained environments. Future developments aim to explore non-centrifugal, ultrasound-based measurement techniques.

Keywords: Packed Cell Volume, Raspberry Pi, YOLO model, Automated Diagnostics, Portable Centrifuge

INTRODUCTION

Packed Cell Volume (PCV), also known as hematocrit, is a fundamental parameter in hematology that quantifies the proportion of red blood cells (RBCs) in whole blood. It plays a crucial role in diagnosing and monitoring a wide range of clinical conditions, including anemia, dehydration, polycythemia, and other hematological disorders. Accurate determination of PCV is essential for guiding appropriate medical interventions and treatment plans.

Conventional PCV measurement techniques involve manual centrifugation of blood samples followed by visual inspection of the separated layers in capillary tubes. While simple in concept, these methods are time-consuming, require trained personnel for interpretation, and are prone to human error [1]. Moreover, laboratory-grade hematology analyzers, though highly accurate, are expensive, bulky, and often inaccessible in remote or low-resource healthcare settings. This limits the availability of reliable PCV testing at the point of-care, particularly in field operations, rural clinics, and mobile health services.

Addressing this gap, the present project proposes the design and development of a portable, fully automated PCV analyzer capable of delivering fast and reliable results with minimal user intervention. The system integrates several key technologies: a Raspberry Pi-controlled compact centrifuge to separate blood components efficiently; a high-resolution camera for capturing post-centrifugation images.

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YOLO-based machine learning model for automated image analysis. The PCV value is calculated based on the relative height of the RBC and plasma layers and transmitted to a Firebase cloud database. A React Native-based mobile application provides real-time access to test results, enhancing usability in decentralized healthcare environments.

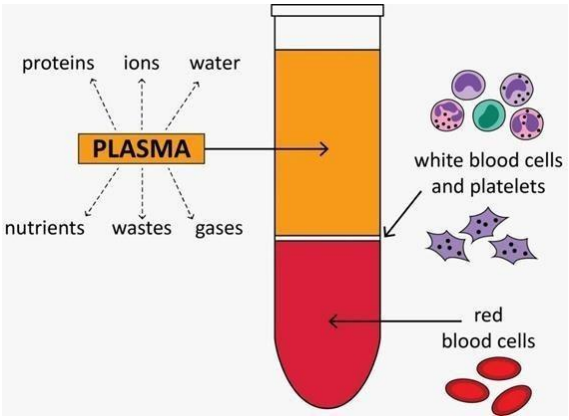

Figure 1: Centrifuged Sample

This innovative approach aims to create an affordable, compact, and user-friendly PCV analyzer suitable for point-of-care applications. By automating the entire testing process and enabling IoT connectivity, the device eliminates the need for complex laboratory equipment and skilled technicians, making accurate hematological analysis more accessible and scalable. Furthermore, the system's accuracy is benchmarked against commercial analyzers (Sysmex), demonstrating its clinical reliability.

This project highlights the transformative potential of embedded systems, machine learning, and IoT technologies in developing low-cost, automated diagnostic solutions to improve healthcare delivery in resource-constrained environments

METHODOLOGY

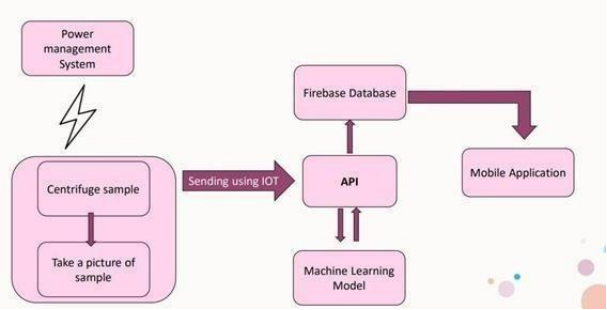

Figure 2: Overall Architecture

To develop a user-friendly and portable PCV analyzer, we divided the system into four key parts: power management, centrifuge operation, image processing, and data handling via a mobile app. Each part was carefully designed to be low-cost, compact, and optimized for use in field conditions.

A. Power Management System Design

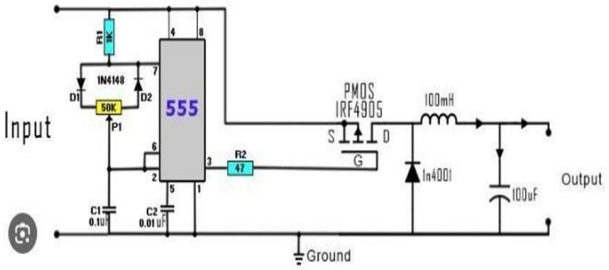

Figure 3: Buck Converter

To make the PCV analyzer truly portable and usable in remote or off-grid locations, a reliable and energy-efficient power system was essential. The design focused on using renewable energy, battery storage, and intelligent voltage regulation to keep the device lightweight and self-sustaining.

At the heart of the system is a 12V, 4Ah rechargeable battery, which acts as the primary power source for all components. This battery is charged using solar power through a custom-built buck converter circuit. The converter is designed to step down the higher voltage from the solar panel to a safe level suitable for charging the battery. To achieve this, a 555-timer IC is used to generate a pulse-width modulation (PWM) signal, which controls an IRF4905 PMOS transistor acting as a high-efficiency switch.

This setup allows the system to manage power intelligently and only what's needed is used. For example, during image capture, the camera flash LED is activated briefly and then turned off to save power. Once the battery is charged, power is distributed through two lines: a 7805-voltage regulator supplies a stable 5V for the Raspberry Pi and camera module, while a direct 12V connection powers the centrifuge motor through an L298N motor driver.

We also carefully designed the system to handle voltage fluctuations and to minimize energy waste. Based on calculations, the battery can provide power for about 1.4 hours of continuous operation under full load.

This is more than enough for multiple test cycles in one session, even in places where grid electricity isn't available.

B. Compact Centrifuge System Implementation

To make the PCV analyzer both portable and affordable, we built a compact centrifuge system from the ground up. Traditional lab centrifuges are bulky, expensive, and not designed for point-of-care use-especially in rural or low-resource settings [2]. Our goal was to create a reliable, small-scale alternative that could perform the same task: separating red blood cells from plasma in a capillary tube.

At the heart of our design is a 12V brushless DC motor, known for its smooth operation, low noise, and long lifespan. We mounted this motor onto a PVC foam board chassis, which is lightweight, sturdy, and easy to work with. This setup helped us keep the device compact without sacrificing stability.

Motor control is handled by a Raspberry Pi 2 Model B, which sends signals to an L298N motor driver. These signals adjust the motor speed 3000RPM using pulse-width modulation (PWM) [3]. When activated, the centrifuge gradually ramps up its speed and spins the sample for around five minutes. LED indicators provide visual feedback, so users know when the process begins and ends. A custom 3D-printed rotor securely holds the capillary tubes in place to prevent misalignment or wobbling. The result is a stable, reliable, and low-cost centrifuge suitable for field deployment.

B. Automated Image Processing & PCV Calculation

After the centrifuge finishes spinning the blood sample, the next step is to measure the red blood cell (RBC) level accurately. Traditionally, this is done manually by visually inspecting the capillary tube and estimating the RBC percentage, a method that can be slow and prone to human error. To improve both speed and accuracy, our system automates this process using image analysis and machine learning [4].

A Raspberry Pi Camera Module captures a 1920 × 1080 pixels-resolution photo of the blood-filled capillary tube right after centrifugation. This photo clearly shows the separate layers: the red blood cells at the bottom and the plasma on top. Once captured, the image is sent via Wi-Fi to a nearby Flask server, which handles the processing.

There, we use a YOLOv8 object detection model-trained [5], [6] using 20 images of real samples to locate and measure the RBC and plasma layers. It draws bounding boxes using a manual annotation protocol and calculates the PCV using a simple formula:

$$\text{PCV (\%)} = \frac{RBC\ Height}{RBC\ Height + WBC\ Height} * 100$$

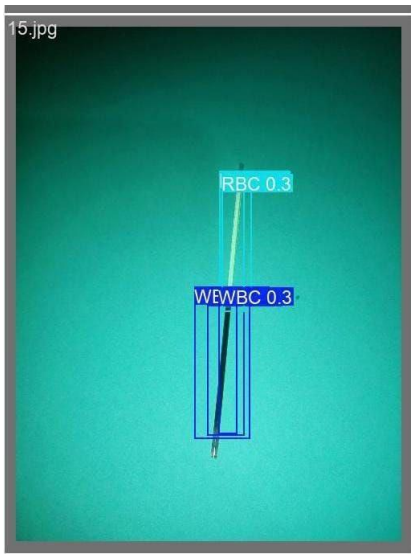

Figure 4: Bounded sample

The result, along with the annotated image and timestamp, is uploaded to Firebase and displayed in real-time through a mobile app. This automated approach eliminates human error and provides fast, consistent results even in low resource settings.

C. Data storage and Mobile Application integration

To make the PCV analyzer more user-friendly and connected, we developed a simple yet effective mobile application that works alongside the device. After the PCV is calculated, the result along with the annotated image and time stamp is automatically uploaded to the Firebase Realtime Database. This allows the data to be securely stored in the cloud and accessed from anywhere [7], [8].

We built a mobile app using React Native, which supports both Android and iOS platforms. The app fetches the data from Firebase and presents it in a clean, easy-to-read format. Users can view their PCV history, see visual charts, and even zoom in on the analyzed image with the detected red and plasma layers.

This mobile integration adds real-time accessibility and supports better record-keeping for both patients and healthcare workers. It also sets the foundation for future features like multi-user access, doctor integration, and long-term health monitoring.

RESULTS AND DISCUTION

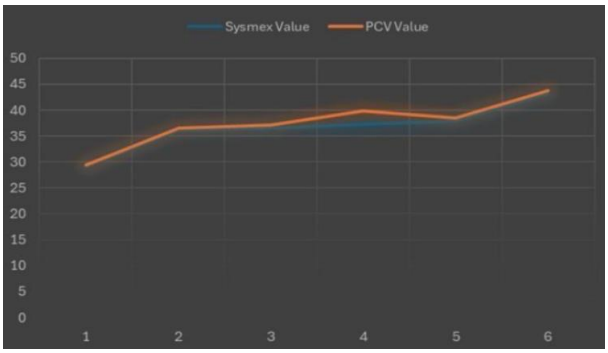

Figure 5: Comparison of PCV Values from Sysmex and Developed Analyzer with Accuracy curve

To evaluate the performance and accuracy of the automated PCV analyzer, we conducted tests using six different blood samples. Each sample was processed using our system and analyzed with a standard laboratory hematology analyzer (Sysmex), which served as the benchmark. The PCV results from both methods were compared to assess accuracy. Our system achieved an average accuracy of 97.67 % across all samples. In most cases, the difference between the automated PCV value and the lab result was less than 1.5 %, which falls well within acceptable clinical limits. This level of accuracy demonstrates the system's reliability, especially considering it operates in non-laboratory environments. Here, the error with the capillary tube filled with blood about 1/4 of the way up was 6.79 %. This may be due to the small data set we used.

Table 1: Comparison of PCV values from Sysmex and developed analyzer with accuracy

Sysmex Machine	PCV Analyzer Value	Relative Error	Accuracy
29.2 %	29.5 %	1.03 %	98.97 %
36 %	36.5 %	1.39 %	98.61 %
36.5 %	37.1 %	1.64 %	98.36 %
37.3 %	39.9 %	6.79 %	93.03 %
37,9 %	38.8 %	1.58 %	98.42 %
43,2 %	43.2 %	1.39 %	98.61 %
Average Value			97.67 %

Minor discrepancies observed were mainly due to image quality issues such as shadows or misalignment of the tube during capture and occasional variance in the motor speed. However, these did not significantly impact the final PCV calculations.

The processing time from centrifugation to result display was approximately 7 – 8 minutes, making the device suitable for point of care diagnostics where quick turnaround is essential. All test results, including the captured images and bounding boxes, were correctly stored in firebase and successfully retrieved via the mobile app.

Overall, the results validate that the proposed system is not only accurate but also practical for real-world use. Its portability, automation, and real-time mobile integration offer a significant advantage for use in rural clinics, mobile health units, or emergency situations where traditional lab equipment is unavailable.

CONCLUSION

This research successfully demonstrates the feasibility of a portable, automated PCV analyzer tailored for use in low resource and field environments. By integrating a compact centrifuge system, Raspberry Pi-based control, high resolution imaging, and YOLO-based machine learning, we were able to deliver a device capable of accurately measuring Packed Cell Volume with minimal human intervention. The system's average accuracy of 97.67%, when benchmarked against commercial hematology analyzers, confirms its potential for clinical use. Additionally, real-time data transmission through Firebase and intuitive access via a mobile application positions this solution as a powerful tool for decentralized healthcare delivery.

The challenges of image clarity, motor control, and power management were met with practical engineering solutions, including precision 3D printing and a solar-charged power system. Our design strikes a balance between affordability, portability, and performance, opening new possibilities for diagnostic services in rural clinics, mobile health units, and emergency response scenarios. Future iterations may explore ultrasound-based methods for even more compact and non-invasive applications. Ultimately, this project emphasizes the transformative potential of embedded systems and machine learning in democratizing access to essential medical diagnostics.

ACKNOWLEDGMENT

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RESEARCH ARTICLE

Bridging Leadership and Performance: Staff Commitment as a Mediating Factor Between Transformational-Transactional Leadership and Academic Outcomes in Private Higher Education Institutes

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Abstract: This study examines the impact of transformational and transactional leadership styles on the performance of internal academic staff in Sri Lankan private higher education institutions, with a special reference to the mediating impact of staff commitment. Following a quantitative cross-sectional design, data were collected from 223 internal academic staff from two reputed institutions. It was revealed that both leadership styles have a substantial impact on staff performance, with transformational leadership having a higher impact. Staff commitment was also an important mediator that heightened the indirect leadership effects on performance. The model exhibited high explanatory ($R^2 = 0.71$) and predictive ($Q^2 = 0.50$) power. Reflective constructs of leadership, commitment, and performance were highly reliable and valid. Findings align with social exchange and motivation theories in that leadership begets commitment, which enhances academic performance. This research contributes to the literature on leadership in the context of a developing country and offers practical implications for leadership development in the competitive higher education sector in Sri Lanka.

Keywords: Transformational Leadership, Transaction Leadership, Academic Staff Performance, Staff Commitment, Private Higher Education

INTRODUCTION

This study investigates the effects of perceived leadership styles on academic staff performance in private higher education institutions in Sri Lanka. Higher education institutions and their academic personnel play a critical role in national development, particularly in developing countries like Sri Lanka. As per the 2018 Global Competitiveness Report findings, Sri Lanka's skills ranking system falls into several areas. Out of 140 countries, vocational training quality was ranked 60th. The population's digital skills score 85 out of 140 countries, and the ease of getting qualified workers rates 57 out of 140. Additionally, out of 140 countries, the graduation rank's skill set was 44. The best rankings in this report range from one to seven (1 – 7). The fact that the performance in the current vocational education system falls short of the competence levels that employers require was further implied by this ranking level [1]. However, there is a research gap regarding how leadership styles, specifically transformational and transactional leadership, impact the performance of academic staff in Sri Lanka's private education sector. While leadership styles have been studied in other contexts, recent comprehensive research focusing on Sri Lankan private institutions is lacking [2], [3].

Leadership in academic institutions is crucial, especially in developing nations, as it directly influences the performance and effectiveness of academic staff. In Sri Lanka, higher education institutions significantly contribute to national economic growth, making effective leadership essential for institutional success [4].

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Leadership not only impacts staff motivation and commitment but also fosters innovation, creates a positive work environment, and enhances the quality of education provided [5]. The significance of studying leadership lies in its ability to inspire faculty to apply their skills toward institutional goals, thereby improving educational outcomes [6]. Furthermore, understanding leadership's impact on academic staff performance can help guide leadership development programs and institutional policies in Sri Lanka's higher education sector [7].

This research aims to fill the gap in the literature by examining the influence of transformational and transactional leadership styles on academic staff performance at private higher education institutions in Sri Lanka. The study will explore how academic staff perceive these leadership styles and how such perceptions affect their performance, including teaching effectiveness, research productivity, and contribution to institutional goals [8]. The findings are expected to provide insights into effective leadership strategies that could improve staff performance and inform policy development, helping Sri Lanka's private higher education sector enhance its overall quality and competitiveness [9].

The conceptual framework of this study is based on six major variables. Transformational and transactional leadership styles are considered independent variables. The academic staff's job performance is treated as the dependent variable, while staff commitment, job autonomy, and workplace climate serve as mediating variables [10].

The primary study question investigates the level of performance of academic staff in private higher education institutions in Sri Lanka, emphasizing the potential impact of superiors' leadership styles on this problem. The issues affecting Sri Lanka's education sector, such as a growing skills gap and low productivity of internal academic staff, are larger than this issue.

The reason is Private Higher Education Institutes almost always drive to get more profit in the competitive market with other academic performance indicators like no of graduates, on time delivery and quality of graduates. Three primary goals are sought after by the research: first, to ascertain how commitment, job autonomy, and workplace climate affect academic staff performance with Leadership styles.

The study's concentration on internal full-time academic personnel and exclusion of visiting academics are significant drawbacks that may restrict the study's generalizability. To obtain data for the study, private higher education institutions' geographic distribution variations that concentrate on certain areas are chosen. Furthermore, the entire range of private higher education available in the nation might be represented if only profit-oriented institutions are included. Future studies could take into account several strategies to alleviate these limitations, including: involving non-profit private institutions to compare leadership effects across various organizational structures; implementing a longitudinal design to assess leadership impacts over time and capture potential changes; expanding the sample to include visiting academics and part-time staff; and adopting a multi-institutional approach by incorporating other private higher education institutions to extend the geographical coverage to more provinces and districts. These adjustments would provide a more comprehensive and representative view of leadership impacts in Sri Lanka's private higher education sector [11].

LITERATURE REVIEW

Leadership research was vital for improving organizational effectiveness, especially as work structures change and human resources become more crucial. It helps identify new leadership approaches, evaluate existing ones, and refine traditional techniques. Leadership must adapt to different situations, as no single style fits all contexts [12]. Research explores leaders' traits, actions, and methods, analyzing current behaviors to predict future leadership needs. Various theories, including trait, behavioral, contingency, and style approaches, were examined. The text emphasizes transformational and transactional leadership theories, noting their role in leadership frameworks. While global research was abundant, Sri Lanka lacks studies on leadership's impact on employee performance, highlighting the need for further investigation [13].

A. Transformational Leadership style

James Macgregor Burns, a presidential biographer and leadership expert, is credited with first introducing the idea of transformative leadership. Transformative leadership is when leaders and followers make each other advance to a higher degree of morality and motivation [14].

Transformational leaders can motivate followers to shift expectations, attitudes, and motives to work toward shared objectives through the power of their vision and personality. Later, scholar Bernard M. Bass developed what was now known as Bass's Transformational Leadership Theory by building upon Burns' initial concepts. According to Bass, the influence a leader had on their followers can be used to define transformative leadership. Bass argued that followers of transformational leaders were more likely to trust, respect, and admire them [15].

B. Transactional leadership style

Transactional leadership was a structured leadership style that focuses on clear expectations and a system of rewards and punishments to achieve specific objectives. It assumes that employee motivation stems from well-defined roles, supervision, and performance-based incentives.

Transactional leadership prioritizes maintaining the status quo, focusing on short-term goals and immediate results rather than fostering innovation or long-term growth. While effective in certain situations, it lacks the inspirational and visionary qualities of transformational leadership [16]. Transactional leaders emphasize individual performance, offering rewards for meeting goals, but typically did not inspire followers to go beyond their defined roles. This leadership style provided a foundational framework for managing organizational performance and operations, often serving as a basis for more complex leadership approaches [17].

C. Transformational leadership and Academic staff performance

Research shows that leadership styles have varying effects on employee attitudes and organizational outcomes. Transformational leadership typically enhances self-efficacy, motivation, creativity, and performance, especially during organizational change [18]. HI: Transformational leadership has a significant influence on the perceived performance of staff.

D. Transactional leadership and staff performance

Transactional leadership, focused on rewards and punishments, can improve job satisfaction and organizational identity but may encourage complacency. While some research indicates transactional leadership boosts performance more, others favor transformational leadership [17]. H2: Transactional leadership has a significant influence on the perceived performance of staff.

E. Transformational leadership styles and staff commitment

Leadership style was shaped by a leader's characteristics, behaviors, and interactions with subordinates [19]. Transformational leadership was directly linked to employee commitment, with transformational leadership often having a greater impact [9], [20]. Research in Malaysia's manufacturing sector showed transformational leadership styles positively influence organizational commitment. H3: Transformational leadership has a significant influence on the perceived commitment of staff.

F. Transactional leadership styles and staff commitment

Transactional leadership had a stronger effect and Studies in Ghana and Oman similarly found that transformational leadership enhances employee commitment, while laissez-faire leadership weakens it. Transactional leaders inspire change and cooperation, resulting in greater staff commitment and lower turnover [21], [22]. H4: Transactional leadership has a significant influence on perceived commitment of staff.

G. Commitment and academic staff performance

Research shows a positive correlation between organizational commitment and employee performance. Normative commitment has a strong link with job performance [19]. Both affective and normative commitments significantly impact performance, with affective commitment boosting network performance. However, continued commitment negatively correlates with network performance, indicating complexity in this relationship. Organizational commitment and corporate culture also significantly influence performance.
H9: The Commitment has a significant influence on Staff's Performance.

METHODOLOGY

This methodology establishes a theoretical foundation by discussing several leadership styles. It describes the investigation of leadership styles and their potential connection to outcome factors in the performance of academic staff in higher education institutions in Sri Lanka. In the current study, a quantitative survey

method is utilized to get the answers to the research questions and test the suggested model. Data collection from more populations can be done effectively and affordably using the quantitative survey method [23].

This study uses a post-positivist paradigm, which emphasizes systematic measurement, statistical analysis, and hypothesis testing-all of which are consistent with quantitative techniques. Although it is challenging to establish absolute truth, this philosophical framework recognizes that rigorous scientific approaches can provide factual data that helps us understand reality.

This section presents the conceptual framework, operationalization of variables, population, tools used for data collection, data collection process, data validity, and data analysis method [10].

A. Research design

A research design describes the strategies and procedures used to conduct a study. The current investigation is based on a cross-sectional survey methodology. The survey method is suitable for gathering data from a larger population and increases the researcher's control over the research process. The main tool used in the survey method is a questionnaire.

The current study is useful for understanding attitude, perception, and behavioral components because it is exploratory and explanatory [24]. Also, the study used quantitative research methodology, which involved grading participant replies to quantify the data. The current study is based on an analysis at the personal level.

The researcher administered the pre-made questionnaires directly to the respondents to obtain the necessary data [25].

B. The Conceptual framework

An effective and useful method for investigating or interpreting anticipated correlations between variables is a conceptual framework. The framework may be based on the practitioner's knowledge or on what the researcher thought was pertinent and significant to solving the challenges raised by the research. The quantitative study's conceptual framework makes the connection between effective leadership practice and both transformational and transactional leadership styles [10].

The conceptual framework that underpins this study is based on five key variables, including

a) Transactional leadership style
b) Transformational leadership style as independent variables
c) Job performance of staff as a dependent variable
d) Staff commitment
e) Job autonomy as mediators between leadership
f) Job performance relationships.

To further understand how these variables affect the relationship between the independent variables (transformational and transactional leadership styles) and dependent variables, the mediating influence of staff commitment is tested (academic staff job performance). When lowering or amplifying the impact of one dependent variable on another, mediator effects are very important practically [26].

The conceptual framework of the current study assumes that both transactional and transformational leadership qualities can support academic staff Commitment and Job autonomy. It also presupposes that strong leadership practices influence academic staff's performance through commitment and job autonomy.

C. The Operationalization

The practical application of the study's areas and variables is shown in Table 1.

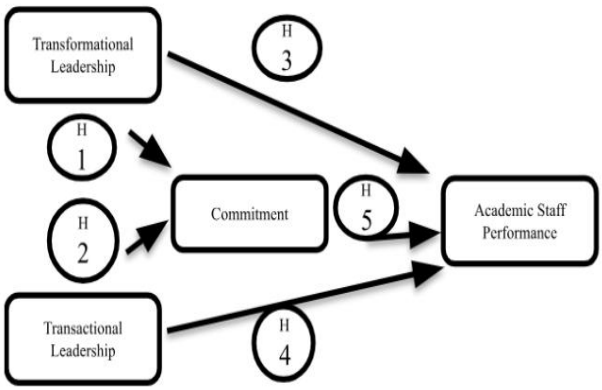

Figure 1: The Conceptual Framework

D. Procedure and Instruments

Questionnaires and the survey approach utilized in this study are used to gather data from research participants. The proposed constructs for measuring the model variables. Prior to use, the instruments were pretested.

E. The Population and sample

The researcher would have to conduct a census or include every member of the target demographic in his study to gather the entire population as a sample for research. This method makes it possible to collect information from every member of the target population, guaranteeing full representation via an online questionnaire. If conducting a census for this research is feasible, it can offer the following justifications:

F. Full representation

A census assures that every member of the population is counted, removing any bias that might result from sampling methods. The research findings' accuracy and generalizability are improved by this thorough interpretation.

Elimination of sampling error: Since data are gathered from the entire population during a census, there is no sampling error. This improves the accuracy of my research findings and lowers the uncertainty related to predicting population parameters.

G. Extensive analysis

A census enables a thorough examination of demographic subgroups. By considering every person, it may evaluate traits, patterns, and trends at a detailed level, giving us a thorough picture of the population.

Small-scale analyses: Comparing conducting a census with larger populations, it may be more practical if the population is relatively small. In such circumstances, the logistical difficulties and expenses of a census might be more manageable, making it a justifiable strategy [27].

In line with the general aim of this study to test the impact of leadership styles between internal academic staff and their immediate superiors, data were collected from two renowned Sri Lankan private higher education institutions with an island-wide network. The former has 40 branches with approximately 400 internal academic staff, while the latter has 8 branches with a total of 125 internal academic staff. To gain comprehensive coverage, a structured questionnaire was dispatched to every 525 members of the academic staff in the Two institutions. 223 responses were obtained, providing an adequate response rate for quantitative analysis [28].

LIMITATIONS OF THE RESEARCH AND FUTURE RESEARCH SUGGESTIONS

This research was conducted among academic staff of higher education institutions in Sri Lanka for two types of perceived leadership styles. Therefore, for future research, it is recommended to include staff of higher education institutions in Public and Private and more leadership styles and dimensions. Mainly this study considered the importance of staff commitment and effect on academic staff performance connected with Transformational and Transactional leadership styles.

MEASURES

The measurement model of reflection in the study focused on six first-order constructs, namely Transformational Leadership (TFL), Transactional Leadership (TSL), Commitment, Job Autonomy, Climate, and Performance. The analysis of construct measures provided strong psychometric properties for all reflective indicators. Specifically, factor loadings of items under the Transformational Leadership construct were, in all instances, well over the 0.70 benchmark, between 0.76 and 0.88, thereby obtaining convergent validity. Reliability was also ensured by Cronbach's Alpha values greater than 0.70 for all the constructs, with TFL recording an extremely high alpha value of 0.91, indicating perfect internal consistency. Composite Reliability (CR) values were also higher than the threshold limit of 0.70, with TFL recording a CR of 0.93, indicating high reliability. Furthermore, the Average Variance Extracted (AVE) of TFL was 0.65, well over the minimum of 0.50, and this testifies to adequate convergent validity. In sum, results confirm the robustness of the reflective measurement model, confirming the reliability and validity of the first-order constructs used in measuring the impact of leadership styles on the performance of academic staff.

This operationalization framework was developed by the authors for the present study. The constructs, operational definitions, and measurement indicators were synthesized from established literature and validated measurement scales. The framework was specifically developed to align with the objectives and conceptual model of the present study.

Table 1: The Operationalization View

Variables	Definition	Indicators	Constructs	Measurement
The Transformational leadership	According to definitions, transformational leadership is a style of leadership in which interactions between interested parties are planned around a common goal in a way that influences, inspires, and improves followers' behavior and ethical ambitions [13].	• Coaching • Moral and ethics • Needs and motivation • Creativity • Standards [4]	The questionnaire for Multifactor leadership [2].	Questionnaire – Part B
The Transactional Leadership	A task is agreed upon and defined between the leader and follower as part of a social exchange process known as transactional leadership, with the understanding that a task that is properly accomplished will lead to a reward and the avoidance of punishment [6].	• Possible expectation • Problems • Standards and agreements [4].	The questionnaire of Multifactor leadership [2].	
Staff Performance	Work results, comprising efficacy, efficiency, and effectiveness, are referred to as job performance of Staff [19].	• Job • Innovator • Carrer • Team • Institute [3]	Five-factor performance scale [19].	Questionnaire – Part C
Staff Commitment	The Staff commitment refers to the degree of identification and involvement that individuals have with the mission, values, and goals of their organization [9].	• Affective Commitment • Continuance Commitment • Normative commitment [4].	Academic staff Commitment Questionnaire [7]	Questionnaire – Part D

A. Assessment of Formative Measures (Second-Order Constructs)

Though not detailed in the dataset explicitly, formative constructs like overall leadership effectiveness might have been conceptualized. However, if treated as second-order, proper steps such as evaluating weights, multicollinearity, and outer VIFs are needed.

Table 2: Multicollinearity Check (Vif)

Path	VIF
Transformational -> Commitment	2.1
Transactional -> Commitment	1.9

All VIFs are below 3.3 (e.g. Transformational -> Commitment = 2.1), indicating no multicollinearity concerns.

Structural Model Assessment Coefficients & Significance

All structural path coefficients are statistically significant with $p < 0.05$.

Notably:

Transformational → Performance ($\beta = 0.35$, $t = 5.21$)

Transactional → Performance ($\beta = 0.25$, $t = 3.78$)

Table 3: Structural Model Assessment

Path	β	t-value	p-value	Significance
Transformational → Performance	0.35	5.21	0	Yes
Transactional → Performance	0.25	3.78	0	Yes
Commitment → Performance	0.30	4.91	0	Yes

Interpretation - All structural paths are statistically significant (**$p < 0.05$**), confirming strong direct effects.

Table 4: R^2 and Q^2 Values

Construct	R^2	Q^2
Commitment	0.52	0.35
Performance	0.71	0.50

- **$R^2 \geq 0.50$** = strong explanatory power.
- **$Q^2 > 0$** confirms **predictive relevance**.

The model explains 71% of the variance in Performance, showing substantial explanatory power.

Table 5: Direct Hypothesis Testing Summary

Hypothesis	Statement	Supported?
H1	TFL → Performance	✓ Yes
H2	TSL → Performance	✓ Yes
H3	TFL → Commitment	✓ Yes
H4	TSL → Commitment	✓ Yes
H5	Commitment → Performance	✓ Yes

All eight hypotheses are supported with statistically significant results.

All five hypotheses (H1–H5) are statistically supported. Both leadership styles positively influence performance and are mediated by Commitment and Job Autonomy.

Indirect Effects / Mediation (Hypothesis Testing for Mediation)

The mediation is evident as:

- TFL and TSL influence Commitment which in turn significantly affect Performance.
- Hence, Commitment mediates the effects of leadership on performance.

The mediation paths are statistically supported.

Assessment of Validity and Reliability (Reflective Measures)

To evaluate the measurement model, the validity and reliability of the reflective constructs were assessed using four key indicators: indicator loadings, Cronbach's Alpha, Composite Reliability (CR), and Average Variance Extracted (AVE).

Table 6: Validity and Reliability Assessment

Construct	Average Loading	Cronbach's Alpha	Composite Reliability (CR)	Average Variance Extracted (AVE)
Transformational Leadership	0.82	0.91	0.93	0.65
Transactional Leadership	0.79	0.89	0.91	0.62
Commitment	0.81	0.90	0.92	0.66
Performance	0.83	0.92	0.94	0.68

Indicator Loadings: All constructs demonstrated strong item loadings, with average values above the recommended threshold of 0.70. This indicates that the observed variables adequately represent their respective latent constructs.

Cronbach's Alpha: All constructs showed Cronbach's Alpha values exceeding 0.70, which confirms internal consistency and reliability of the constructs used in the model.

Composite Reliability (CR): CR values for all constructs were above 0.70, suggesting that the constructs demonstrate high reliability and are free from random measurement error.

Average Variance Extracted (AVE): Each construct had an AVE above the minimum threshold of 0.50. This validates that the constructs exhibit acceptable convergent validity, meaning they explain more than half of the variance of their respective indicators.

Based on the above results, all reflective constructs in the study are considered valid and reliable. This confirms that the measurement model is statistically sound and suitable for further analysis in the structural model phase.

Theoretical Implications

- Confirms Transformational Leadership is more effective than Transactional Leadership in enhancing academic staff performance.
- Supports social exchange and motivation theory: employees reciprocate supportive leadership with higher performance and commitment.
- Expands the body of literature by applying these constructs in the Sri Lankan private education context, a previously under-researched area.

Practical Implications

- Leadership training for Superiors should emphasize transformational behaviors (coaching, motivation, ethics).
- Enhancing and reinforcing organizational commitment improves academic output.

LIMITATIONS

This study examines several limitations. First, it is based on private higher education institutions in Sri Lanka and therefore does not generalize to public institutions or other educational settings. The study also does not include visiting staff members but only internal academic staff, which may be lacking the heterogeneity of other staff interactions. Cross-sectional data limit the ability to make causal inferences regarding the relationships examined. Furthermore, since the information was collected through self-reporting questionnaires, there is a potential for social desirability bias, which could affect the truthfulness of the responses.

Future research can improve the generalizability of this study by including public institutions and part-time teaching staff to allow for the extension of results' generalizability to the whole higher education institution. Future research could also consider other mediating factors such as organizational climate, staff motivation, or job satisfaction to understand more clearly the mechanisms through which leadership styles affect academic staff performance. Longitudinal study designs would enable researchers to capture the long-term effects of leadership without the limitations of cross-sectional data.

Multi-level modeling is also recommended to control for hierarchical structure in departments and institutions as well as for more nuanced context effects.

This study offers robust evidence that both transformational and transactional leadership styles significantly influence academic staff performance directly and indirectly through commitment and job autonomy. Leadership development initiatives tailored to Sri Lanka's private education sector can benefit significantly from these insights, ultimately enhancing educational quality and staff satisfaction.

DISCUSSION

The results of the study indicate good empirical support for the conceptual model, which investigates transformational and transactional leadership patterns and their influence on Sri Lanka's private higher education institutions' academic staff performance. The measurement model was very valid and reliable for all reflective constructs in that it showed good average factor loadings, Cronbach's Alpha, Composite Reliability, and Average Variance Extracted (AVE). The results confirm the efficacy of the instrument for leadership, commitment, autonomy, and performance measurement.

Structural model further reveals that transformational and transactional leadership styles both have statistically significant and positive direct effects on academic staff performance. Transformational leadership has a larger effect, which reveals that it has a key role to play in the creation of innovation, motivation, and quality academic production. In addition to this, these mediating variables of staff commitment and job autonomy were also significantly associated with performance, again suggesting that effective leadership does not operate so much through direct motivation but by enabling employees to work in an organizational environment in which they are empowered and committed.

The strong R^2 value for staff performance (0.71) demonstrates that the model possesses good explanatory power. This lends validity to the theoretical assumption that leadership is among the most powerful determinants of individual behavior as well as organizational performance in the academic environment. Further, the high Q^2 values demonstrate that the model possesses good predictive power, justifying its effectiveness in applied scenarios in institutions.

Theoretically, the findings are in line with social exchange and motivation theories that posit that leadership behavior moderates subordinate responses through direct and indirect avenues such as commitment. In practice, the research necessitates the setup of leadership initiatives with high emphasis on coaching, ethical leadership, more so in competitive learning environments where employees' commitment is directly associated with the success of institutions.

While results are substantial, the study is limited. The sample was restricted to full-time academic faculty in private institutions, and this may limit generalizability. Future research could involve public sector organizations, part-time academics, and examine other mediators such as organizational climate and employee engagement. Longitudinal design would be best to capture change over a period. Lastly, this study corroborates the existence of the impact of effective leadership or better yet, transformational leadership on the academic staff performance directly and indirectly through enhanced commitment. Such types of findings are helpful for higher education institutions in attempts to boost productivity among their workforce, job satisfaction, and overall academic quality.

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RESEARCH ARTICLE

Enhancing Athleisure bras design and construction for Sri Lankan consumers

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Abstract: Balancing work and wellness are central to modern Sri Lankan women, driving growth in athleisure wear, particularly athleisure bras that fuse style, comfort, and utility for both everyday activities and exercise. This study systematically explores the gap between Sri Lankan consumer needs and current market options. Research was conducted by combining shop visits, professional interviews, and laboratory experiments on fabric performance. Findings indicate that most athleisure bras available locally, mainly in Colombo are compression types, with prices ranging from LKR 2,500 – LKR 7,000 for local brands and up to LKR 12,000 for international offerings. But in Sri Lanka's hot and humid climate, common materials such as polyester/spandex and nylon/spandex usually don't offer enough comfort. Lab tests indicated that polyester/cotton/spandex blended interlock fabrics are superior in wicking, recovering, and absorbing moisture, all of which enhance fitness and comfort. To comply with international standards, interviewees recommended the use of alpha-numeric size methods, highlighting continuing sizing difficulties in the local market. As revealed, purchase behavior is influenced by cultural norms; for modesty, many women wear athleisure bras underneath their clothes which further highlights the need for comfortable fabrics. However, semi-bonding techniques provide more comfort. All things considered, the study shows unmet demand and substantial potential for Sri Lankan companies to develop cutting-edge fabrics, sizing, and culturally relevant designs to cater to an expanding population of active and health-conscious women.

Keywords: Athleisure Bra, Consumer Fabrics, Textile Innovation, Activewear Apparel

INTRODUCTION

In an era when health is an investment, the woman is considered at her best when she is healthy and active. Athleisure clothing emerged as a revolutionary fashion trend movement and has become a wardrobe essential for women. Athleisure is a hybrid style combining 'athletics' and 'leisure' and is defined as "A fashion trend that combines athletic and leisure wear, creating a comfortable and fashionable style that can be worn for various occasions, from casual outings to workout sessions." [1] "Athleisure is faux athletic gear sold largely to non- athletes who care about fashion, not necessarily function. Technical wear is for active individuals who value performance first, plus the flexibility of clothing stylish enough to wear on the street." [2] "Casual clothing designed to be worn both for exercising and for general use" [3].

Global market size for athleisure clothing was USD 330.97 billion by 2022, and it is anticipated to grow by 9.1% at a compound annual growth rate (CAGR) from 2023 to 2030. The well-known players in the international athleisure market are Nike Inc, Adidas, Lululemon, Athleta, Under Armor, and GAP, and they are targeting countries such as Europe, North America, Asia Pacific, the Middle East, South America, and Africa [4]. Athleisure clothing consists of sweatpants, leggings, bras, joggers, hoodies, and skinnies. Among the athleisure clothing, athleisure bras feature versatility and are designed to be stylish and comfortable yet functional for performance [5]. They are a perfect fusion for a comfortable style that transforms from gym to casual date [6].

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A. Athleisure bras in the Sri Lankan market

The Sri Lankan athleisure clothing market has enormous potential to grow because the upcoming consuming generation of Gen Z and alpha consumers are aware of and willing to follow health-conscious and sustainable trends [4]. In addition, the Sri Lankan sports apparel market is forecasted to increase by 5.1 % CAGR from 2020 to 2026 [7].

However, as per the initial observations of the Sri Lankan shops, most of the athleisure brands are international, such as Nike, Adidas, Puma, Lululemon, Carnage, FOA, Bolt Gear, Under Armor, and Moose. These brands consist of seasonal clothing that is not suitable for the Sri Lankan climate [8].

The commercial capital of Sri Lanka experiences an average temperature of 28 - 29 °C with a slight variation throughout the year [9]. Hence, problems with comfort, breathability, and sweat may arise. Meanwhile, as discovered in interviews Sri Lankan consumers prefer not to wear body- revealing clothes due to cultural and social restrictions, leading to higher need of moisture wicking and breathability in the fabrics. Also, the interviews and market observations identified the problem of sizing being underdeveloped in the local context.

Textiles of polyester, nylon, cotton and spandex are currently controlling most of the market, it is crucial to conduct an experimental assessment of their behavior in tropical environments to identify their technical advantages and disadvantages. Leading to a need for baseline assessment data-driven improvements for climate-appropriate product development by enabling objective comparison with alternative blends [10].

Therefore, it's necessary to find solutions through designs and construction methods with materials and trims to be used, and sizing solutions while considering cultural and social requirements for this growing market of athleisure bras suiting Sri Lankan consumers. This study focused on identifying the needs and gaps within the local market while evaluating the most suitable solutions through design and construction. The research question of the study is.

RQ — What are the most suitable solutions through design and constructions to bridge the gaps and needs of athleisure bras for Sri Lankan consumers?

LITERATURE REVIEW

A. Types of Athleisure Bras

The sports bras can be categorized into two different categories: according to the activity engaged and according to the main functionality of it, which is the breast support [6]. According to its main functionality, the bra can be categorized into two.

- Encapsulation bras — The encapsulation bra contains two molded cups that support two separated breasts. These are more effective for women with cup sizes C or above.
- Compression bras — The compression bra is designed to restrict breast movement by flattening the breasts against the chest wall. These have been thought to be more effective for women with smaller breasts (cup sizes A or B).

According to sports or the activities, sports bras are categorized into three [11].

- Low impact: less vigorous physical activities such as yoga, Pilates, swimming and stretching.
- Medium impact: moderate physical activities such as hiking, road cycling and skiing
- High impact: more vigorous activities such as running, trail running, triathlons, aerobics, dancing, boxing and racquet sports.

The categorization of sports bra is illustrated in Figure 1.

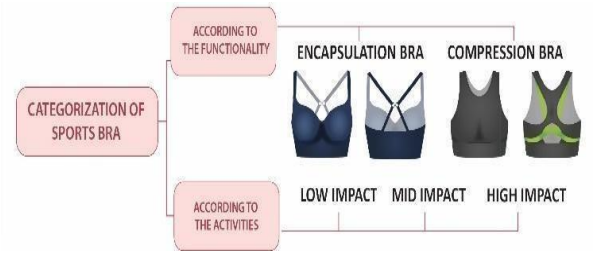

Figure 1: Types Of Sports Bras

B. Fabrics Used for Athleisure Bras

The choice of fabric is crucial in the dynamic realm of athleisure wear for its comfort and functionality. Moisture wicking, easy-to-care-for, stretchable, lightweight, and breathable properties of materials are acknowledged as important [12]. The current market is

compromised with polyester, nylon, cotton and spandex [10]. The most popular fabrics blends used in sports apparel are Polyester/spandex fabric.

It is a high-performance option for athleisure bras, offering moisture-wicking, breathability, durability, and flexibility [12]. The blend is highly durable, with polyester ensuring shape retention and spandex providing elasticity for continuous support. Its flexibility allows for a full range of motion, making it ideal for active wear [13].

Cotton/Spandex Fabric

It is a great choice for athleisure bras, offering softness, breathability, and flexibility [12]. Its gentle texture reduces irritation, making it ideal for all-day wear, while high breathability keeps the wearer cool in hot climates of Sri Lanka [10]. The moisture-absorbing properties help wick sweat away, though it dries slower than polyester blends. Spandex enhances stretchability and shape retention, ensuring a snug yet flexible fit for low to moderate-impact activities such as yoga [11].

Nylon/Spandex Fabric

It is lightweight, durable, and flexible for athleisure bras, offering breathability, moisture-wicking, and excellent stretch [12]. Its airy feel keeps the wearer cool and comfortable, making it ideal for hot climates of Sri Lanka. Known for its high strength and durability,

It resists tearing, abrasion, and sagging, ensuring long-Lasting wear. The spandex blend provides exceptional stretch and recovery, allowing a full range of motion while maintaining a snug fit [11].

Polyester/Cotton/Spandex Fabric

This is an ideal blend for athleisure bras, offering a balance of moisture management, breathability, durability, and flexibility [12]. The polyester component enhances moisture-wicking and quick drying, while cotton provides breathability and natural softness, keeping the wearer cool and comfortable a key benefit for Sri Lanka's hot and humid climate [9].

C. Construction techniques and technologies used in athleisure bras.

One of the several techniques employed in the apparel manufacturing sector is cut and sewing.

Using specialized machinery, it entails cutting off pre-designed or patterned cloth pieces from big rolls or sheets. Industrial sewing machines or professional sewing machine operators then assemble these parts. Before being sewed together, each piece of cloth in cut and sew is precisely measured and trimmed to size. As a result, when the garment is finished, there is no excess material to trim off [14].

The process of joining two or more layers of material together by heat, pressure, or glue is known as bonding fabric. This method is well-liked in a variety of sectors, including the fashion, automotive, and medical industries, since it produces a strong and long-lasting connection that is resistant to abrasion [15].

Also, Seamless or circular knitting involves creating a garment by designing a three-dimensional fabric, as opposed to cut-and-sew knits, where the three-dimensional shaping of a garment is achieved by assembling flat, two-dimensional fabric pieces [16].

D. Consumers of athleisure bra

Consumers of athleisure bras can be based on their preferences and day-to-day activities.

Casual Activewear Consumers mainly focus on and consider the comfort and fashion style of athleisure wear in their day-to-day life.

Fashion - Conscious Consumers focusing on both style and functionality when they are choosing the clothes
Athletes and Fitness Enthusiast Consumers doing actual physical activities such as sports/heavy workouts, who need some actual support & comfort during their workouts.

Health and comfort-seeking consumers prioritize the comfort and well-being of their body Athleisure bra consumers are usually looking for a combination of comfort and other qualities that enhance their overall experience of the sports bra. These are some major considerations when the consumer is focusing on them [17].

Versatility- For athleisure bras, versatility is key. Customers appreciate bras that seamlessly transition from workout to casual wear, offering comfort in various settings.

Comfortable Fit - a comfortable fit that provides good support without causing discomfort or chafing during both physical activities and day – to - day wear.

Moisture Wicking fabrics- Especially in sports bras, moisture-wicking properties are one of the most important things. Fabrics that remove sweat away from the body to keep the wearer dry and comfortable during workouts.

Breathability- Breathable materials and designs that help comfort by allowing air circulation and preventing overheating and sweating during activities.

Seamless Construction- Seamless designs help to reduce irritation, enhancing the overall comfort.

E. Global athleisure bra market

Popular athleisure bra brands are Lululemon, Nike, Adidas, Under Armor, Aerie, Athlete, Sweaty Betty are some of the many international brands in the Sri Lankan market. Lululemon is well known as a brand that caters high quality yoga and athleisure wear. Meanwhile, Nike is the world's largest athletic apparel brand. Nike is dominating the market with their performance driven product, new cutting end technology and sustainability. Adidas aims to be performance and style. Under Armor is known for specializing in performance athletic wear and their innovative designs. Athleta, owned by Gap ink, focuses on women's athleisure and performance wear with sustainability. These brands are well known for their comfortable and well-designed activewear [18] however, these brands are targeting countries such as Europe, North America, Asia Pacific, the Middle East, South America, and Africa [4]. Hence, the suitability of these brands in the Sri Lankan market is questionable.

METHODOLOGY

Interviews, shop visits and experiments on fabrics were the data gathering techniques employed in this study.

A. Interviews

The sample for the interviews was chosen through purposive sampling, targeting athleisure related professionals to determine consumer and market needs regarding the Sri Lankan market. The number of interviews was seven, including professionals of senior designers, athleisure fit models, fabric technicians, research and developers, merchants, and pattern technicians who had more than five years of experience in the apparel industry of manufacturing athleisure bras. Although consumers were not directly interviewed, these professionals regularly interact with consumers and have deep knowledge of consumer preferences, behaviors, and needs through their daily professions. Hence, their insights provide information to understand consumer and market demands. As recommended, purposive sampling for qualitative research the small sample is adequate for capturing a range of expert views within the exploratory study managing a focused samples for in-depth insights.

Therefore, the first section of the interview questions was to determine the interviewee's involvement in manufacturing athleisure bras. Identifying the construction techniques and fabrics used for athleisure bras was the focus of the questions of the second section. The questions of the third section concentrate on revealing the demand and preference of Sri Lankan consumers. The interviews were tape-recorded and transcribed.

B. Shop visits

Shop visits observed and explored the available brands, designs, and construction methods with fabrics and trims currently available in Sri Lanka. Shops in the Western province of Colombo were selected as a higher number of gyms and sport-related activities are located around Colombo. The four shops were Carnage (One Galle face, Colombo), FOA (One Galle Face, Colombo), Bolt Gear (Thibirigasyaya), and Triumph (majestic city, Colombo). The findings were recorded in a format.

C. Experiments (Fabric Tests)

Sri Lanka is considered a country closer to the equator, while consisting of only dry and wet seasons throughout the year. The warm climate in Sri Lanka requires breathability and moisture-wicking ability of a garment to make it comfortable.

The stretchability and modulus of fabrics are also important to achieve the fitness of the athleisure bras. Therefore, the focus of the experiments with fabrics was two-fold. The first objective of the experiments was to determine the best fabric composition, and the second objective was to identify the best fabric structure that supports stretchability and modulus.

C.1 Experiments to determine the best fabric composition

The most found fabric blends in the activewear market were selected for the experiments. Since athleisure bras need higher recovery, 6 to 10 percent spandex was selected. In addition, a GSM level of 240 - 260 was selected as it is the regular range seen in most brands.

- 90 % Polyester and 10 % spandex
- 92 % Cotton and 8 % spandex
- 94 % Nylon and 6 % spandex
- 33 % Polyester, 33 % cotton and 6 % spandex

C.1.1 Wicking test

To determine the moisture absorbency of the fabric, a wicking test was conducted. The wicking test is conducted in two ways: the horizontal method (AATCC 198 [19]) and the vertical method (AATCC 197 [20]). The vertical method was chosen in this study. Accordingly, 3 cm width and 27 cm length fabric strips were cut from each fabric composition. 1cm of fabric was immersed in the water, and fabrics were observed throughout an hour with every 15-minute recording of water level.

C.1.2 Moisture management test

The moisture management test (AATCC method) is an advanced method to identify moisture absorbency, wicking, quickness of absorbency, and transportation of liquid in fabrics. It is used to identify dynamic liquid transport properties in three dimensions: absorption rate (time of moisture absorbency in inner and outer layers), one-way transport capability (the ability of fabrics to transport moisture one way from the inner to the outer layer), and spreading/drying rate (speed of spreading of moisture from the inner to the outer layer). This test used a test solution of synthetic sweat (16 mS +/- 0.2 mS); hence, it increases the accuracy of determining the comfortability of an athleisure bra for a Sri Lankan consumer in sweaty weather. The test was done at an ambient temperature of 20 °C with 3 samples for each fabric composition.

C.2 Experiments to identify the best fabric structure

The EMR test (elongation, modulus, and recovery) helps to find the amount of stretch and recovery of a fabric (Ltd. 06). Therefore, after choosing the best fabric composition through the above-mentioned tests, it was tested again from different structures to find stretch and recovery suitable for an athleisure bra. For this, some of the most common fabric structures are chosen by jersey structure, rib structure, and interlock structure.

FINDINGS

A. Findings From Interviews

The study interviewed seven professionals in the athleisure sector of Sri Lanka, including a pattern technician (interviewee 01), fabric technologists (interviewee 02 and 03), a merchant (interviewee 04), designers (interviewee 05 and 06), R&D Engineer (interviewee 07), to understand market and customer preferences for athleisure bras.

The first section explores Sri Lankan cultural and personal values regarding athleisure bras, revealing that usage is primarily among Colombo, indicating lower usage across the country. fabric technologist (Interviewee 02), notes women in Sri Lanka often wear tops or t-shirts above athleisure bras due to cultural difficulties. However, a designer, (Interviewee 04) suggests, there is a growing trend for sports bras among Gen Z and Alpha in Sri Lanka. Concluding, although there is a cultural barrier for Sri Lankan consumers, younger generations are increasingly embracing sports bras.

The second section addresses constructions, fabrics, trimmings, pricing, and suppliers in the current local market. Prices have risen from LKR 2000 to LKR 7000, with many suggesting Pettah and Pamunuwa markets for supplies, while few suggested online or international suppliers. Fabrics such as nylon/spandex and polyester/spandex are mentioned by fabric technologists, (interviewee 03) and a designer (interviewee 05) states that "hook and eye or the closure options and the adjustability ring and sliders are the key trims". The majority stated the construction method is cut and sew. The third section discusses prominent brands including Gap, Nike, Skims, Carnage, Puma, Asteroid, FOA, Amanté, and Adidas, buying habits, fitness, comfort, and tastings.

Many interviewees address the issue of sizes, with a designer (interviewee 05) suggesting a solution of “sizes indication in alpha and numeric.” In the importance of comfortability in product design, R&D engineer (interviewee 07) suggested construction and modern technologies such as bonding with perforated adhesives can enhance comfort. Fabric technologist, (interviewee

03) highlighted the role of fabric in product comfort. Designer (interviewee 06) suggested fewer seams, comfortable fabrics, constructions, and trims. Pattern technologist highlighted (interviewee 01) the use of comfortable straps.

The last questions targeted consumer buying patterns and suggestions. Some suggested Sri Lankan consumers prioritize aesthetics over support, while others believe trends of wearing sports bras is increasing. R&D Engineer, (interviewee 07) stated that the increasing number of women attending gyms is causing a rise in demand for sports bras, indicating a potential future growth in the athleisure market.

B. Observation studies on shop visits

The information gathered through visits to Carnage, FOA, Bolt gear, and Triumph focused on 5 topics: bra types, fabrics, fastening, construction, and cost.

B.1. Shop visit findings from the Sri Lankan brands situated in Colombo

As observed in Figure 2, the cost of a FOA bra starts from LKR 2500, which is the lowest price in the Sri Lankan market and leads to a Triumph bra of LKR 21999. The price range of Carnage and Bolt gear bras is LKR 2990 to LKR 7500. Comparatively, FOA is the most affordable brand for Sri Lankan consumers. Carnage & Bolt gear brands are in the middle.

Hence, the average price point of the sports bra in the Sri Lankan market is LKR 6679.

Bra type available in the local market is divided into two segments of Encapsulation and Compression bras. Triumph is the only brand providing Encapsulation bras to the local market. while other brands provide compression bras.

The most used fabric combination is Polyester/Spandex. Secondly, Nylon/Spandex. FOA and Triumph use Polyester/Cotton/Spandex in very limited quantities. The lease using fabric combination is cotton/spandex.

Although fastening methods of hooking and eye to zippers are used, the most common one is pullover. Cut and sew is the frequent construction method and the least used construction method is bonding. Triumph is using underwire, and all four brands are using cups.

Shop Observation format - Local brands								
Categories	Carnage One Galle face, Colombo		FOA One Galle face, Colombo		BOLT GEAR Thibirigasyaya		TRIUMPH Majestic City Colombo	
	Online	In-Store	Online	In-Store	Online	In-Store	Online	In-Store
Bra Types								
Encapsulation Bra							Yes	Yes
Compression Bra	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fabrics								
Polyester / Spandex	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cotton / Spandex							Yes	Yes
Nylon / Spandex	Yes	Yes	Yes	Yes	Yes	Yes		
Polyester / Cotton / Spandex			Yes	Yes			Yes	Yes
Any other fabrics			Yes	Yes			Yes	Yes
Fastening								
Hook & Eye							Yes	Yes
Magnets							Yes	Yes
Zippers							Yes	Yes
Any Other fastenings	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Trims								
Under-wire							Yes	Yes
Cups	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Straps	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sliders,Ring, J-hook							Yes	Yes
Constructions								
Cut & Sew	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Engineered Fabrics			Yes	Yes	Yes	Yes	Yes	Yes
Bonding							Yes	Yes
Cost								
Lowest (LKR)	3500	3500	2500	2500	2990	2990	6150	6150
Highest (LKR)	7500	7500	4900	4900	4900	4900	21999	21999

Figure 2: findings from the Sri Lankan brands

B.2 Shop visit findings from the international brands sold in Colombo.

Comparatively as in Figure 3, the cost of Aerie bras starts from LKR 8697 and leads to Sweaty Betty bras at LKR 32389. The starting price range of Lululemon, Nike, Adidas, and Athleta bras is between LKR 11396 to LKR 29990. When comparing prices Aerie is the most affordable brand to Sri Lankan consumers. Lululemon, Nike, Adidas, and Athleta stay in the middle. Hence, the average price of international brands in the Sri Lankan market starts from a minimum of LKR 12595 leading to a maximum average price of LKR 25362.

Shop Observation format - International brands							
Categories	Lululemon	Nike	Addidas	Under Armor	Aerie	Athleta	Sweaty Betty
Bra Types							
Encapsulation Bra	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Compression Bra	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fabrics							
Polyester / Spandex	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cotton / Spandex			Yes		Yes		
Nylon / Spandex	Yes		Yes	Yes		Yes	
Polyester / Cotton / Spandex			Yes		Yes		
Any other fabrics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fastening							
Hook & Eye	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Magnets					Yes		
Zippers					Yes		
Any Other fastenings	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Trims							
Under-wire							Yes
Cups	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Straps	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sliders,Ring, J-hook		Yes	Yes	Yes	Yes		Yes
Constructions							
Cut & Sew	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Engineered Fabrics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bonding	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cost							
Lowest (LKR)	11,396	11,996	11,996	8,997	8,697	14,695	20,393
Highest (LKR)	29,390	26,391	29,999	23,992	14,695	20,693	32,389

Figure 3: Findings from the selling of international brands in Sri Lanka

All international bras supply both Encapsulation and Compression bras to the local market. The most used fabric combination is Polyester/Spandex.

The second most used fabric combination is Nylon/Spandex. Only Adidas and Aerie are using Polyester/ Cotton / Spandex Cut and sew, and bonding are used by all international brands in Sri Lanka. As a design detail only Under Armor and Sweaty Betty brands are using underwire, All the brands are using cups.

C. Results of the Wicking Test

As per the wicking test results shown in Figure 4, cotton/polyester/spandex fabric had the highest water level of 17 cm within the first 15 minutes. This indicates that this fabric is highly absorbent when compared with the other fabrics. The nylon/spandex had the least water level of 9 cm.

The water level continued to increase for the next 45 minutes. Cotton/spandex had a difference of 2.5 cm to 1.5 cm to 1.5 cm in the timelines while the polyester/spandex had differences of 3.5 cm to 2 cm to 2 cm, but the polyester cotton spandex had a decelerating difference of 2 cm to 1.5 cm differences. The decreasing values of differences between levels of water rising shows that fabrics can easily release water to the outer layer. Hence, cotton/polyester/spandex shows a higher rate of releasing and drying than the other two combinations. Based on the wicking test, cotton/polyester/spandex combination is chosen as the fabric with the shortest time of absorbance and fastest drying among the other fabrics.

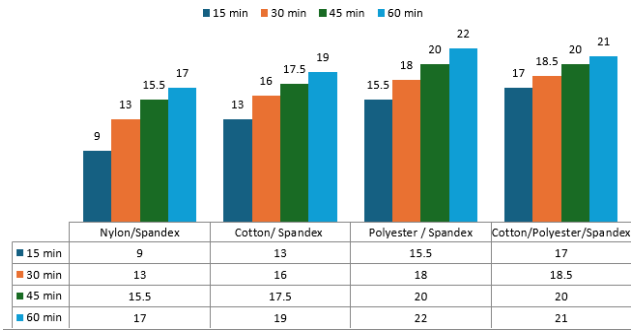

Figure 4: Wicking test results

D. Results Of the Moisture Management Test

The moisture management test uses a test solution of synthetic sweat (16 mS+/- 0.2mS); hence, it increases the accuracy of determining the comfortability of an athleisure bra for a Sri Lankan consumer in sweaty weather. The test was done at an ambient temperature of 20 ^{0}C with 3 samples for each fabric composition. The test results are given in Table 1.

Table 1: Moisture Management Test Analysis

Fabric	Nylon/ Spandex	Cotton/ Spandex	Polyester / Cotton	Cotton / Polyester / Spandex
Sample 01	0.716	0.4834	0.5078	0.7012
Sample 02	0.6974	0.4278	0.5165	0.6836
Sample 03	0.5656	0.447	0.5656	0.6614
Overall moisture management	0.6597	0.4527	0.4970	0.6820

The results show that the combination of cotton/polyester/spandex has a higher moisture management property than other fabrics.

E. Results of the EMR Test

Table 2 shows the load of stretch level at 40 % to warp and weft directions in 1ply and 2ply of fabrics. Interlock fabric is required with higher load of 0.90 lbs. when compared with other fabrics for weft direction. Further, recovery of a fabric is highly needed to a knit fabric to be in the right shape when going through various activities by the user. Snagging of a fabric will create discomfort and even various injuries. Table 2 also shows the recovery levels of each fabric. Interlock fabric is having highest recovery percentage.

Table 2: Load of stretch levels at 40 % and Immediate recover percentage

Structure	Warp or Weft Directions	Load of stretch levels at 40%		Immediate recover percentage	
		1ply	*2ply*	*1ply*	*2ply*
Rib	Warp	0.68	1.51	77%	84.6%
	Weft	0.31	1.06	80%	81.7%
Single Jersey	Warp	0.89	1.87	79.1%	83.4%
	Weft	0.47	1.13	76.4%	79.3%
Interlock	Warp	1.05	1.93	89.7%	92.4 %
	Weft	0. 90	1.37	91.2%	94.1%

Hence, interlock structure was selected as having the highest rate modulus suiting for an athleisure bra with best recovery.

CONCLUSION

A balanced lifestyle between health and work is a prominent future trend. Living to adoptability athleisure bras play a major role in today's economy. With observantly growing demand, this research focuses on exploring the current market and existing product properties to understand available products, identifying Sri Lankan consumer's needs and preferences for athleisure bras, and propose the best construction solutions to bridge the gap in the local athleisure bras market.

Observations and interviews revealed that Sri Lankan brands situated in Colombo lead to a conclusion about major concerns as most buyers are from the western province. Accordingly, the average highest price point is LKR 6679 and affordable options ranging from LKR 2500 to LKR 7000. When compared to international brands, the maximum price could be up to LKR 12000.

Compression bras are dominating the local market with most used fabric combination of Polyester/Spandex. However, the wicking, moisture management and EMR tests, indicates the most suitable fabric is polyester/cotton/spandex with an interlock structure for comfort in Sri Lankan climate. This was observed only in two bras of triumph and FOA, clearly indicating the gap of fabrics comfort suiting for environment and climate of Sri Lanka.

The most common fastening method is pull over and construction method is cut and sew due to cost effectiveness. Though, few semi bonding bras are available with higher advantages of comfort to the consumers in brands such as Triumph.

Interviewees explained regarding cultural barriers experienced by Sri Lankan consumers where many consumers are wearing a top above athleisure bras. Here, the importance of the moisture management property of polyester/cotton/spandex fabric is further highlighted. Also, the sizing issue can be addressed by alpha and numeric sizing systems as of international brands such as Third love given in Figure 5 when compared with sizing of a local brand, carnage.

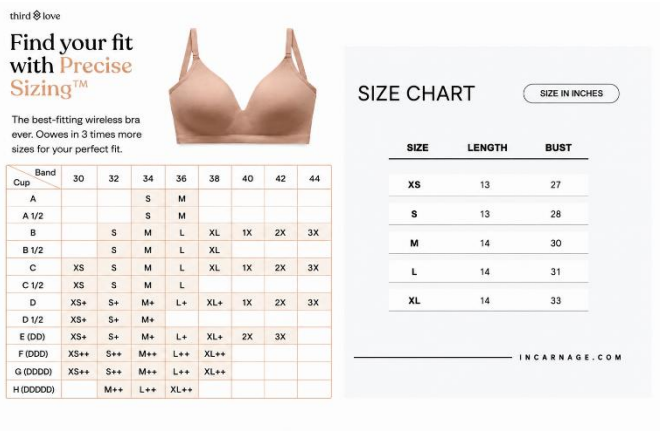

Figure 5: Sizing comparison of a local brand; carnage with Third love

In comparatively, no single parameter of fabric or construction excels independently when deciding to develop an athleisure bra but when analyzing for the most suitable constructions and design for solutions of comfort, cost effectiveness and sizing. The Figure 6 proposed a prototype of embodying optimum parameters through a compression bra for Sri Lankan market. This is a compression bra as it is the major type of bra found in the market and constructed using both cut and sew with semi bonding for comfort, support and durability. Made of cotton/polyester/spandex interlock fabric with two plies on the front from perforated glue for compression needed in low to mid impact and breathability. 1 ply on the back side for further breathability and moisture wicking. Razer back straps for higher support as it is consisting of pull over with no trims to have less cost in manufacturing. Turn bonded seams for neckline, armholes and waistline to provide support and durability as front panel needs a higher support in a bra (6). Used pullout seams for the sides to achieve less sewing construction to reduce cost and to increase durability due to being a pullover bra. Finally, the bra must be sized with numeric and alphabetic size to have a better fit and consumer satisfaction.

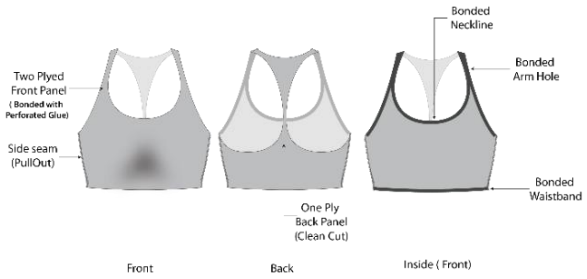

Figure 6: Prototyped bra suiting to Sri Lankan market

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RESEARCH ARTICLE

Evaluation of Seed Priming and Priming Agents for Enhancing Seed Germination and Vigor of Cowpea Seedlings (*Vigna unguiculata*)

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Abstract: Cowpea is a leguminous crop grown in tropical regions, including Sri Lanka, where abiotic stress factors, such as drought and soil salinity, often limit its productivity. This study aimed to evaluate the effects of different seed priming agents and early seedling growth under controlled environmental conditions. Nine priming treatments were tested, including Sodium Chloride, Oral Rehydration Salts, Albert solution, Sodium bicarbonate, Potassium chloride, Trichoderma asperellum, Kody mix, Hydrogen peroxide, and Triple super phosphate. Seeds were primed and monitored over a ten-week period. Germination performance was assessed using parameters such as time to first germination, time to fifty percent germination, final germination percentage, shoot length, root length.

The results revealed that all priming agents improved germination and seedling growth to varying degrees compared to the unprimed control. Among the treatments, Potassium chloride, Trichoderma asperellum, Kody mix, and Hydrogen peroxide showed the most significant enhancement in germination rate, uniformity, and seedling vigor. These findings indicate that appropriate seed priming agents can be effectively utilized to enhance germination performance and early seedling establishment of cowpea, thereby improving its productivity under tropical conditions.

Keywords: Cowpea, Seed Priming, Germination, Vigor Index, Shoot Length, Root Length.

INTRODUCTION

Cowpea is a drought-tolerant legume that plays a crucial role in food and nutritional security as a rich protein source in tropical and sub-tropical regions, especially in sub-Saharan Africa and parts of Asia.

Globally, Africa accounts for nearly 90% of cowpea production [1]. In Sri Lanka, cowpea is cultivated in the dry and intermediate zones such as Anuradhapura, Polonnaruwa, and Monaragala districts [2].

Cowpea production faces considerable challenges due to abiotic stress. Such stress disrupts the physiological processes of seed germination and often results in delayed emergence, poor seedling establishment, and reduced crop yields. Seed priming has emerged as a pre-sowing technique to improve germination and early seedling vigor. Seed priming is a controlled hydration technique that improves seed performance by partially hydrating seeds to a point where germination-related metabolic processes begin, but radicle emergence is withheld. As a result, primed seeds exhibit enhanced germination speed, uniformity, and tolerance to abiotic stresses [3].

Different priming methods have been explored in recent studies. Chemical priming with hydrogen peroxide (H_2O_2) and potassium chloride (KCl). Strengthens the antioxidant defense system and reduces oxidative damage caused by reactive oxygen species [4].

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In addition to improving stress tolerance, advances in cowpea breeding and crop improvement have highlighted seed enhancement technologies as an important strategy for increasing productivity under diverse environmental conditions [5]. Several studies have further demonstrated that seed priming enhances germination, seedling establishment, and overall crop performance under both biotic and abiotic stress conditions [6]. Previous studies have specifically reported that hydrogen peroxide pre-treatment alleviates salinity stress and improves germination and early seedling development in cowpea [7]. Recent investigations on cowpea have also shown that seed priming positively influences several physiological parameters, leading to improved germination and seedling vigor under field and laboratory conditions [8].

In Sri Lanka, cowpea is mostly cultivated under rainfed conditions. The risk of germination failure and low vigor is high due to irregular rainfall and soil degradation. Seed priming is a practical solution that enhances crop establishment, reduces seedling mortality, and ultimately ensures higher yields [2]. Moreover, the use of priming agents could help reduce production costs and support sustainable farming practices. This study was conducted to determine suitable seed priming agents and their optimal concentrations to enhance seed germination, seedling vigor, and ultimately increase growth, development, and seed yields of cowpea.

METHODOLOGY

This experiment was conducted from April to August 2024 (Yala season) at the Central Seed Testing Laboratory of the Seed Certification & Plant Protection Centre, Gannoruwa, Kandy, Sri Lanka (7° 2′ N latitude, 80° 56′ E longitude, and at approximately 490 m above mean sea level). The location was in the Agro-Ecological Region Mid-Country Intermediate Zone. The area experiences a moderate climate with intermittent rainfall and an average daytime temperature ranging from 25 °C to 31 °C during the study period.

The experiment was arranged in a two-factor factorial design, where nine priming agents and their concentrations were tested. Priming solutions were prepared using Sodium chloride (NaCl), Potassium chloride (KCl), Oral Rehydration Salt, Albert Solution, Sodium bicarbonate ($NaHCO_3$), Hydrogen peroxide (H_2O_2), Triple Super Phosphate (TSP), Kody mix (a multiplication medium used for shoot proliferation in banana tissue culture), and *Trichoderma asperellum*. For each agent, five concentration levels (0.5%, 1%, 1.5%, 2%, and 2.5%) were prepared by dissolving the required mass or equivalent volumes in 100 ml of distilled water. Hydrogen peroxide dilutions were calculated using the dilution formula $C_1V_1 = C_2V_2$, with the initial concentration being 6%. For *Trichoderma asperellum*, a series of dilutions was prepared.

Cowpea seeds of the Waruni variety were obtained from the Seed and Planting Material Development Center, Department of Agriculture, Sri Lanka. Seeds were

manually cleaned to remove physical contaminants and sorted for uniformity. Each treatment consisted of 50 seeds. Seeds were soaked in the priming solutions for 2 hours at 25 °C in a controlled environment chamber. After soaking, the seeds were air-dried at room temperature for 23 hours to restore the initial moisture level and prevent early germination. Primed seeds were placed in germination boxes filled with filtered sand. Each box received 50 seeds per treatment per replicate.

The following observations were recorded during the study,

- Time to first germination,
- Time to 50% germination
- Mean Germination Time (MGT)
- Germination percentage (GP)
- Seedling Vigor Index (SVI)

Seedling Vigor Index (SVI) was calculated as described [4] using the following equation;

Seedling Vigor Index = Seedling length x Germination Percentage.

Where SVI is the Seedling vigor index, and seedling length and germination percentage were derived from germination data (shoot and root lengths (cm) were measured from 25 randomly selected cowpea seedlings per replicate)

Statistical Analysis

Analysis of Variance (ANOVA) was performed for data using SAS statistical software. Mean separation was performed using the Least Significant Difference (LSD) test at the 5% significance level. Means comparisons were made to determine the effect of different priming agents and concentrations on cowpea seed germination and vigor parameters.

RESULT AND DISCUSSION

The experimental treatments significantly influenced parameters. Except for the time to 50% germination showed a significant interaction between the priming agent and the concentrations. The results are shown in Figures 1 to 5. The observations made on time to seed germination and percent germination, shoot length, root length, and vigor index are discussed below.

Time for 50 % germination

The percentage of germination among different priming agents and their concentrations was significant at $p \leq 0.05$. The treatment with H_2O_2 at a 0.5% concentration significantly reduced the time required for 50% germination, indicating its strong potential to accelerate germination in cowpea seeds. Sodium bicarbonate ($NaHCO_3$) also promoted earlier germination at 0.5 %. However, higher concentrations of $NaHCO_3$ were detrimental. This adverse effect may be attributed to osmotic stress and elevated pH, which reduced water uptake and seedling abnormalities such as root and shoot intertwining. These results suggest that the use of H_2O_2 at low concentrations, such as 0.5 %, is optimal for promoting rapid and uniform germination.

Shoot length

The interaction between priming agents and concentrations gave the longest shots (19.04 cm) by Kody mix solution at 0.5 % (Figure 1). This may be attributed to its balanced nutrient content, which supplies essential macronutrients, including nitrogen, phosphorus, and potassium. Along with plant growth regulators which support robust shoot growth. Other priming agents, such as Oral Rehydration Salt and Albert solution, also showed moderate but stable improvement. H_2O_2 treatments promoted thick and strong shoots across a wide range of concentrations. *Trichoderma asperellum,* a biological priming agent, also enhanced the shoot growth.

Root length

Trichoderma asperellum and KCl significantly increased root length, and *Trichoderma* at 0.5 % concentration produced the longest roots. The beneficial effect of *Trichoderma* is likely due to its improvement of soil health, leading to enhanced nutrient and water uptake under abiotic stress conditions. KCl and Albert Solution supported root growth at lower concentrations but reduced effectiveness at higher concentrations. H_2O_2 consistently promoted root growth, possibly by modulating reactive oxygen species involved in stress tolerance and root development (Figure 2).

Seedling Length

Lower concentrations of priming solutions (0.5 % and 1%) generally produced longer seedlings compared to

the higher concentrations tested. KCl, Trichoderma, and Kody mix maintained stable seedling lengths across all priming solutions. However, higher concentrations of $NaHCO_3$ and TSP reduced seedling growth (Figure 3).

Vigor Index

The highest and most stable vigor index was found with KCl and *Trichoderma* treatments. KCl reached a peak vigor index of 4111.66 at 1 %, reflecting its strong positive effect on seedling health and growth. *Trichoderma* also showed high vigor indices at lower concentrations, though a decline was observed at higher levels. H_2O_2 was effective at both low (0.5%) and high (2.5%) concentrations (Figure 4).

Germination Percentage

NaCl, KCl, and H_2O_2 treatments enabled up to 100 % germination of cowpea seeds. In contrast, $NaHCO_3$ inhibited germination when used as a priming agent. Moderate concentrations (0.5 %- 1 %) consistently gave the best results, while higher concentrations used decreased germination rates (Figure 5).

CONCLUSION

Seed priming with Hydrogen peroxide (H_2O_2), Potassium chloride (KCl), and *Trichoderma asperellum* at moderate concentration (0.5 % - 1 %) significantly improved cowpea germination, seedling vigor, and early growth. H_2O_2 at 0.5 % effectively reduced the time required for 50 % germination by enhancing enzyme activity and braking dormancy. KCl and *Trichoderma asperellum* promoted superior root and shoot development. Higher concentrations of sodium bicarbonate ($NaHCO_3$) negatively affected seed performance. Therefore, priming H_2O_2, KCl, and *Trichoderma asperellum* at 0.5 % -1 % is recommended for improving cowpea seed germination and establishment under stress conditions.

Table 1: Effects of priming agents and their concentration on germination and seedling growth parameters in cowpea

Treatment Priming Agent and Concentration	Time for 50 % germination days a
Priming agent	
NaCl	3.20a
Oral Rehydration Salt	3.00b
Albert Solution	3.00b
KCl	3.20a
Kody Mix Solution	3.13a
$NaHCO_3$	2.53c
H_2O_2	2.40d
TSP	3.00b
Trichoderma asperellum	3.00b
LSD (p≥0.05)	0.12
Concentration	0.24
0.5 %	3.03b
1 %	3.03b
1.5 %	3.22a
2 %	2.55d
2.5 %	2.85c
LSD (p≥0.05)	0.24

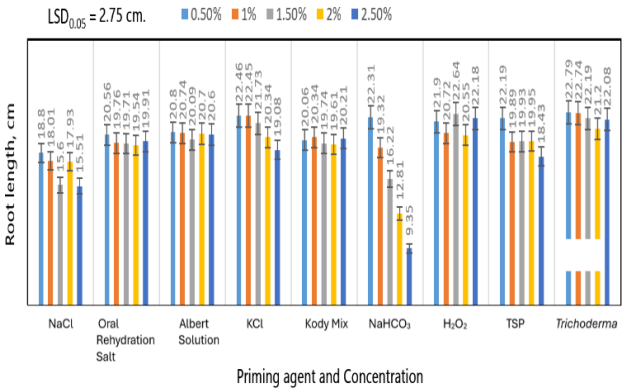

Figure 1: Effect of the priming agent and its concentration on the mean shoot length of cowpea seedlings

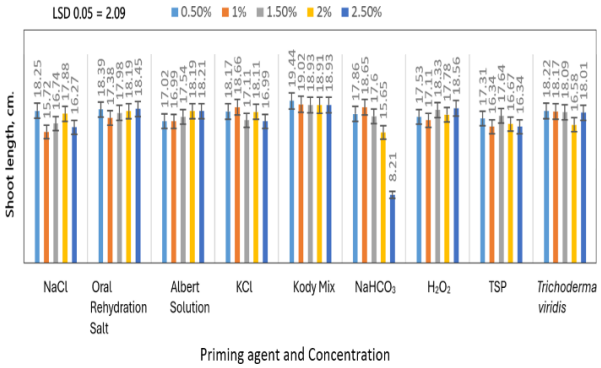

Figure 2: Effect of the priming agent and its concentration on the mean root length of cowpea seedlings.

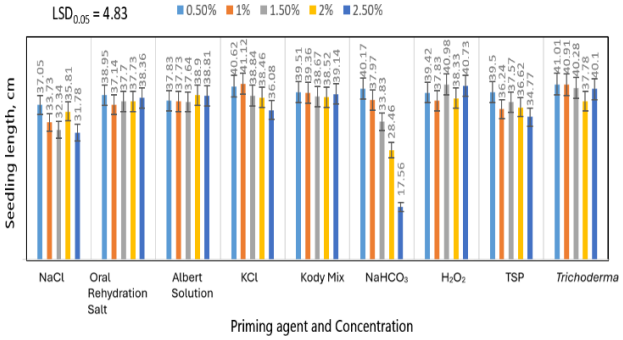

Figure 3: Effect of priming agent and concentration on the mean seedling length of cowpea seedlings.

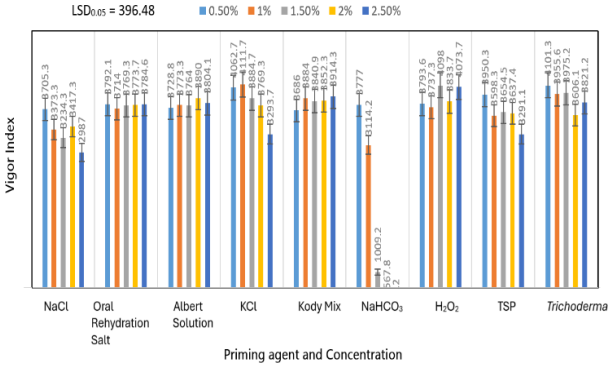

Figure 4: Effect of priming agent and their concentration on the vigor index of cowpea seedlings.

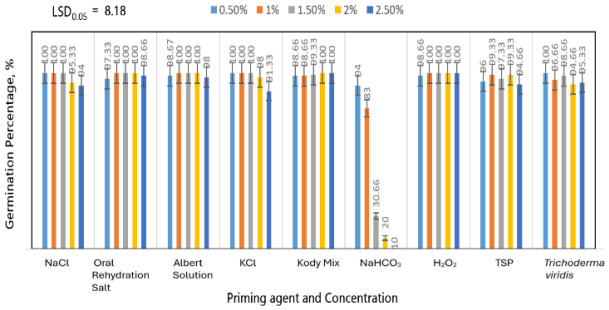

Figure 5: Effect of priming agent and concentration on mean germination percentage of cowpea seeds

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RESEARCH ARTICLE

Farmer Perceptions and Adoption of Voice- Based AI in Agricultural Advisory: A case Study of "Govi Mithuru" by Dialog Axiata in Sri Lanka

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Abstract: Agriculture can be introduced as an important sector in Sri Lanka with the approximate contribution of 7% to the national GDP and ensuring employment opportunities to over 30% of the population in Sri Lanka. Smallholder farmers who cultivate less than two hectares can be considered vital in ensuring food security by contributing the major rice, fruits and vegetables production. To help these farmers, Dialog Axiata launched Govi Mithuru ("Farmer's Friend"), a mobile based voice AI advisory service providing tailored agricultural guidance on land preparation, pest control, harvesting and family nutrition. This study was conducted to analyze the small holder farmers' use, satisfaction and experience with Govi Mithuru voice AI in the Galle district. A quantitative descriptive research design was developed to collect the data using a structured questionnaire in Sinhala. Out of 88 targeted farmers, 35 respondents completed the survey within the given time. Data was analyzed using descriptive statistics and cross tabulation in SPSS. According to the results of the study, 91.4% of farmers agreed that the service was attractive, 82.9% were satisfied with the speed of responses, and 68.6% perceived the information as accurate and trustworthy. Overall, farmers reported positive experiences with 100 % of farmers recommending the Govi Mithuru Voice AI service to other farmers. There were minor network and language issues reporting only by six respondents. Farmers indicated the importance of Govi Mithuru Voice AI service in enhancing agricultural knowledge and accessibility, especially for less experienced farmers. This study suggests the significance of Govi Mithuru Voice AI in improving agricultural knowledge among communities and improving agricultural productivity.

Keywords: Agriculture, Digital Advisory Service, Govi Mithuru, Small holder farmers, Sri Lanka, Voice AI

INTRODUCTION

Sri Lankan agricultural sector is an important economic sector contributing to approximately 7% of the GDP and giving employment opportunities over 30% of the Sri Lankan population. Major crops growing in Sri Lanka are paddy, tea, rubber, coconut and different types of fruits and vegetables. Agriculture sector plays a vital role in assuring food security and poverty reduction in Sri Lanka [1].

Small holder farmers are important to Sri Lankan agriculture since they produce most rice, fruits and vegetables on less than 2 hectares of land and contribute majorly to food security. Mithuru voice AI system small holder farmers were aimed at in this study (Ministry of Agriculture) [2].

Eighty-eight farmers were selected for the study. Only 35 percent famers were completed the survey. Phone call interviews were conducted to collect the data.

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Govi Mithuru, which translates from Sinhala to "Farmer's Friend," is a mobile-based agricultural advisory service launched by Dialog Axiata in 2015 to empower farmers across Sri Lanka with critical, timely information. Initially, the service operated on Interactive Voice Response (IVR) technology, delivering pre-recorded, customized voice messages on topics such as land preparation, sowing schedules, pest control, harvesting, and family nutrition. Upon registration, users could select their crops and location, prompting the system to automatically send personalized voice calls with step-by-step guidance throughout the crop cycle.

A key design principle was inclusivity; by using IVR, the service remained accessible to individuals with basic mobile phones, overcoming barriers related to smartphone ownership and literacy. To cater to Sri Lanka's diverse population, all content was provided in Sinhala, Tamil, and English.

In 2025, the service was significantly upgraded with the launch of the Govi Mithuru Voice AI (beta version), transforming it from a one-way information-push system to a fully interactive advisory platform. This evolution is driven by an integrated AI system built on a Retrieval-Augmented Generation (RAG) architecture and a speech-to-speech Large Language Model (LLM).

This advanced approach allows a farmer to ask a question in their natural spoken language; the system then searches a curated agricultural knowledge base for relevant facts and uses the generative model to synthesize a precise and contextually appropriate verbal response.

The RAG framework is crucial as it grounds the AI's answers in factual data, mitigating the risk of inaccurate "hallucinations" and ensuring reliable advice. By offering a fully conversational voice interface, Govi Mithuru Voice AI is designed to completely overcome literacy barriers, empowering any farmer to receive instant, tailored advice whenever they need it [3].

After developing partnership with the Ministry of Agriculture, Ministry of Health and CABI, this service was tailored to each farmer’s crop, location cultivation stage. Govi Mithuru is important to bridge the information gap in rural farming communities, empowering smallholder farmers to improve productivity, protect crops and enhance household well-being.

It can be seen a growing integration of voice-based AI technologies in agriculture. However, there is a significant gap in understanding how farmers, particularly smallholders in developing regions- interact with these systems. While platforms like Govi Mithuru aim to democratize access to agricultural knowledge through voice interfaces, empirical research on user experience, trust, and behavioral adoption is limited.

Most studies focus on technical feasibility or system architecture, rather than farmer- centric usability and engagement [4]. Hence this research study was conducted to identify the farmer centric usability and engagement of the Govi Mithuru Voice AI in Galle district Southern Province in Sri Lanka. In here, the ease of use of the system, the level of satisfaction with its speed, relevance, and usefulness, and the accuracy and trustworthiness of the responses were evaluated.

The study also explored the extent to which the language and style of the service are relatable to farmers and network and language barriers.

METHODOLOGY

This study used a quantitative descriptive research design to analyze the user perceptions and experiences with the Govi Mithuru Voice AI service. The approach was selected to systematically collect the measurable data on usability, accuracy and adoption factors of Govi Mithuru Voice AI among Sri Lankan small holder farmers.

A structured questionnaire was used to collect the primary data, and a comprehensive literature review was conducted to collect the secondary data. The target population was registered small holder farmers in Galle district, southern Province in Sri Lanka. A purposive sampling technique was used to identify participants who actively engage with the Govi Mithuru Voice AI service.

A sample of 35 small holder farmers in Galle district was selected for the study.

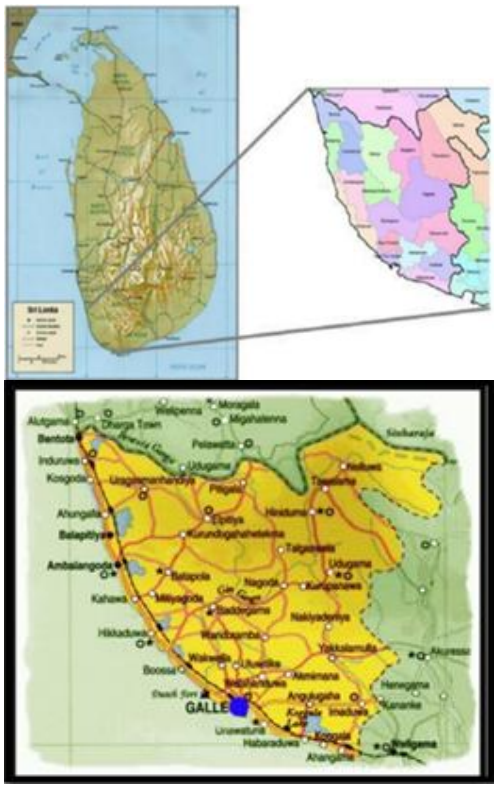

Figure 1: Area of research study- Galle district

A structured questionnaire was used to collect the primary data. The questionnaire was developed in English and Sinhala to ensure linguistic accessibility. Questionnaire was divided into 8 sections, and first section was used to gather data on general information about the farmers. Second section was developed to gather data on ease of use of the Govi Mithuru Voice AI. Third section was used to collect data on user experience. Other sections were used to collect data on accuracy of the responses, familiarity of the model, usefulness, willingness to pay and potential problems, issues of using voice AI. Most items were measured using a 5-point Likert scale (1= Strongly Disagree to 5= Strongly Agree), along with multiple –choice and open-ended questions to capture qualitative insights.

Data was collected through telephone interviews and in-person surveys depending on the respondents' location and accessibility. Respondents were assured of confidentiality and the academic purpose of the study. Quantitative data were analyzed using descriptive statistics (mean, frequency, percentage) and cross tabulation to identify patterns across demographic groups. Statistical software named SPSS was used to analyze the data.

RESULTS AND DISCUSSION

A. General information of the respondents

A total of 88 farmers in Galle district were contacted for the study, and 35 respondents completed the survey. Majority of the participants of this study were smallholder farmers cultivating mainly paddy. Besides paddy most of the farmers were in the cultivation process of vegetables, cereals, Plantation crops (tea, coconut, rubber, oil palm, and sugarcane), fruit crops, mushroom, leafy vegetables, ornamental plants and medicinal plants for subsistence and local market. When considering farming experience, most of the farmers had more than 15 years of farming experience highlighting a sample composed largely of experienced cultivators. 96.4% of farmers agreed that they use any agricultural advisory service to get cultivation related advice. From that, 87.6% farmers considered government services as their current agricultural advisory service provider. Other farmers were using private consultancy, online platforms (websites, apps and social media) to get agricultural advice. 96.6% of farmers agreed that they are satisfied with their current agricultural advisory service provider.

B. Ease of use of the Govi Mithuru Voice AI

Table 1: Ease of use Govi Mithuru Voice AI. (n=35)

Scale	Percentage of Respondent				Mean	Standard Deviation
	D	N	A	SA		
It is easy to start the Govi Mithuru Voice AI	5.7	2.9	71.4	20	4.05	0.68
The Voice AI language is familiar and relatable	8.6	5.7	80	5.7	3.82	0.66
Interacting with voice AI helps to think and stay mentally active	20	8.6	68.6	2.9	3.54	0.85
Overall, the voice AI is good and attractive	0	2.9	91.4	5.7	4.028	0.29

Source: Author compile (2025)

(D-Disagree, N-Neutral, A - Agree, SA-Strongly Agree)

As presented in Table 1, Most farmers reported that the Govi Mithuru Voice AI was easy to start (71.4% agreed, 20% strongly agreed, M= 4.06, SD=0.66).

This is further illustrated in Figure 2.

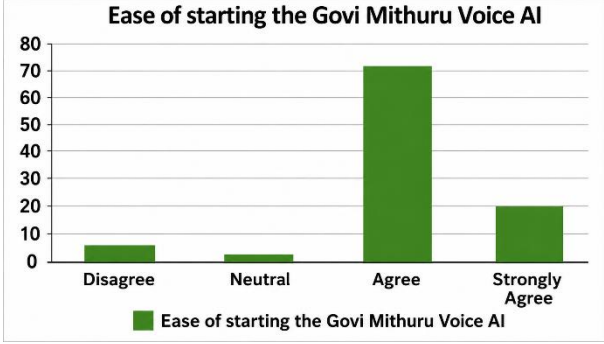

Figure 2: Ease of starting Govi Mithuru Voice AI

This high level of acceptance indicates the service is user-friendly and accessible.

Similarly, 80% agreed that the system was familiar and relatable (M=3.83, SD= 0.66). However, responses were more mixed regarding whether interacting with Voice AI helped them stay mentally active, with 20% disagreeing and 68.6% agreeing (M=3.54, SD= 0.84). 91.4% of farmers agreed that they felt that the voice AI is good and attractive, and 5.7% strongly agreed with the statement.

These findings indicate that the system is accessible and linguistically relatable to rural users.

These findings are aligned with the research finding that discusses the importance of localized content in agricultural extension services [5].

C. User experience of the Govi Mithuru Voice AI

As shown in Table 2, 82.9% of farmers expressed satisfaction with the speed of responses by the Govi Mithuru Voice AI. 74.3% agreed that the information provided was relevant and useful (M=3.77, SD=0.69). 91.4% agreed that, according to their opinion, it was very desirable and worthwhile to use the Voice AI for farming and related purposes. Furthermore, 97.1% showed positive feelings towards the Voice AI (M=4.14, SD=0.43).

Table 2: User Experience of the Govi Mithuru Voice AI

Scale	Percentage of Respondents				Mean	Standard Deviation
	D	N	A	SA		
Satisfaction with the speed of the Voice AI responses for queries	5.7	11.4	82.9	0	3.77	0.54
The voice AI provides relevant and useful information to queries	8.6	11.4	74.3	5.7	3.77	0.68
It is very desirable and worthwhile to use Voice AI for farming and related purposes	5.7	2.9	80	11.4	3.97	0.61
Overall, there are positive feelings towards the Voice AI	0	2.9	80	17.1	4.14	0.42

Source: Author Compile (2025)

(D-Disagree, N-Neutral, A-Agree, SA-Strongly Agree)

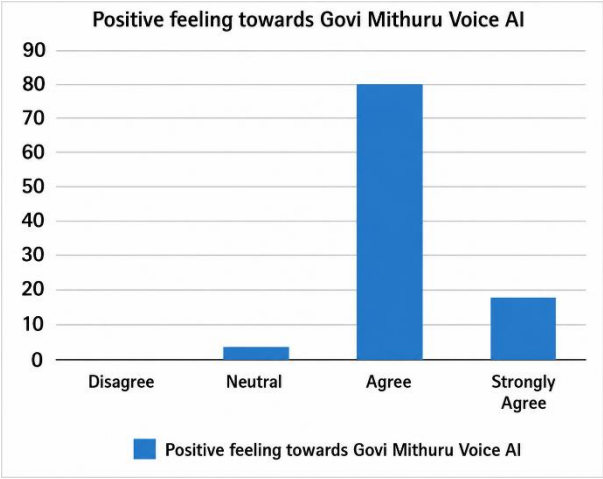

Figure 3: Positive feeling towards the voice AI

According to these results, the service is perceived as efficient and valuable aligning with evidence regarding mobile based advisory tools that enhance knowledge dissemination and decision- making among smallholders [6].

D. Accuracy of Responses

Table 3: Accuracy of responses of the Govi Mithuru Voice AI

Scale	Percentage of Respondents					Mean	Standard Deviation
	SD	D	N	A	SA		
The voice AI provide accurate and trustworthy information	2.9	11.4	8.6	68.6	8.6	3.68	0.90
The answers of the Voice AI correspond to the question asked.	2.9	11.4	8.6	71.4	5.7	3.65	0.87
Satisfaction with the Voice AI responses for my queries as a farmer.	0	11.4	5.7	82.9	0	3.71	0.66

Source: Author compile (2025)

(SD-Strongly disagree, D-Disagree, N-Neutral, A-Agree, SA-Strongly Agree)

According to the above table 3, Perception of accuracy was largely favorable with 68.6% agreeing that the information was accurate and trustworthy (M=3.69, SD=0.90). Similarly, 82.9% were satisfied with the responses to their queries (M=3.71, SD= 0.67) while these findings indicate high levels of trust in the Govi Mithuru Voice AI service, a small proportion of respondents (11.4%) expressed dissatisfaction, suggesting occasional mismatches between queries and system responses. This can be due to contextual limitations of AI driven advisory systems as also notes in previous ICT4D studies [7].

E. Familiarity of the model

Table 4: Familiarity of the model (n = 35)

Statement	Percentage of Respondents				Mean	Standard Deviation
	D	N	A	SA		
The Voice AI language aligns with communication pattern of farmer	11.4	5.7	80	2.9	3.74	0.70
Voice AI is relatable and understands farmer context as the farmer.	11.4	5.7	80	2.9	3.74	0.70
The Voice AI answer style meets farmer expectations and preferences	14.3	5.7	74.3	5.7	3.71	0.78

Source: Author compile (2025)

(D-Disagree, N-Neutral, A-Agree, SA-Strongly Agree)

According to table 4, most respondents agreed that the language and communication style aligned with their expectations (M=3.74, SD=0.70).

F. Usefulness Of the Service

Table 5: Usefulness of the Govi Mithuru Voice AI (n=35)

Statement	Percentage of Respondents				Mean	Standard Deviation
	D	N	A	SA		
Voice AI provides service and information very useful in farming activities	17.1	8.6	71.4	2.9	3.60	0.81
Using voice AI would improve performance in farming activities	14.3	8.6	77.1	0	3.62	0.73
Voice AI adds value to farming activities	14.3	5.7	77.1	2.9	3.68	0.75

Source: Author compile (2025)

(Disagree, N-Neutral, A-Agree, SA-Strongly Agree)

According to the above table 5, 71.4% agreed that the service is valuable for farming activities, and 77.1% believed it improved performance. Hence it is clear that Govi Mithuru Voice AI has the capacity to supply traditional extension services and improve decision making in rural environments.

G. Challenges and Recommendations

When considering the challenges, six respondents reported challenges, five related to network connectivity and another one related to language barriers. Farmers also highlighted the need for regular content updates for the better knowledge updates among farmers on different topics such as emerging crop diseases, fertilizer use and water management.

H. Willingness to pay

None of the farmers currently paid for advisory services, yet 57.6% of farmers indicated their willingness to pay a

small fee for the regular usage of the Govi Mithuru Voice AI service. This is further illustrated in figure 4.

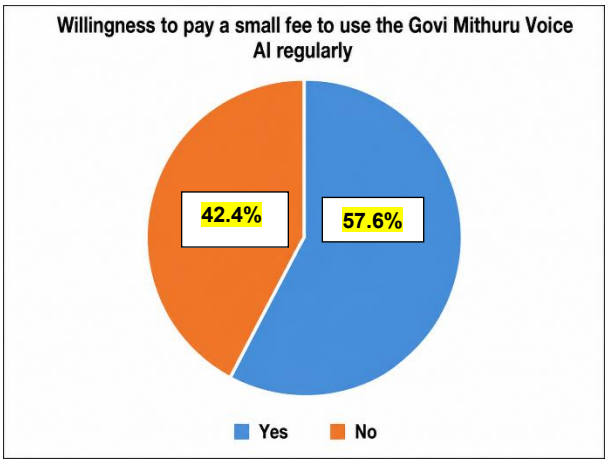

Figure 4: Willingness to pay for Govi Mithuru Voice AI service

Following figure 4 shows the amount that farmers are willing to pay for the Govi Mithuru Voice AI service.

Majority of the farmers (95.2%) mentioned their willingness to pay RS 250-RS 500 per month and only 4.8% of farmers indicated that they are willing to pay RS 500 - RS 750 per month. 100% of the farmers indicated willingness to recommend Govi Mithuru Service to others, mentioning its ability to provide timely knowledge, especially for less experienced farmers.

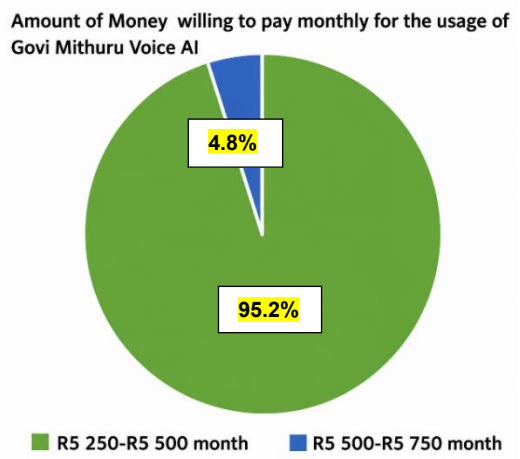

Figure 5: Amount of money that farmers are willing to pay for the Govi Mithuru Voice AI service.

I. Relationships Between Farmer Characteristics and Govi Mithuru Voice AI Usage

Table 6: Cross tabulation of Farming Experience and Satisfaction with Voice AI responses

Farming Experience	Disagree	Neutral	Agree	Total
< 5 years	0	0	3	3
5-10 years	0	0	3	3
10-15 years	0	1	4	5
>15 years	4	1	19	24
Total	4	2	29	35

Source: Author's survey data (2025)

Cross tabulation (Table 6) shows that all farmers with less than 10 years of experience agreed with the Voice AI satisfaction. Among those with 10-15 years of experience, four agreed while one was neutral. Farmers with more than 15 years' experience showed mixed responses. 19 agreed, one neutral and four disagreed. Overall, the majority across all experience groups reported satisfaction with the service. This shows the broad applicability of the Govi Mithuru Voice AI regardless of the user farming experience.

Table 7: Cross tabulation of Age range and ease of use Govi Mithuru Voice AI.

Age range	Disagree	Neutral	Agree	Strongly Agree	Total
25-35	0	0	2	0	2
35-45	0	0	3	1	4
45-55	0	0	8	4	12
>55	2	1	12	2	17
Total	2	1	25	7	35

Source: Authors survey data (2025)

According to Table 7, it can be seen a clear pattern between age range and the ease of starting the Govi Mithuru Voice AI. Younger farmers (25-35 years) all agreed that the system was easy to start, while older farmers (> 55 years) showed more mixed responses, with two disagreeing and 1 reporting neutral views. Most respondents across all age groups, however, agreed or strongly agreed that system was easy to start (91.4% in total), indicating that age had little negative impact on usability. Overall, the study indicates that the Govi Mithuru Voice AI is widely accepted, accessible, and trusted among Sri Lankan smallholder farmers. It addresses information gaps in agriculture, particularly where access to extension officers is limited. These results confirm prior evidence on the role of mobile-based advisory systems in enhancing productivity, reducing knowledge asymmetry, and contributing to food security [8]. For the sustainable use of the Govi Mithuru Voice AI among farmers, it is important to overcome the challenges such as limited technical infrastructure and the need for updated content.

CONCLUSION

This study analyzed how smallholder farmers in Galle district interact with and experience the Govi Mithuru Voice AI as an agricultural advisory service. According to the results of the study farmers indicate the service as highly valuable and practical, especially for providing timely and relevant farming advice. The results of the study show that most of the farmers in Galle district had positive experiences with the Govi Mithuru Voice AI service. Most farmers (71.4% agree, 20% strongly agree) agreed that the service is easy to start, and 80% reported that the language was familiar and relatable. 82.9% of farmers considered the information relevant and 74.3% of farmers indicated that the service is useful. A large majority (91.4%) agreed that the system was attractive, while 80% expressed positive feelings towards using it.

Even though this research findings confirm the usefulness and acceptance of the Govi Mithuru Voice AI, study was limited to a small sample in one district. Future research should be expanded into other regions and explore long-term impacts on productivity and income. This service is a useful digital advisory tool and can be used to strengthen the food security and support the smallholder farmers in Sri Lanka.

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RESEARCH ARTICLE

Gate-to-Grave Life Cycle Assessment of Ceramic Tile: A Case Study of a Colombo Luxury Residence

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Abstract: This study carries out a gate-to-grave Life Cycle Assessment (LCA) of ceramic tiles to evaluate their environmental impacts in a luxury residential project in Colombo, Sri Lanka. The assessment compares manual carbon footprint calculations with results from SimaPro LCA software, encompassing the transportation, installation, usage, and disposal phases. Updated results show that the cleaning phase is the highest contributor to emissions. Manual calculations estimated 615,078.34 $kgCO_2eq$ (83.85 $kgCO_2eq/m^2$) over a 100-year lifespan, while SimaPro reported 632,197 $kgCO_2eq$. Emissions from tile production, adhesive application, and grout usage were also reassessed, with only minor differences between methods. Both approaches identified the same high-impact stages, confirming the reliability of manual methods, while SimaPro offered a more detailed impact category breakdown. Recommended sustainability strategies include switching to eco-friendly cleaning agents, recycling waste tiles into concrete aggregates, and optimizing water usage to reduce greenhouse gas emissions and resource consumption in Sri Lanka's construction sector.

Keywords: Life Cycle Assessment, Sustainability, Ceramic Tile Waste, Construction Waste, Greenhouse Gases

INTRODUCTION

A. Background of Research

The construction industry is one of the largest users of materials and energy, creating significant environmental impacts through raw material extraction, manufacturing, transportation, and waste generation. Among the many finishing materials, ceramic tiles are widely chosen because of their durability, low maintenance, and attractive appearance. However, ceramic tile production is highly energy-intensive, involving clay extraction, glazing, and high-temperature firing processes, which release large amounts of greenhouse gases (GHGs) and contribute to climate change [1].

Life Cycle Assessment (LCA) is a systematic analytical methodology for evaluating the environmental impacts of a product or process throughout its entire lifecycle. This includes looking at raw materials, manufacturing, transportation, use, and disposal [2]. In construction, LCA can identify which steps cause the most harm to the environment and help find better solutions. For ceramic tiles, LCA can show how making and wasting tiles affects the environment and suggest ways to recycle or reuse the tiles [3]. Many studies focus on the cradle-to-gate part of the LCA, which looks at environmental effects from raw material extraction to when the tile leaves the factory.

Research in Sri Lanka shows that the most energy is used during glazing and firing [4] processes. The firing process alone takes up 40% of total energy because the kilns must reach extremely high temperatures. Some studies suggest that reducing energy use by just 1% can lower CO_2 emissions significantly [5]. Earlier research on ceramic tiles focused only on the cradle-to-gate phase, which includes raw material extraction and manufacturing. However, recent studies show it is also very important to look at the entire lifecycle, including transportation, installation, long-term cleaning and maintenance, and end-of-life disposal.

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For example, [6] a cradle-to-grave Life Cycle Assessment (LCA) of glazed ceramic tiles was carried out in Spain. They found that cleaning and maintenance during the building's lifetime added a large amount to the total carbon footprint, sometimes even higher than the emissions from tile manufacturing. This is similar to the findings at selected construction sites, where cleaning the tiles over 100 years caused more than 60% of the total lifecycle emissions.

It is highlighted that firing ceramic tiles at very high temperatures (around 1200 °C) [7] using fossil fuels is the biggest source of greenhouse gas emissions in the tile lifecycle. It is also suggested that using eco-design strategies, like renewable-energy kilns and low-impact glazing, could reduce emissions by up to 20%. Similarly, a case study in China [8] showed that replacing coal-based electricity with hydropower in tile factories reduced lifecycle emissions by 98%, although problems like marine ecotoxicity from glaze chemicals remain. A wider review by Vierra [9] found that the ceramic tile industry still depends heavily on non-renewable fuels, and recycling at the end of a tile's life is very limited. The study recommended more gate-to-grave assessments that also look at installation waste, transport emissions, and disposal impacts, which are very important for large-scale projects like luxury apartments.

By quantifying emissions and proposing sustainable alternatives, the research aims to minimize impacts and support circular economy practices in the local construction sector. The assessment builds on global findings that maintenance phases, like cleaning, often dominate emissions, while installation waste exacerbates financial and environmental costs. Local challenges, such as limited recycling infrastructure, highlight the need for targeted solutions to reduce the sector's carbon footprint.

B. Aim and Objectives

This research aims to identify the environmental impact of ceramic tiles by conducting a life cycle assessment and proposing a sustainable waste management solution to minimize the overall environmental impact.

Objectives of the research are,

1. Identify the parameters required for conducting an LCA on ceramic tiles.
2. Study the life cycle of ceramic tiles, including production, use, and disposal phases.
3. Evaluate the environmental impact of ceramic tiles using LCA methodologies.
4. Propose sustainable waste management strategies for recycling and environmentally safe disposal of ceramic tiles.

METHODOLOGY

The life cycle assessment of Ceramic Tiles was done by following the steps.

A. Establish the goals and Scope
B. Conduct inventory analysis
C. Assess the Impact
D. Interpret the results

The main goal of this Life Cycle Assessment (LCA) is to evaluate how ceramic tile impacts the environment in Sri Lanka's construction industry. Construction projects generate significant amounts of tile waste due to factors like breakage, incorrect sizing, and design modifications. If this waste is not managed properly, it can lead to environmental problems such as resource depletion, energy waste, and excessive landfill use.

The scope of this study covers the life cycle of ceramic tiles, following a gate-to-grave approach. This means the research will analyze each stage of the tile's existence, from the point where the product arrives at the construction or usage site, until it is disposed of at the end of its life, ensuring a comprehensive assessment of its environmental impact.

Data were collected from the Colombo luxury residence site, including tile quantities (20,780 tiles imported, 5 percent wastage), adhesive (3,400 bags at 25 kilograms each), grout (1,000 kilograms), transport details (diesel trucks over short distances), and maintenance practices (cleaning 4 times monthly per apartment over 100 years). The functional unit was 1 square meter of ceramic tile, with a system boundary from gate-to-grave, excluding infrastructure. Life cycle inventory used field data and emission factors (Eg, Emission factor of carbon dioxide for ceramic tile was 14.4 $kgCO_2eq/m^2$, Emission factor of carbon dioxide for Adhesive was 1.2 $kgCO_2eq$). Impacts were calculated manually in Excel. Assumptions included average tile weight (3 kilograms per tile) and fuel consumption (3.3-3.5 kilometers per liter). Alternative flooring options were compared based on literature data for embodied carbon, durability, maintenance, and recyclability.

Waste quantification involved summarizing balance sheets for tiles, adhesives, and grouts. Environmental impacts were assessed across phases: tile usage, adhesives/grouts, transport, cleaning, and disposal. The key stages included in this study are:

- Transportation and Distribution - The movement of raw materials and finished tiles relies on fuel-powered transportation, mainly diesel and petrol, which contributes to carbon emissions. This study assesses how transportation impacts the environment and explores methods to optimize logistics and reduce emissions.
- Installation and Usage Phase - Ceramic tiles are durable and require little maintenance once installed. However, installation generates waste due to breakage, cutting, and incorrect sizing. This study quantifies tile waste during installation and examines how improper handling contributes to material loss.
- Waste Generation and Disposal-Large amounts of broken or unused tiles from construction projects are often discarded in landfills, contributing to waste accumulation and land occupation. This research evaluates the long-term environmental risks of tile waste disposal.
- Opportunities for Recycling and Reuse - Recycling is a more environmentally friendly option than disposing of waste in landfills. This study investigates several recycling techniques, such as breaking broken tiles for mosaics or landscaping, crushing waste tiles for use in concrete, and grinding them into powder for the creation of new tiles. Considering variables like cost, material qualities, and industry acceptance, the study also evaluates the viability of these recycling options in Sri Lanka.

A. Functional Unit

This study uses one square meter (1 m^2) of ceramic floor tile as the functional unit to precisely measure and compare environmental impacts [4]. This means that all calculations, whether related to energy consumption, raw material use, emissions, or waste generation, will be based on the impact per 1m² of ceramic tile and the system of the analysis is the single-fired ceramic tile with an average density of 17.23 kg/m^2. [6]

B. System Boundary

This study adopts a gate-to-grave boundary, meaning it covers all life cycle stages from the point where the product arrives at the construction or usage site, until it is disposed of at the end of its life or recycling of tile waste. However, some factors are excluded from the assessment:

- Infrastructure and Capital Goods - The environmental impact of setting up tile manufacturing plants, machinery, and transportation infrastructure is not included. This exclusion is because factories, equipment, and transport systems serve multiple production cycles and are not exclusive to ceramic tiles.
- Non-Material Emissions - Indirect environmental effects like noise pollution from machinery and aesthetic impacts of mining are not assessed. While these factors can have social and ecological consequences, they are outside the core environmental focus of this LCA.

C. Conduct Inventory Analysis

To conduct an LCA of ceramic tile waste, it is essential to collect detailed Life Cycle Inventory (LCI) data. This data provides the necessary input for the software to calculate environmental impacts, ensuring a comprehensive and data-driven sustainability analysis.

The critical data categories required for the LCA model are as follows:

I. Transportation and Distribution Data

Once ceramic tiles are manufactured, they must be transported to distribution centers and construction sites. The environmental impact of this stage is influenced by:

- Fuel consumption and emissions - The mode of transport (trucks, ships, or containers) determines the amount of diesel or gasoline used, affecting CO_2 emissions.
- Distance traveled – The total transportation distance from the factory to warehouses and construction sites directly impacts the environmental footprint.

II. Installation and Use Phase Data

The installation and usage phase considers how tiles are applied in buildings, how long they last, and whether they require maintenance.

- Material waste during installation – A certain percentage of tiles are damaged or cut during installation, adding to overall waste.
- Maintenance requirements – Ceramic tiles generally require minimal cleaning and no chemical treatments, reducing their impact in this phase.

III. End-of-Life (EOL) and Waste Management Data

At the end of their life cycle, ceramic tiles can be disposed of, recycled, or reused. Understanding how waste is managed is important for an LCA study.

- Disposal methods – Many ceramic tiles end up in landfills, which contribute to waste accumulation and land use issues.
- Recycling and reuse possibilities – Some waste tiles can be crushed and reused in construction, such as aggregates in concrete or road base material.

IV. Field Data Collection

As part of the primary research for this Life Cycle Assessment, a field visit was conducted at the construction project. The purpose of the visit was to collect real-world data on tile usage, material consumption, transport methods, installation practices, and waste management processes. This step is essential in improving the accuracy of the LCA by supplementing secondary data with first-hand observations.

During the site visit, the following key information was gathered:

- The quantity of tiles imported and used for each apartment
- Average area covered per apartment (3000 square feet)
- Tile wastage percentage during installation (approximately 5%)
- Number and type of adhesives and grouts used
- Transport distance and method (diesel trucks covering 6 km)
- Frequency of cleaning and maintenance practices per apartment

D. Impact Assessment

The LCA analysis was done by manual method and by using SimaPro Life Cycle Assessment software.

I. Impact Assessment by Manual Calculation

After collecting the required field data, a manual calculation was performed to assess the environmental impacts associated with ceramic tile use, following a gate-to-grave approach. The calculation considered emissions from different life cycle stages, including adhesive and grout usage, cleaning and water consumption, transport, and final disposal.

Table 1: Environmental impact assessment of adhesive usage

Description	Value
Weight per bag (kg)	25
Number of adhesive bags	3400
Total adhesive used (kg)	85000
Emission factor ($kgCO_2eq/kg$)	1.2
Total ($kgCO_2eq$)	102000

Table 2: Environmental impact assessment of grout usage

Description	Value
Number of Grout packets	1000
Weight per packet (kg)	1
Total Grout weight (kg)	1000
Emission factor ($kgCO_2eq/kg$)	0.8
Total ($kgCO_2eq$)	800

Table 3: Environmental impact assessment of tile transportation

Description	Value
Transport distance for tile at one time (km)	6
Number of trips to transport tiles	10
Total distance (km)	60
Fuel consumption	3.3km/ L
Total fuel used (L)	18.18
Emission factor ($kgCO_2eq/L$)	3.12
Total ($kgCO_2eq$)	56.73

Table 4: Environmental impact assessment of adhesive transportation

Description	Value
Transport distance for adhesive at one time (km)	1.5
Number of trips to transport adhesive	20
Total distance (km)	30
Fuel consumption	3.5km/L
Total fuel used (L)	8.57
Emission factor ($kgCO_2eq/L$)	3.12
Total ($kgCO_2eq$)	26.24

Table 5: Environmental impact assessment of the cleaning phase

Description	Value
Cleaners per apartment per month (L)	1
Number of apartments	121
Cleaners per year (L)	1452
Lifespan(years)	100
Total cleaners(L)	145200
Density (kg/L)	1
Total weight (kg)	145200
Emission factor($kgCO_2eq/kg$)	2.8
Total CO_2eq from cleaning phase (kg)	406560

Table 6: Environmental Impact Assessment of Tile Disposal after usage at the End of Life

Description	Value
Number of tiles	19741
Total area (m^2)	7335.4
Tile emission factor ($kgCO_2eq/m^2$)	14.4
Total CO_2eq (kg)	105634.87

The manual calculations for each inventory data are performed, and the total environmental impact was calculated according to Table 7.

Impact Assessment by Sima Pro LCA Software

Impact Assessment of the SimaPro is carried out following the steps below.

1. Generation of Tree
2. Characterization
4. Normalization
5. Weighting
6. Single Score

Table 7: Total Environmental Impact from Manual Calculation

Description	Value
Adhesive usage emissions ($kgCO_2eq$)	102000
Grout usage emissions ($kgCO_2eq$)	800
Transportation emissions ($kgCO_2eq$)	83.47
Cleaning phase emissions ($kgCO_2eq$)	406560
Disposal emissions ($kgCO_2eq$)	105634.87
Total $kgCO_2eq$	**615078.34**
Per Functional Unit	
Usable tile area (m^2)	7335.4
Total $kgCO_2eq$ per m^2 over 100 years	83.85

RESULTS

A. Impact Assessment by Manual Calculation Method

The ceramic tile at the selected construction generates approximately 615078.34 $kgCO_2eq$ over a 100-year lifespan, equivalent to 83.85 $kgCO_2eq$ per m^2 of 7,335.4 m^2 usable tiled area. This carbon footprint represents the total greenhouse gas emissions, including Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O), contributing to global warming across the tile's lifecycle, from construction usage to disposal. This significant Impact underscores the need for sustainable practices to reduce environmental harm in Sri Lanka's construction industry. The emissions are distributed across various lifecycle phases. The environmental impact of ceramic tile use over its full life cycle can be categorized into high, moderate, and low impact stages based on total CO_2 emissions. The highest environmental impact comes from the cleaning phase, which contributes 406,560 $kgCO_2eq$ to 66.1% of total life cycle emissions. This high value is mainly due to the continuous use of tile cleaners and water for over 100 years across 121 apartments. Any phase contributing over 40% of total emissions is considered to have a high impact in this analysis. Final disposal of tiles at the end of the life disposal contributes 105634.87 $kgCO_2eq$, or 17.2% of total emissions. There is still an opportunity for development through better material planning and recycling. Stages with emissions between 10% and 40% are considered moderate in this context. Another moderate impact stage is adhesive usage, which adds 102,000 $kgCO_2eq$ or 16.6% of emissions. The energy-heavy chemical processes involved in manufacturing adhesives significantly affect the project's carbon footprint. Transportation contributes only 83.47 $kgCO_2eq$, or 0.01%, and is considered very low impact. This is due to the short distances between the factory and the construction site. Similarly, grout usage results

in just 800 $kgCO_2eq$, representing 0.1% of total emissions, making it another very low-impact phase. Finally, the total impact of 83.85 kg CO_2eq/m^2 provides a benchmark for comparing the project's sustainability with other construction projects in Sri Lanka.

B. Impact Assessment Using Sima Pro Software

The network diagram in Figure 1, it is notice that there is one colored arrow, which is red; when the arrows get thicker, it means the environmental impact of the category also increases. In the Analysis method of IPCC GWP 100a, which is used to identify the climate changes under the Intergovernmental Panel on Climate Change (IPCC) for 100 years. The amount of heat that a greenhouse gas retains in the atmosphere over a given time in relation to carbon dioxide (CO_2eq) is known as the global warming potential (GWP). The global warming potential (GWP) of greenhouse gases (GHGs) over 100 years was evaluated in this study using the characterization model for mid-point assessment. According to the tree diagram, the Total Global Warming produced by the analysis of ceramic tiles, the Gate-to-Grave approach is 6.32 x 10^5 $kgCO_2eq$. The tree diagram can be seen that the Forming agent, which is used in the cleaning phase, has the most significant potential impact (3.70 × 10^5 kg CO_2eq) on global warming, equivalent to 57.4% of total life cycle emissions. A moderate percentage of 20.1% of Impact assessed from Adhesive Mortar, that equivalent to 1.30 x 10^5 $kgCO_2eq$ and 7.90 $kgCO_2eq$ generated as greenhouse gases from Ceramic tile usage. The Disposal of the broken tile as Municipal solid waste generated GWP values is 8.15 x 10^4 kg CO_2eq. The transportation processes are not shown in the diagram because to are applied as the Process stage of ceramic tile installation. These include all the details in the SimaPro Ecoinvent 3.0 update database.

C. Comparative Analysis with International LCA Studies

The results of this study align closely with international research on ceramic tile lifecycle impacts. The findings that the cleaning phase contributes the highest proportion of lifecycle emissions (66.1% manually, 58.5% via SimaPro) are consistent with European studies. For instance, [6] reported that the use phase, particularly cleaning operations, accounted for approximately 60% of total environmental impacts in Spanish ceramic tile installations over 50 years. Similarly, in a previous study [8] it was found that post-installation maintenance contributed 55-65 % of lifecycle greenhouse gas emissions, predominantly due to chemical cleaning agents and water heating requirements. The adhesive usage contribution observed in this study (16.6-20.4 %) is comparable to Italian research findings, where mortar and adhesive applications represented 15-18 % of total embodied carbon in tile installations [18]. The relatively low transportation impact (0.01-0.22 %) in the current study is attributed to short supply chain distances in Sri Lanka, contrasting with European studies where transportation typically accounts for 3-5 % of total impacts due to longer distribution networks. The total gate-to-grave carbon footprint of 83.85 $kgCO_2eq/m^2$ over 100 years is moderately higher than the European average of 65-75 $kgCO_2eq/m^2$ reported for similar functional units, potentially reflecting differences in energy sources, cleaning frequencies, and climatic conditions requiring more intensive maintenance in tropical environments. However, when normalized to a 50-year lifespan for direct comparison with international studies, the impact reduces to approximately 41.9 $kgCO_2eq/m^2$, which falls within the global range of 35-50 $kgCO_2eq/m^2$ for ceramic tile installations in residential buildings. These comparisons validate the methodology employed in this study while highlighting regional variations in lifecycle impacts, particularly in the cleaning phase, which appears more significant in tropical climates compared to temperate regions.

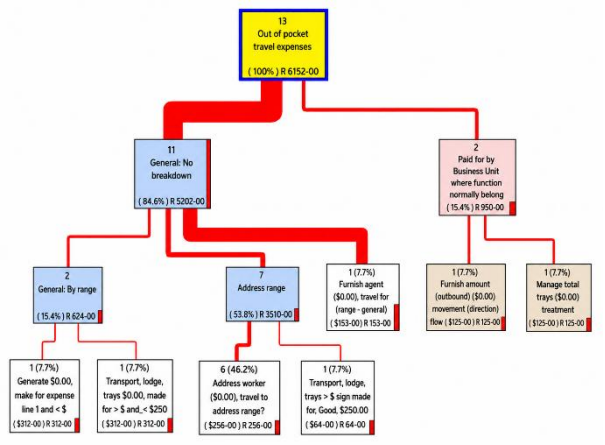

Figure 1: Network Diagram of Gate to Grave Analysis using SimaPro

D. Results interpretation of manual calculation and Semipro software results

The environmental effects from manual calculations were compared with SimaPro results to assess

consistency and accuracy, as in Table 8. In addition to emphasizing important impact categories and the processes that contribute to them, this interpretation seeks to assess the consistency and differences between the two approaches, offering insights into the precision and dependability of the life cycle assessment for ceramic tile production.

Table 8: Comparative Analysis of Manual Calculation and SimaPro LCA Results.

Phase	Total $kgCO_2eq$ Manual Method	Percentage of Total Manual Method (%)	Total $kgCO_2eq$ Sima Pro Software	Percentage of Total SimaPro (%)
Adhesive usage	102000	16.6	129000	20.4
Grout usage	800	0.1	281	0.05
Transportation	83.47	0.01	1397	0.22
Cleaning phase	406560	66.1	370000	58.5
Tile usage and disposal	105634.87	17.2	131519	20.8
Total $kgCO_2eq$	615078.34	100	632197	100

Adhesive Usage:

The manual calculation gives 102,000 $kgCO_2eq$ (16.6%), but SimaPro shows 129000 $kgCO_2eq$ (20.4%). This variation may happen because SimaPro includes a broader scope, such as raw material extraction and curing process emissions, which may not be fully included in the manual calculation.

Grout Usage:

Manual calculation reports 800 $kgCO_2eq$ (0.1%), while SimaPro shows 281 $kgCO_2eq$ (0.05%). The lower SimaPro value might be due to a more conservative estimate of cement mortar emissions, possibly leaving out minor secondary impacts that the manual method considered.

Transportation:

Manual calculation gives 83.47 $kgCO_2eq$ (0.01%), while SimaPro shows 1,397 $kgCO_2eq$ (0.22%). The higher SimaPro value suggests it accounts for more detailed transport emissions, such as longer supply chains and additional logistics impacts, which the manual approach may not fully include.

Cleaning Phase:

Manual calculation shows 406,560 $kgCO_2eq$ (66.1%), while SimaPro reports 370,000 $kgCO_2eq$ (58.5%). The slight difference may come from different modeling of foaming agent impacts, where the manual method might overestimate usage or energy demand compared to SimaPro's market-based assumptions.

Tile Usage and Disposal:

Manual calculation indicates 105634.87 $kgCO_2eq$ (17.2%), while SimaPro records 131519 $kgCO_2eq$ (20.8%). The slight difference might suggest that the Simapro calculation considered extra factors. In summary, Manual calculation was done according to estimated and collected data, referring to research articles and pointing out the emission factors related to the phases and materials. So manual calculation might have some misrepresented data and limitations. But SimaPro is more accurate and efficient software that includes Global Databases and accurate actors, especially for Life Cycle Assessment. SimaPro, using the ReCiPe midpoint method, IPCC GWP 100 method, and Ecoinvent database, includes detailed life-cycle inventories, such as upstream raw material extraction, transport logistics, and long-term landfill emissions. So, it provided more reliable results than manual calculation without input errors. But Simapro also has limitations due to the Demo version the percentages as it includes data.

E. Alternative Floor Finishing Solutions

Ceramic tiles require substantial energy for glazing and high-temperature kiln firing, resulting in elevated carbon emissions across their lifecycle from transportation through installation to disposal. Among the alternative flooring materials evaluated, engineered wood, bamboo, linoleum, cork flooring, polished concrete, and terrazzo demonstrate superior environmental performance with significantly lower gate-to-grave carbon emissions.

Polished concrete uses the existing concrete slab in a building as the final flooring. It is finished by grinding, polishing, and sealing, so no extra flooring materials or adhesives are needed. Because it reuses what is already there, it has one of the lowest embodied carbon footprints (3–5 $kgCO_2eq/m^2$) [10]. It is also very durable, lasting more than 50 years with almost no maintenance. This means fewer repairs and less waste of time. Polished concrete can also help keep buildings cooler in

warm climates because it acts as a thermal mass, storing heat and reducing cool energy. However, it can feel hard and cold underfoot, so rugs may be needed for comfort. It also needs skilled workers to achieve a smooth, high-quality finish.

Terrazzo is a decorative flooring made from recycled marble, glass, or stone chips mixed with cement or epoxy binder, then polished. Unlike ceramic tiles, it does not require energy-intensive kiln firing, which makes it 50–60% less energy-demanding [11]. It usually contains 60–80% recycled content, helping to reduce waste and support the circular economy [12]. Terrazzo is extremely long-lasting (50+ years) and easy to clean because it is non-porous, so it does not trap stains or bacteria. It also produces low or zero VOCs, which improves indoor air quality [13]. The downside is that terrazzo has a higher upfront cost, and like concrete, it feels cold and hard unless underlay or rugs are used.

Linoleum is made from natural, renewable materials like linseed oil, wood flour, cork dust, and jute backing. It is biodegradable and compostable at the end of its life, so it doesn't create landfill waste [10]. It has a low embodied carbon (4–6 $kgCO_2eq/m^2$) and can last 20–40 years if cared for properly [12]. Linoleum is naturally anti-bacterial and hypoallergenic, making it great for healthy indoor spaces. It also feels softer and warmer underfoot than concrete or terrazzo. However, it needs careful installation to avoid cracking and sometimes requires waxing or sealing to keep its protective surface.

Bamboo is a fast-growing, renewable grass that reaches maturity in just 3–5 years, making it much more sustainable than slow-growing hardwood [14]. Bamboo flooring is strong and moisture-resistant, even harder than oak in some cases. It has a moderate carbon footprint (6–9 $kgCO_2eq/m^2$). However, most bamboo is imported from Asia, which adds transport emissions. Some bamboo flooring is made with formaldehyde-based adhesives, which can release VOCs. It's better to choose low-emission certified products [15]. Bamboo flooring lasts 25–30 years but may scratch more easily than hardwood.

Engineered wood has a thin hardwood veneer on top of layers of wood. It uses less raw wood than solid hardwood and stores carbon while the trees are growing. Its embodied carbon (7–10 $kgCO_2eq/m^2$) is moderate [16].

Good-quality engineered wood can be sanded and refinished several times, so it can last 30–50 years. It is also more stable than solid hardwood, meaning it won't warp or expand easily. To make it more sustainable, it's important to choose FSC-certified wood and low-VOC adhesives. The downside is that manufacturing uses more energy than bamboo or linoleum, which raises its overall carbon footprint. Cork comes from the bark of cork oak trees, which can be harvested every 9–12 years without cutting down the tree. This makes it a renewable resource [17]. Cork flooring provides natural thermal and sound insulation, is resistant to mold and pests, and is biodegradable at the end of its life. It has a low embodied carbon (5–7 $kgCO_2eq/m^2$) and feels soft and comfortable underfoot, which makes it ideal for living spaces. However, cork needs sealing to protect it from moisture, and it can dent under heavy furniture. It usually lasts 20–25 years.

Table 9: Comparative Environmental Performance of Alternative Floor Finishing Solutions

Flooring Type	Embodied Carbon ($kgCO_2eq/m^2$)	Recycled/ enewable	Durability (years)	Maintenance	End-of-Life
Polished Concrete	3–5 (very low)	Uses existing slab	50+	Very low	Fully reusable
Terrazzo	5–8 (50–60% lower than ceramic)	60–80% recycled chips	50+	Very low	Recyclable
Linoleum	4–6 (low)	100% renewable	25–40	Low	Compostable
Bamboo Flooring	6–9 (moderate)	Fast renewable grass	25–30	Low	Partly recyclable
Engineered Wood	7–10 (moderate)	30–50% recycled core	30–50	Low	Reusable

F. Limitations and Assumptions

This study acknowledges several limitations that should be considered when interpreting the results. First, the manual calculation methodology relies on emission factors derived from international databases and published literature, which may not fully capture the specific conditions and technologies used in Sri Lankan ceramic tile production and installation. The emission factor for ceramic tiles (14.4 $kgCO_2eq/m^2$) was adopted

from regional studies and may vary depending on kiln technology, fuel sources, and manufacturing efficiency.

Second, the system boundary excludes infrastructure impacts, including the environmental footprint of manufacturing facilities, machinery, and transportation infrastructure. While this exclusion is common practice in LCA studies to avoid allocation complexities, it may underestimate the total environmental burden, particularly for short-lived projects where infrastructure impacts are more significant per functional unit.

Third, the study assumes uniform cleaning practices across all 121 apartments over the 100-year lifespan, with constant cleaner consumption rates (1 liter per apartment per month). Maintenance practices may vary significantly based on occupant behavior, socioeconomic factors, and evolving cleaning technologies. This assumption may overestimate or underestimate actual cleaning-phase impacts.

Fourth, the manual calculations assume average tile weight (3 kg per tile) and standard fuel consumption rates (3.3-3.5 km/L) for transportation. Variations in tile specifications, vehicle efficiency, and load capacity could affect the accuracy of transportation impact estimates. The SimaPro analysis, while more comprehensive, is limited by the demo version constraints and the availability of region-specific data in the Ecoinvent 3.0 database, necessitating the use of proxy data from similar geographic contexts.

Fifth, the end-of-life disposal scenario assumes landfilling as the primary waste management route, reflecting current practices in Sri Lanka. However, emerging recycling technologies and circular economy initiatives could significantly alter future disposal impacts. The study does not account for potential carbon sequestration in recycled applications or the avoided burdens from material substitution.

Finally, scope exclusions such as worker health impacts, noise pollution, aesthetic environmental effects, and indirect land-use changes were necessary to maintain focus on greenhouse gas emissions, but limit the comprehensiveness of the environmental assessment. Future research incorporating broader impact categories, regional emission factors, and dynamic lifecycle modeling would enhance the robustness and applicability of LCA findings for Sri Lankan construction contexts.

CONCLUSION

This research is the first gate to grave life cycle analysis of Ceramic Tiles in Sri Lanka. The Life Cycle Assessment found that the cleaning phase is the largest source of environmental impact for ceramic tiles. Manual calculations estimated 615078.34 $kgCO_2eq$ over 100 years (83.85 $kgCO_2eq/m^2$), while SimaPro software gave 632197 $kgCO_2eq$. In both methods, cleaning contributed over 50% of total emissions due to the long-term use of chemical cleaners. Tile production, adhesive application, and grout usage followed with small differences between methods. Manual calculations provided reliable total results, while SimaPro offered a more detailed impact category breakdown (eutrophication, acidification, particulate matter formation, fossil fuel depletion). The findings show that reducing cleaning frequency, using eco-friendly cleaning agents, recycling waste tiles into concrete aggregates, and sourcing low-carbon, locally made materials can reduce greenhouse gas emissions and resource use, improving environmental sustainability in Sri Lanka's construction sector.

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RESEARCH ARTICLE

Gender-wise Trends and Dynamics of Sri Lankan Foreign Employment Departures (1986–2023)

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Abstract: This study examines the long-term trends and statistical relationships in gender-wise foreign employment departures from Sri Lanka between 1986 and 2023. Using secondary data from the Sri Lanka Bureau of Foreign Employment (SLBFE) and Central Bank of Sri Lanka (CBSL), the analysis applies descriptive statistics, cointegration testing, and the Vector Error Correction Model (VECM) to explore short- and long-run dynamics between male and female departures. Results indicate a structural transformation in migration patterns: while female workers, particularly in domestic roles, dominated departures during the 1990s, male departures have surpassed female departures since the mid-2010s, largely due to policy interventions, changing labor market demands, and socio-economic shifts. VECM results confirm a long-run equilibrium relationship between male and female departures, with significant short-run adjustments reflecting responses to domestic and international labor market conditions. The findings provide policy insights to enhance gender equity in migration, improve skills development, and safeguard vulnerable groups.

Keywords: Foreign Employment, Gender, Labor Migration, VECM, Sri Lanka

INTRODUCTION

Foreign employment has been a key contributor to Sri Lanka's economy, generating substantial remittances and offering livelihood opportunities for hundreds of thousands of households annually. Since the liberalization of the economy in the late 1970s, the Sri Lankan government has actively promoted labor migration, with the Middle East as the primary destination. Gender has historically been a defining feature of this migration: in the early years, women predominantly employed as domestic workers formed most departures. Over the past two decades, however, the gender composition has shifted. Male workers now dominate, primarily in skilled and semi-skilled occupations such as construction, transport, and manufacturing. This transition has been shaped by multiple factors, including protective policies for female domestic workers, global labor demand fluctuations, and domestic economic pressures.

This paper focuses on the period 1986–2023, aiming to:

1. Examine the trends and patterns of male and female foreign employment departures.
2. Model the statistical relationships between male and female departures using VECM.
3. Interpret the policy implications of these gendered migration patterns.

METHODOLOGY

A. Data Sources

This study is based entirely on secondary data covering the period 1986–2023. The primary data source is the Annual Statistical Reports of the Sri Lanka Bureau of Foreign Employment (SLBFE), which provide gender-disaggregated figures for annual foreign employment departures.

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These statistics are considered the most comprehensive national record of labor migration, as all legal departures for overseas employment are required to be registered with the SLBFE.

To ensure accuracy and consistency, the SLBFE data were cross verified with corresponding figures from the Annual Reports of the Central Bank of Sri Lanka (CBSL). Where discrepancies were observed, the SLBFE statistics were prioritized due to their role as the principal registration authority, while CBSL data served as a validation reference. This dual-source verification process minimized the risk of data entry errors, missing records, or inconsistencies caused by subsequent revisions.

The dataset consists of two time series variables:

- MALE: Annual number of male foreign employment departures.
- FEMALE: Annual number of female foreign employment departures.

Both are measured in absolute numbers for each year and cover 38 observations per variable.

B. Literature Context on Male and Female Departures

Gender has historically played a defining role in Sri Lanka's foreign employment sector. According to Sri Lankan international labor migration initially emerged in the late 1970s with a predominance of female workers, particularly those engaged in domestic service in the Middle East [1]. This trend was driven by high demand for household workers, relatively low entry requirements, and the attractiveness of overseas earnings compared to local wages.

However, as documented by the International Labour Organization [2] a structural shift began in the mid-2000s. Factors contributing to this change include,

- Protective regulations restricting the migration of women under certain ages or without adequate safeguards.
- Increased demand for male labor in sectors such as construction, manufacturing, and transport in Gulf and East Asian economies.

- Skills diversification programs encouraging male participation in foreign employment.

By the mid-2010s, male departures had overtaken female departures in absolute terms, reflecting broader global labor market trends and national policy adjustments. This transformation underscores the need for statistical analysis to understand the interdependence of male and female migration patterns over time.

C. Statistical Tools and Software

Two main software packages were used in the analysis:

1. **Microsoft Excel** - Employed for the initial descriptive analysis, including the creation of plots in a time series, summary statistics, and percentage share calculations. Excel was also used for preliminary data cleaning, consistency checks, and visual presentation of trends.

2. **EViews (Econometric Views)** - Used for advanced statistical modeling and econometric analysis. All econometric tests, transformations, cointegration analyses, and the estimation of the Vector Error Correction Model (VECM) were performed in EViews due to its suitability for time series analysis and cointegration frameworks.

D. Econometric Approach

1) Stationarity Testing

Time series econometrics requires that the statistical properties of the data (mean, variance, autocorrelation) remain constant over time. To assess this property, the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests were applied to both MALE and FEMALE series.

The results indicated that both variables were non-stationary in levels but became stationary after first difference. Therefore, the transformation applied was:

$$\Delta MALE_t = MALE_t - MALE_{t-1}$$

$$\Delta FEMALE_t = FEMALE_t - FEMALE_{t-1}$$

This ensured that the series met the integration order requirement (I (1)) for cointegration testing and VECM estimation.

2) Cointegration Testing

Given the I (1) nature of both variables, the Johansen cointegration test was conducted to determine the existence of a long-run equilibrium relationship. Both the trace and maximum eigenvalue statistics were evaluated at the 5% significance level, and the optimal lag length was selected using the Akaike Information Criterion (AIC) and Schwarz Bayesian Criterion (SBC).

3) Vector Error Correction Model (VECM)

The Johansen test indicated one cointegrating equation between male and female departures, supporting the use of a VECM framework to capture both short-run dynamics and the long-run equilibrium relationship.
The normalized cointegrating equation (on ΔFEMALE) is,

$$CointEq1_{t-1} = D1FEMALE_{t-1} + 3.2768D1MALE_{t-1} - 19896.1$$

Estimated VECM equations,

1. **Female departures equation**

$$\Delta D1FEMALE_t = -0.2496ECT_{t-1} - 0.3625\Delta D1FEMALE_{t-1} + 0.7380\Delta D1MALE_{t-1}$$

2. **Male departures equation**

$$\Delta D1MALE_t = -0.4303ECT_{t-1} + 0.3067\Delta D1FEMALE_{t-1} + 0.4919\Delta D1MALE_{t-1} -$$

Where ECT_{t-1} is the error correction term representing deviations from the long-run equilibrium. The negative and statistically significant coefficients on the error correction terms (−0.2496 for FEMALE, −0.4303 for MALE) indicate that both series adjust towards long-run equilibrium, with male departures showing a faster adjustment speed. In the short run, increases in male departures significantly influence female departures (coefficient = 0.7380), while the reverse effect is weaker.

RESULTS AND FINDINGS

A. Descriptive Analysis of Gender-wise Departures

The analysis of foreign employment departures by gender from 1986 to 2023 reveals notable shifts in the composition of Sri Lanka's migrant workforce. In the late 1980s and throughout the 1990s, female departures consistently outnumbered male departures, largely due to the high demand for domestic workers in the Middle East. Women, particularly those from rural and lower-income households, viewed foreign employment as a viable path to supplement household income, and destination countries such as Saudi Arabia, Kuwait, and the United Arab Emirates actively recruited female domestic workers.

From the early 2000s onward, a gradual but significant reversal occurred. Male departures began to rise steadily, overtaking female departures around the mid-2000s. By the 2010s, the gap widened, with males becoming the dominant group in Sri Lanka's foreign employment market. This shift was driven by a combination of factors:

- Government policy changes imposing minimum age and family care requirements for female migrants.
- Expansion of foreign job opportunities for men in construction, manufacturing, and transport sectors, particularly in the Gulf and East Asian economies.
- Skill development initiatives aimed at improving the employability of male workers for skilled and semi-skilled positions abroad.

The COVID-19 pandemic in 2020 led to a temporary decline in both male and female departures due to travel restrictions and reduced overseas recruitment. However, recovery was evident from 2021 onwards, with male departures rebounding more sharply than female departures.

A. Stationarity and Cointegration Results

Unit root tests (ADF and PP) confirmed that both MALE and FEMALE series were non-stationary in their original levels but became stationary after first differencing, meaning both variables are integrated of order one, I (1).

Johansen's cointegration test identified one cointegrating vector between male and female departures, indicating the presence of a stable long-run relationship between the two series despite short-term fluctuations.

B. Vector Error Correction Model (VECM) Results

1) Long-run Relationship

The normalized cointegrating equation is given by,

$$CointEq1_{t-1} = D1FEMALE_{t-1} + 3.2767 D1MALE_{t-1} - 19896.19$$

The positive coefficient on male departures (3.2768) implies that, in the long run, increases in male departures are associated with corresponding increases in female departures. This reflects a structural linkage in labor migration patterns, where economic and policy factors influencing one gender often spill over to the other.

2) Short-run Dynamics

The estimated short-run VECM equations are,

Female departures equation

$$\Delta D1FEMALE_t = -0.2496 ECT_{t-1} - 0.3625 \Delta D1FEMALE_{t-1} + 0.7380 \Delta D1MALE_{t-1} - 1241.98$$

Male departures equation

$$\Delta D1MALE_t = -0.4303 ECT_{t-1} + 0.3067 \Delta D1FEMALE_{t-1} + 0.4919 \Delta D1MALE_{t-1} - 2791.69$$

The error correction terms (−0.2496 for FEMALE, −0.4303 for MALE) are negative and statistically significant, confirming that both series adjust towards the long-run equilibrium after short-term deviations. Male departures adjust faster to equilibrium compared to female departures.

D. Interpretation of Short-run Effects

- The coefficient of **0.7380** in the FEMALE equation means that a one-unit increase in male departures in the previous period leads to a 0.738-unit increase in female departures in the current period, holding other factors constant.
- Conversely, the coefficient of **0.3067** in the MALE equation indicates that a one-unit increase in female departures in the previous period increases male departures by only 0.3067 units.

This asymmetry confirms that the short-run effect from male departures to female departures is stronger, while the reverse effect is positive but weaker.

From a practical standpoint, this suggests that changes in male migration perhaps driven by demand surges in male-dominated industries tend to influence female migration more strongly than the reverse. This could be due to family-linked migration decisions, shared recruitment networks, or similar economic drivers affecting entire communities.

E. Policy and Practical Implications

The results highlight the interconnected nature of male and female foreign employment departures. Policymakers should note that measures targeting one gender such as training programs, migration policy changes, or bilateral labor agreements may have spillover effects on the other.

Given the stronger short-run influence of male migration on female migration, policies boosting male employment opportunities abroad could indirectly stimulate female migration. Conversely, restrictive measures on female migration may not substantially affect male migration volumes in the short term but could influence them over a longer horizon through household-level economic impacts.

DISCUSSION

The results of this study confirm that male and female foreign employment departures in Sri Lanka are statistically interconnected both in the short run and in the long run. This is consistent with prior research emphasizing the gendered dynamics of Sri Lanka's migration flows. Female migration dominated the outflow in the 1980s and 1990s due to demand for domestic workers in the Middle East [1]. However, later policy restrictions imposed in the 2000s, combined with growing overseas demand for male workers in construction and technical sectors, shifted the balance in favor of male migration [2], [3].

The stronger short-run effect from male to female departures observed in the VECM suggests that male migration creates enabling conditions for female migration within households and communities. Migration decisions in Sri Lanka are rarely individual but rather collective, shaped by household strategies to diversify risk and maximize remittance inflows [4]. When men migrate first, the remittances and networks they establish reduce the financial and informational barriers for women to migrate subsequently [5].

Male migration often acts as a catalyst for female family members to follow, particularly when the initial migration creates a stable support system abroad [6].

By contrast, the reverse effect from female to male departures is positive but weaker. This may reflect the structural segmentation of Sri Lanka's overseas labor market, where women's migration has been concentrated in domestic and caregiving roles with relatively lower wages compared to male-dominated occupations in construction, driving, and skilled trades [7]. The lower remittance potential from female migrants limits the capacity of households to finance additional male migrations [8]. Furthermore, social norms and family responsibilities mean that female migration does not carry the same "demonstration effect" for male relatives as male migration does for females [9].

The long-run positive cointegration between male and female departures highlights that both genders are influenced by common macroeconomic and policy factors. Bilateral labor agreements with Middle Eastern countries, foreign exchange crises in Sri Lanka, and global demand cycles affect the overall flow of migrants irrespective of gender [10], [11]. This supports the notion that while the immediate drivers of male and female migration differ, the broader structural forces binding them together are similar.

The findings also carry significant policy implications. The strong male-to-female linkage suggests that interventions targeting male employment abroad—such as skills training, language programs, or agreements for construction and technical jobs—could indirectly stimulate female migration as well. However, policies that restrict female migration, such as minimum-age requirements or mandatory family care provisions, may not substantially reduce male migration flows in the short run but could indirectly weaken female migration through long-run household effects [12]. This reinforces the need for gender-sensitive migration policies that recognize interdependencies rather than treating male and female flows as isolated phenomena [13].

From a developmental perspective, the reliance on male-dominated foreign employment has created vulnerabilities. Male migration is closely tied to cyclical demand in Gulf construction, leaving Sri Lanka exposed to external shocks. Overdependence on low- and semi-skilled male migration can limit the potential for long-term gains from remittances [1]. Strengthening female participation through safe migration pathways and skill diversification could provide a more balanced and sustainable migration portfolio [14].

Nevertheless, this study has limitations. The analysis is based on aggregate annual data, which masks intra-year variations and micro-level decision-making processes. Individual-level factors such as education, household composition, or recruitment practices were not captured in the VECM framework. Future studies could extend this analysis using household survey data or panel methods to examine how intra-household bargaining power, remittance use, and social networks mediate gendered migration flows. In addition, incorporating external variables such as unemployment rates, wage differentials, or policy shocks could enrich the understanding of causality.

In summary, Sri Lanka's male and female foreign employment flows are deeply interconnected. The stronger influence of male migration on female migration reflects household dynamics, financial enablers, and the relative wage advantages of male-dominated sectors. The long-run linkages suggest that both genders remain sensitive to macroeconomic and policy conditions. These findings reinforce the importance of designing migration policies that are both gender-sensitive and holistic, recognizing that interventions aimed at one group will inevitably have ripple effects on the other.

F. Forecast of Foreign Employment Departures by Gender (2024–2028)

Five-year projections of Sri Lanka's foreign employment departures, broken down by male and female workers, were produced using the gender-wise Vector Error Correction Model (VECM). The model's strength is its capacity to represent the long-term equilibrium relationships between the two gendered flows as well as the short-term adjustments. The forecasts offer practical, policy-relevant insights by first applying first-differenced data to achieve stationarity and then re-transforming the results into their original scale using the observed 2023 values as a benchmark.

The projections show different but related trends for male and female departures from 2024 to 2028. The pattern for male departures is defined by a sharp decrease in 2024, from 164,603.77 in 2023 to 89,921.76. Possible short-term external shocks, like tightening labor demand in Middle Eastern construction markets or changes in domestic policy regarding hiring procedures, could account for this immediate contraction. However, the recovery trajectory starts in 2025, when male departures increase to 102,602.57. It then strengthens significantly in 2026, reaching a predicted peak of

156,151.05. This recovery is consistent with past data showing that cyclical demand for technical, construction, and transportation jobs overseas is strongly linked to male migration flows. The following years exhibit a slight decrease, falling to 111,445.51 in 2027 from 149,436.99 in 2027 A slight decrease in subsequent years-149,436.99 in 2027 and even lower to 111,445.51 in 2028-indicates that although male departures will bounce back nicely, they will still be susceptible to cyclical slowdowns and changes in global demand.

Female foreign employment departures follow a different but equally significant trajectory. From the observed 133,052.23 in 2023, female departures are projected to decrease to 94,482.67 in 2024, mirroring the initial contraction seen in male migration. However, unlike the sharp bounce observed for men, the female trend is more gradual but sustained. Female departures climb to 109,289.12 in 2025, then increase considerably to 158,517 in 2026, and peak at 172,831.59 in 2027 before slightly declining to 161,206.88 in 2028. These projections emphasize the resilience of female migration, particularly in caregiving and domestic work sectors, which tend to have more stable long-term demand compared to male-dominated sectors that are highly sensitive to oil prices and infrastructure investment cycles in destination countries.

Table 1: Male and Female forecast data

Year	Male Forecast	Female Forecast
2024	89,922	94,483
2025	102,603	109,289
2026	156,151	158,517
2027	149,437	172,832
2028	111,446	161,207

The comparative analysis of forecasts suggests that while male migration dominates during cyclical upswings (such as the strong 2026 rebound), female migration demonstrates more consistent growth, peaking higher than male departures in 2027. This shift is crucial for understanding the evolving gender balance in Sri Lanka's foreign employment. For decades, female migration was constrained by regulatory measures such as age restrictions and family-responsibility-based exit rules. However, the forecast suggests that female participation is set to re-emerge as a central feature of labor outflows in the mid-term.

These projections have important implications for policymakers. First, the forecasted contraction in 2024 highlights the need for immediate measures to mitigate potential income and remittance shocks. Since remittances form a significant share of Sri Lanka's foreign exchange inflows, ensuring a safety net during periods of reduced migration is vital for macroeconomic stability. Second, the robust mid-term growth in female departures underscores the need for gender-responsive migration policies. As the forecast shows, women will constitute a major share of the migrant workforce from 2025 onwards, peaking in 2027. Thus, policy interventions such as expanding pre-departure training for domestic and caregiving work, enhancing protections through bilateral labor agreements, and strengthening social security mechanisms for female workers abroad are essential.

Additionally, the cyclical nature of male migration, with strong surges followed by downturns, calls for strategies that diversify male workers into more stable, higher-skilled labor markets. Investment in technical and vocational training could open opportunities beyond the Middle Eastern construction sector, including healthcare, ICT, and logistics, where demand is less volatile.

The forecasts also suggest that by 2027–2028, female migration will not only rival but may surpass male migration in significance. This trend reinforces the need to reframe migration policy debates in Sri Lanka. Historically, female migration has been viewed primarily through a lens of protectionism due to social costs such as family separation and risks of exploitation. However, the data now point toward female migration being an unavoidable and critical driver of household incomes and national remittances. Therefore, rather than restrictive policies, a balanced approach that combines protection with empowerment will be required.

In conclusion, the forecasts from the VECM model provide a forward-looking picture of Sri Lanka's gender-wise labor migration. Male departures will continue to fluctuate, reflecting their vulnerability to cyclical economic factors, while female departures are projected to demonstrate stronger resilience and growth in the medium term. These findings highlight the importance of adopting gender-inclusive migration strategies that prepare both men and women for changing patterns of global labor demand, ensuring Sri Lanka maximizes the developmental benefits of its migrant workforce in the years ahead.

CONCLUSION

The study concluded that foreign employment departures in Sri Lanka are driven by complex interrelations between male and female migrants. The presence of cointegrated relationships confirms that these variables are not independent but rather evolve together over time. The significant adjustment coefficients in the VECM confirm the existence of mechanisms that restore equilibrium when deviations occur. In this study both male and female labor outflows respond significantly to past deviations from the long run path.

The successful application of the VECM model in this research confirms its effectiveness in capturing short run dynamics and long-run relationships in time series data. The forecasting results, translated into original values, provide a realistic picture of likely future trends, making the findings relevant for forward planning.

RECOMMENDATIONS

Based on the research findings, it is recommended that policymakers adopt Gender specific strategies that address the unique trends and fluctuations observed in each category. Ensuring the safety, welfare, and empowerment of female migrant workers should be a top priority. Mechanisms such as pre-departure training, legal support systems, and bilateral labor agreements with host countries must be strengthened. Institutional coordination between ministries handling labor, migration, and skills development should be improved to align policy with observed labor market dynamics.

Suggestions for Future Research

To extend the scope of this research, future studies can integrate macroeconomic variables such as GDP growth, exchange rates, inflation, and foreign labor demand to better explain fluctuations in foreign employment. A regional or district level analysis using panel data techniques can provide more localized insights. Incorporating qualitative research elements such as interviews with returnee migrants, assessments of remittance usage, and migrant household case studies can add valuable context to quantitative findings. Comparative studies across South Asian countries may also yield broader policy lessons applicable to regional labor migration patterns.

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RESEARCH ARTICLE

Global Ocean Energy Technologies and Potential Applicability in Sri Lanka

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Abstract: The ocean represents one of the largest untapped sources of renewable energy, offering diverse opportunities through waves, tidal, ocean thermal, and salinity gradient systems. Globally, these technologies have demonstrated significant potential, with case studies highlighting their technical feasibility and contributions to sustainable energy portfolios. For Sri Lanka, an island nation with strong grid connectivity but high reliance on fossil fuels, marine energy offers a promising pathway to enhance energy security, diversify supply, and mitigate environmental impacts. This review synthesizes international advancements in ocean energy technologies and critically evaluates their applicability in the Sri Lankan context. Findings indicate that wave energy along the island's west to south-east coastlines is particularly promising, with consistent swollen waves enabling large- and medium-scale projects. Ocean Thermal Energy Conversion (OTEC) also shows strong feasibility, supported by year-round thermal gradients, with an estimated capacity exceeding 4,000 MW. Conversely, Sri Lanka's low tidal ranges limit the viability of conventional tidal barrages, although micro-tidal and in-stream systems may offer localized solutions. Salinity gradient energy, especially through Pressure Retarded Osmosis (PRO), presents additional opportunities, with selected river basins capable of generating up to 251 MW under optimized flow scenarios. Collectively, these resources could significantly contribute to Sri Lanka's renewable energy mix if supported by targeted research, site-specific assessments, and infrastructure integration. The study emphasizes the need for technological adaptation, investment, and policy support to harness Sri Lanka's marine energy potential, positioning it as viable complement to existing renewable strategies.

Keywords: Ocean Energy, Renewable Energy, Wave Energy, OTEC, Tidal Energy

INTRODUCTION

Renewable energy is vital in addressing global climate change due to its infinite supply and lower environmental impact compared to finite fossil fuels, which emit harmful greenhouse gases [1]. Fossil fuel combustion drives global warming, sea level rise, and extreme weather events [1], [2]. As the global energy transition shifts toward lower-carbon systems, renewable energy is expected to dominate future primary energy growth. Hydropower remains the most widely adopted source, but wind and solar have expanded rapidly over the last decade. The combined share of renewables including wind, solar, geothermal, and biomass rose from 5% in 2018 to over 40% in rapid transition scenarios and nearly 60% in net-zero scenarios by 2050, reducing the contribution of hydrocarbons from 85% to roughly 40% and 20%, respectively [3]. Transitioning to renewables can stabilize energy prices, create employment, enhance energy security, and minimize health risks from air pollution [1], [2].

1.1 Ocean-Based Renewables for Energy Security

Oceans provide abundant alternatives to fossil fuels, offering energy in thermal, kinetic, chemical, and biological forms [3]. Estimates of global potential highlight significant contributions from various sources: tidal energy could produce around 800 TWh, wave energy about 2,000 TWh, osmotic energy between 8,000 and 80,000 TWh, and thermal difference energy from 10,000 to 87,600 TWh [4].

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Other forecasts indicate a potential of 4–18 million tons of oil equivalent [5], 32 TW of electricity globally [6], and deployment of ocean power converters generating 337 GW, yielding 885 TWh per year [7]. Incorporating ocean energy into the global renewable mix can substantially enhance energy security, reduce reliance on fossil fuels, and support climate change mitigation efforts.

1.2 Sri Lanka's Energy Profile and Renewable Distribution

Sri Lanka has achieved an impressive 98% grid connectivity, reflecting strong access to electricity by South Asian standards. The country's total installed power generation capacity is approximately 4,050 MW, comprising 900 MW from coal, 1,335 MW from oil-fired thermal plants, 1,375 MW from hydro power, and 442 MW from non-conventional renewable sources, including wind, mini hydro, biomass, and solar [8]. The annual electricity demand is about 10,500 GWh, with 38% consumed domestically, 39% by industries, 20% by commercial enterprises, and the remainder by other sectors such as religious institutions and street lighting [8].

The cumulative installed capacity of non-conventional renewables in 2020 was 1,114 MW, comprising small biomass (153 MW), mini hydro (873 MW), small solar (161 MW), and small wind projects (401 MW). Despite this, renewable energy still contributes a relatively small share compared to fossil fuel-based generation, showing a heavy reliance on conventional sources [8].

SCOPE AND PURPOSE

This review aims to consolidate existing knowledge on ocean energy technologies and assess their potential applicability in Sri Lanka, an island nation that has yet to initiate large-scale ocean energy projects. While prior studies have provided valuable insights through small-scale experiments and localized assessments, the available data remains fragmented and insufficient to guide comprehensive planning.

The scope of this review is twofold: first, to evaluate global ocean energy technologies such as wave, tidal, ocean thermal, and salinity gradient systems and second, to examine their feasibility within Sri Lanka's coastal and climatic context. The analysis emphasizes technical and environmental considerations while offering a broad national-level perspective rather than detailed sectoral assessments. By synthesizing global advances with local conditions, the review seeks to provide a foundation for researchers, policymakers, and industry stakeholders to identify opportunities, address challenges, and shape future initiatives in ocean energy development for Sri Lanka.

METHODOLOGY

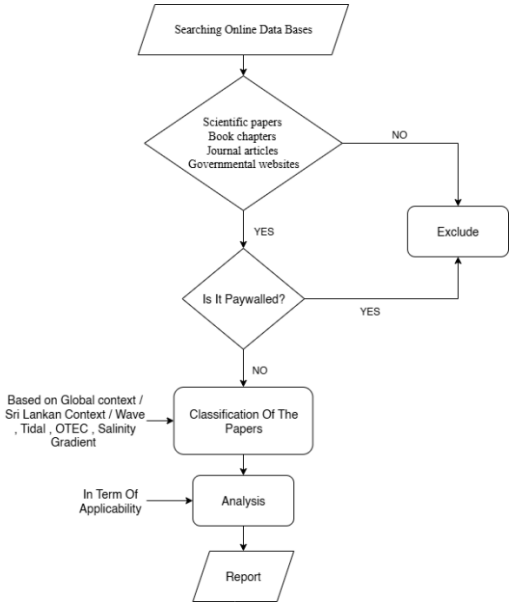

Figure 1: Review Methodology

This critical review was conducted through a structured and selective literature search process, focusing on freely available and reliable sources. Online databases, scientific journals, book chapters, and governmental websites were screened to identify relevant studies on ocean-based renewable energy technologies, including wave, tidal, ocean thermal energy conversion (OTEC), and salinity gradient systems. Paywalled articles were excluded to ensure accessibility, with priority given to open-access research and institutional reports. The selected studies were then classified according to their global or Sri Lankan context, with emphasis on both technological and contextual insights. Case studies were incorporated after the identification of technologies to provide practical examples of application and performance. Finally, the classified literature was critically analyzed in terms of applicability, strengths, limitations, and contextual relevance, forming the basis of the findings presented in this review.

TYPES AND METHODS OF OCEAN ENERGY GENERATION

4.1 Technologies And Methods

Table 1: Technologies and Features of Ocean Energy Technologies

Category	Main Types	Working Principle	Key Features/Applications	Reference
Wave Energy	Oscillating Water Column (OWC)	Waves compress and decompress trapped air in a chamber, creating bidirectional airflow that drives an air turbine-generator.	Simple and robust with an annual harvesting potential of 15–25 kW/m. High commercialization opportunity.	[9] [10] [11]
	Overtopping Converters	Waves over top a ramp into a reservoir and stored water released through turbines.	Stable power output and simple.	[9] [12]
	Point Absorbers	Floating or submerged buoy oscillates (heave/sway/pitch); PTO converts to power.	Compact, omni-directional design; can be deployed in arrays offshore for scalable energy generation.	[9] [13]
	Oscillating Body Converters (OBCs)	Floating/submerged bodies move with waves. Hydraulic/PTO systems generate power.	Advanced designs, small size, versatile and consistent power generation.	[9] [14]
	Wave-Activated Bodies (WABs)	Articulated or hinged floating segments flex as waves pass; the relative motion drives hydraulic pistons linked to generators.	Straightforward design, efficiency typically ranges from 10–35%.	[9] [15] [16] [17]
Tidal Energy	Tidal Barrage	Barrages impound tidal waters in estuaries or bays; turbines harvest energy from the difference in water levels between high and low tide.	Predictable, provides large-scale generation and predictable output, but causes ecological and sedimentation impacts.	[9] [18] [19] [20]
	Tidal Stream Turbines	Underwater horizontal/vertical axis turbines harness kinetic energy of tidal currents.	Categorized into horizontal axis tidal current turbines (HATCTs), crossflow or vertical axis tidal current turbines (VATCTs), and other non-turbine devices. HATCTs account for 76% of all turbines with higher energy efficiency (over 35%). VATCTs account for 12% of turbines; preferably under weaker current conditions due to higher torque generation at lower current velocity and tip speed ratio.	[1] [21] [22] [23] [24] [25]
Ocean Thermal Energy Converter (OTEC)	Closed-Cycle OTEC	Heat transfer from warm saltwater evaporates fluid with low boiling point in the evaporator. The vapor expands through a turbo generator to produce energy.	Compact turbines, sustainable energy generation from ocean thermal gradients.	[26] [27] [28]

	Open-cycle OTEC	Warm seawater is flash evaporated under a partial vacuum (1% to 3% of atmospheric pressure). The steam expands through a turbine generating power, then condenses.	Direct seawater uses and produces freshwater. Surface condenser is costly but yields potable water.	[9] [28]
	Kalina Cycle OTEC	Uses water-ammonia blend as working fluid enhancing conversion efficiency.	Improves efficiency by reducing heat transfer-related irreversibility but higher cost and complexity.	[27] [29]
	Hybrid System	Combines closed and open cycles. Uses warm seawater to generate vapor and produce desalinated water.	Simultaneous power and freshwater generation. Both water and electricity production can be modified independently.	[27] [30] [31]
Salinity Gradient Energy	Pressure Retarded Osmosis (PRO)	Freshwater flows through semi-permeable membrane into seawater, creating pressure that drives a turbine.	Can utilize river water and seawater, or high-saline solutions like Dead Sea water with seawater. Limited adoption.	[9] [32] [33]
	Reverse Electrodialysis (RED)	Alternating ion-exchange membranes allow ions to move between seawater and freshwater, generating voltage.	Limited adoption due to unpredictable compositions and contaminants in water bodies.	[32] [33] [34]

4.2 Case Studies

4.2.1 Tidal Energy Case Studies

The La Rance Tidal Power Plant in France (1966) was the first large-scale tidal station, producing 240 MW and 480 GWh/year with 24 bulb turbines and six sluice gates across a 720 m embankment, impounding a 22 km² basin with a 9–14 m tidal range [35], [36]. The Sihwa Lake Plant in South Korea (2011) is the largest globally, with 254 MW and 552 GWh/year, operating on flood-only generation using 10 turbines across a 42.4 km² basin with a 7.8 m spring tide range [35], [37]. In China, the Jiangxia Plant (1980) generates 4.1 MW with six reversible turbines and two-way pumping from a 1.5 km² basin (5.08 m tidal range), while the Haishan Plant (1975), a unique 150 kW linked-basin scheme, operates up to 22 h/day with pumping and a 4.87 m range [35], [38]. Russia's Kislaya Guba Plant (1968), the only Arctic tidal facility, began at 400 kW (later 1.7 MW), using two-way turbines in a 1.1 km² basin (2.5 m range) and is notable for being built by women engineers [35], [39]. In Canada, the Annapolis Royal Station (1984–2019) operated a 20 MW Straflo turbine on ebb generation but was shut down due to high fish mortality [35], [40].

4.2.2 Wave Energy Case Studies

Wave Energy Converters include several types with notable projects worldwide. Oscillating Water Columns (OWCs) use trapped water columns to drive air turbines, examples being Mutriku (Spain, 296 kW), REWEC3 (Italy, 20 kW), King Island (Australia, 200 kW), Yongsoo (Korea, 500 kW), MARMOK-A-5 (Spain, 30 kW), Ocean Energy Buoy (Ireland, 500 kW), and Islay Limpet (UK, 0.5 MW) [9], [12], [41]. Oscillating Body Converters (OBCs) harness body motion from waves, such as PB3 PowerBuoy (USA, 3 kW), CET06 (Australia, 1000 kW), Atmocean (USA, 10 kW), Seabased (Sweden, 30 kW), Wavepiston (Denmark, 100–200 kW), and WaveRoller (Finland, 350 kW) [9], [12], [42]-[48]. Point Absorbers, floating or submerged bodies that oscillate for energy, include Ada Foah Wave Farm (Ghana, 0.4 MW), Agucadoura Wave Farm (Portugal, 2.25 MW), and Sotenäs Station (Sweden, 3 MW). Overtopping Converters, which store wave water in reservoirs, include the SDE Sea Waves Plant (Israel, 0.04 MW) [9], [49], [50], [51].

4.2.3 OTEC case studies

KRISO (Korean Research Institute of Ships and Ocean Engineering) has extensively researched Ocean Thermal Energy Conversion (OTEC), developing and testing several plants under specific working conditions. Notably, KRISO designed and fabricated a 20 kW OTEC pilot plant as a prototype, and in 2015, they built a 200 kW High-Temperature OTEC (HOTEC) plant that leveraged 70–80°C industrial waste heat and cold deep seawater, achieving a 7.8% improvement in power generation efficiency [51], [52]. Their flagship project, the K-OTEC1000, is a 1 MW closed-cycle OTEC demonstration plant which was successfully tested offshore from Busan, South Korea, in September 2019 [51]. This system utilizes R32 (difluoromethane) as its working fluid, selected for its high heat transfer coefficient and low environmental impact (ODP 0, GWP 675) [51].

In addition to the study already discussed, there are several other notable OTEC projects worldwide that highlight the range of scales and applications of this technology. For instance, a 60-kW closed-cycle plant is under development at Kavaratti in the Lakshadweep Islands, India, aimed at supplying both electricity and freshwater to remote communities [4]. In Hawaii, OTEC International LLC operated a 1,000-kW demonstration facility between 1993 and 1998, providing valuable insights into the technical and operational challenges of large-scale ocean thermal systems [1], [44]. More recently, Lockheed Martin has advanced OTEC development through a 10,000-kW facility at its naval test site in Hawaii, marking one of the largest efforts to integrate OTEC into energy security and defense applications [44].

4.2.4 Salinity gradient energy case studies

The potential sources for PRO include natural water bodies like estuaries, lakes, and ponds, where rivers meet the sea, estimated to have a global energy output of 2.6 TW [46], approximately 20% of the worldwide energy demand [47]. Leading the development efforts are companies such as Kyowakiden Industry Co., Ltd., and Statkraft, both of whom have conducted significant demonstration tests [48]. Kyowakiden's pilot plant in Japan achieved a power density of 10 W/m^2 using concentrated seawater and treated sewage water, demonstrating over a year of continuous operation [49] [50] Reverse Electrodialysis (RED) is a promising membrane-based technology for generating electricity from salinity gradients, currently undergoing testing in demonstration projects [1]. A key case study for Reverse Electrodialysis (RED) involves its integration into a hybrid CDI (capacitive deionization)-RED system [48]. In this setup, a single feed saline water with a concentration of 15,000 ppm was used to produce both freshwater and electric power [48]. Idealized theoretical estimations also suggest significant potential, with 0.74 MJ of electricity possibly generated from the mixing of 1 m^3 of salt water with 1 m^3 of fresh water under ideal conditions (1:50 salinity gradient and 100% efficiency) [48].

APPLICABILITY IN SRI LANKA

5.1 Wave Energy Applicability

Sri Lanka exhibits significant potential for wave energy exploitation, particularly along its west to south-east coastline, due to the predominance of long-distance swell waves interacting with local monsoonal sea waves. Swell waves, being more consistent throughout the year, are particularly favorable for wave energy conversion systems, as they provide a steadier energy density compared to locally generated sea waves [60], [61]. Data from Matara shows that swell waves dominate monthly conditions for most of the year, with values ranging from 57.6% in May to 77.6% in November, indicating a consistently high contribution to the wave climate [61]. Similarly, long-term datasets from the coastal stretch between Negombo and Wadduwa (1979–2019) reveal that the annual average significant wave height is 1.38–1.39 m, with wave periods averaging 8.83–8.85 s, corresponding to an estimated wave energy potential of approximately 2.28 × 10^5 kW/m [62].

The spatial distribution of wave power along the Sri Lankan coast further highlights the west to south-east regions as optimal sites, with average power fluxes between 12–16 kW/m, while the north and east coasts exhibit significantly lower energy levels, ranging from 2–4 kW/m [60]. This makes southern and south-western coastal areas suitable for large-scale, deepwater installations, while most other locations are better suited for small to medium-scale developments [60]. In addition, the consistent swell-dominated waves offer potential synergies for combining energy harvesting with coastal defense, a critical consideration for regions experiencing erosion [60]. Continued high-resolution modeling and near-shore wave measurements are essential to optimize device placement and enhance wave energy extraction strategies across Sri Lanka’s coastline [60].

5.2 Tidal energy applicability

Tidal energy potential is highly site-specific, with existing operational tidal barrage plants around the world demonstrating how tidal range, basin area, and turbine capacity influence energy generation. The La Rance plant in France, for instance, utilizes a tidal range of 9–14 m over a 22 km² basin with 24 × 10 MW turbines, yielding 240 MW of installed capacity and an annual output of 480 GWh [35], [36]. Similarly, the Sihwa Lake tidal power station in South Korea operates with a 7.8 m mean spring tidal range across a 42.4 km² basin and 254 MW of installed capacity [35], [37]. Smaller-scale installations, such as the Jiangxia Experimental TPP in China and Kislaya Guba in Russia, exploit tidal ranges of 5.08–8.39 m and 2.5 m, respectively, with installed capacities ranging from 0.5 MW to 4.1 MW [35], [38], [39]. These case studies indicate that effective tidal power generation relies on tidal ranges typically greater than 2.5 m and substantial impounded basin areas to achieve meaningful electricity output.

By contrast, Sri Lanka exhibits relatively modest tidal ranges along its coastline. The highest observed tidal range is 0.60 m at Colombo, followed closely by Galle at 0.55 m, with other locations ranging between 0.37 m and 0.46 m [63]. From factors vary from 0.16 at Hambantota to 0.46 at Kalpitiya, suggesting moderate asymmetry in tidal cycles [63]. Compared with existing global tidal plants, these low tidal ranges indicate that traditional tidal barrage schemes, which require large tidal amplitudes for economic viability, would not be feasible in Sri Lanka. The standard deviations of the mean sea level are also low (0.03–0.06 m), reflecting limited variability and energy flux potential [63]. Consequently, Sri Lanka's tidal energy exploitation would likely necessitate alternative approaches such as micro-tidal turbines or in-stream tidal generators, rather than large-scale barrages [63]. While the global case studies emphasize large-scale, high-tidal-range installations, Sri Lanka's conditions necessitate technology adaptation to harness its comparatively modest tidal resource effectively.

5.3 Thermal Gradient energy applicability

Ocean Thermal Energy Conversion (OTEC) harnesses the temperature difference between warm surface waters and cold deep waters, requiring a minimum gradient of 20 °C to operate efficiently [64], [65]. Sri Lanka, located in the tropical Indian Ocean, exhibits surface temperatures ranging from 27.5 to 28.6 °C and temperatures at 1000 m depth of 6.5–6.7 °C, resulting in an annual mean ΔT of 18.0 °C at 500 m and 21.3 °C at 1000 m [66].

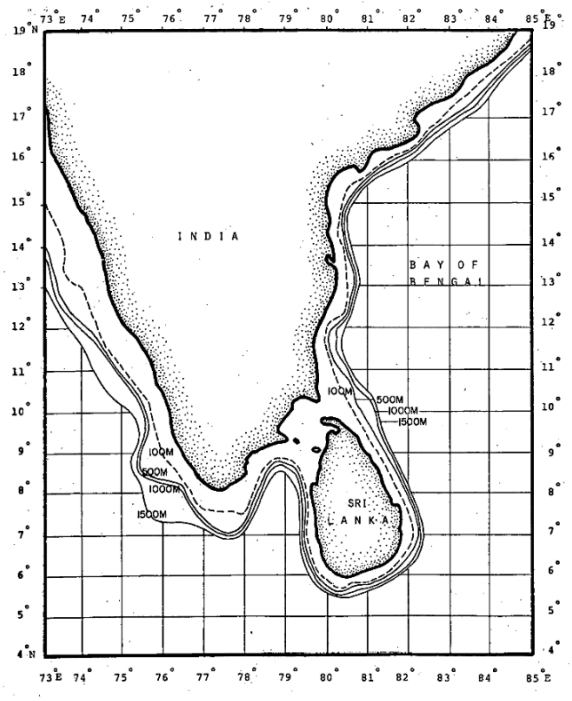

Figure 2: Rough Bathymetry 0-1500 Meters Off Sri Lanka [72]

Even during the coldest months, the ΔT remains above 17.5 °C at 500 m and 20.8 °C at 1000 m, demonstrating that Sri Lanka maintains a sufficiently large thermal gradient throughout the year for OTEC feasibility [66]. Ideal OTEC sites are generally located within 10–15 km of the shoreline to minimize pumping losses for cold-water intake, although sites farther offshore may still be viable if the thermal potential is higher, necessitating detailed analysis [65]. In Sri Lanka, suitable OTEC locations are 22–55 km from shore, which may require additional engineering considerations for cold-water pipelines [66].

With a 1,300-kilometer coastline and tropical location, Sri Lanka is estimated to have over 4,000 MW of potential OTEC capacity, equivalent to approximately 40% of the country's current electricity demand [67]. The western and southern coasts are identified as the most promising regions due to higher surface temperatures and stable deep-water gradients [67]. Overall, the thermal resource in Sri Lanka is adequate for OTEC deployment, although the slightly greater distances to cold-water intake points suggest that system design must carefully balance energy extraction efficiency against infrastructural costs [65], [66].

5.4 Salinity Gradient energy generation

Pressure Retarded Osmosis (PRO) is a promising salinity gradient energy technology that exploits the osmotic pressure difference between freshwater and saline water to generate electricity. The first operational PRO power plant, Stakraft, highlighted the potential of this technology, but also underscored several challenges that currently hinder large-scale adoption. Key barriers include the high cost of membrane production, susceptibility of membranes to fouling by impurities, and the substantial expense of pre-treating feedwater, which collectively make electricity generated from PRO relatively expensive compared to conventional sources [68]. Despite these constraints, PRO remains an attractive renewable energy option due to the continuous availability of riverine freshwater, and the additional potential to extract valuable compounds from the brine byproduct [68].

Sri Lanka's river basins present significant potential for PRO-based power generation. Analysis of selected rivers indicates that harnessing just 5% of total river flow could yield approximately 62.77 MW of electricity, with the highest contributions coming from large rivers such as Kalu Ganga (12.91 MW), Kalani Ganga (8.85 MW), and Mahaweli Ganga (12.91 MW) [68]. Increasing the proportion of river flow allocated to the PRO process directly scales power output, with 10%, 15%, and 20% usage yielding 125.54 MW, 188.31 MW, and 251.08 MW respectively [68]. Under the 20% flow scenario, PRO power generation could account for roughly 7.84% of Sri Lanka's gross electricity generation, indicating substantial potential for supplementing the national grid and reducing reliance on conventional thermal power [68].

It is important to note that this study considers only a small number of river basins. With proper engineering design, optimal site selection, and consideration of additional river systems across the country, the contribution of PRO technology could be significantly higher. Integrating more rivers, enhancing flow allocation strategies, and improving membrane technology could allow Sri Lanka to tap a much larger portion of its salinity gradient energy potential. Furthermore, coupling PRO with existing hydropower infrastructure could maximize efficiency by utilizing existing reservoirs and flow regulation systems [68]. Overall, with appropriate planning and engineering considerations, PRO represents a viable, renewable, and continuous energy source that could play a substantial role in Sri Lanka's future energy mix.

IMPLEMENTATION CHALLENGES OF OCEAN ENERGY IN SRI LANKA

Sri Lanka's ocean energy sector faces significant policy voids, hindering its potential as a renewable resource. Despite studies indicating feasibility for technologies like tidal and wave energy at select coastal sites, site-specific assessments remain constrained by unreliable and insufficient data, impeding informed development. The absence of governmental incentives and robust regulatory frameworks fosters private sector hesitancy toward investments, exacerbating financial barriers. Implementation challenges further compound issues, including the imperative to safeguard marine ecosystems and mitigate disruptions to the vital tourism industry, which may deter stakeholders. Existing GIS maps, while available, lack the granularity and focus required for ocean energy applications, underscoring the urgent need for targeted, high-resolution mapping to guide sustainable progress.

To unlock Sri Lanka's ocean energy potential, efforts should prioritize Ocean Thermal Energy Conversion (OTEC) and wave energy, which is well-suited to the country's tropical waters and consistent wave regimes along the southern and eastern coasts. Tidal energy is deemed unsuitable owing to insufficient tidal ranges in surrounding waters, whereas salinity gradient systems remain nascent, necessitating further global technological advancements to ensure minimal deployment risks.

WAY FORWARD AND FUTURE DIRECTION

Immediate actions must encompass site-specific data acquisition for OTEC and wave energy to underpin robust feasibility analyses and environmental impact assessments. Concurrently, policymakers should formulate comprehensive regulatory frameworks with incentives to mitigate investment risks and streamline permitting processes. Establishing public-private partnerships (PPPs) through targeted engagement with private investors will facilitate capital mobilization, pilot demonstrations, and technology transfer. Public awareness initiatives should emphasize benefits including enhanced energy security, greenhouse gas reductions, and compatibility with marine ecosystems and tourism. International collaborations, particularly with organizations like the International Renewable Energy Agency (IRENA), can provide technical expertise and funding to expedite commercialization and align with national sustainability objectives.

CONCLUSION

Sri Lanka possesses considerable potential for various forms of marine energy, each with unique opportunities and constraints. Wave energy is particularly promising along the west to south-east coastline, where long-distance swell waves consistently interact with local monsoonal seas, producing average power fluxes of 12–16 kW/m suitable for large-scale, deepwater installations, while smaller coastal areas can support medium- to small-scale devices [60], [61], [62]. Tidal energy, in contrast, is limited by the low tidal ranges along the coast, which rarely exceed 0.6 m, making traditional tidal barrages economically unfeasible; micro-tidal turbines or in-stream tidal generators may be more suitable for harnessing these modest tidal resources [63]. Ocean Thermal Energy Conversion (OTEC) benefits from Sri Lanka's tropical location, with warm surface waters (27.5–28.6 °C) and cold deep waters (6.5–6.7 °C at 1000 m) providing a stable thermal gradient of 18–21 °C, enabling a potential base-load capacity exceeding 4,000 MW, particularly along the western and southern coasts [64], [65], [66], [67]. Salinity gradient energy, specifically via Pressure Retarded Osmosis (PRO), shows promise in selected river basins, generating between 62.77 MW and 251.08 MW depending on flow allocation, with the potential to contribute significantly more if additional rivers are utilized and membrane technologies are optimized. Collectively, these marine energy resources, when combined with proper engineering, site selection, and integration into the national grid, could substantially diversify Sri Lanka's renewable energy portfolio, reduce reliance on conventional thermal power, and provide continuous, sustainable electricity for the nation.

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RESEARCH ARTICLE

Identifying Employee Emotions based on Facial Expression Analysis in the IT Sector using Ensemble Learning Techniques

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Abstract: In the contemporary workplace, especially in the IT sector, the emotional well-being of employees is pivotal to organizational success. High workloads and tight deadlines contribute to increased stress levels, making it essential to understand employee emotions to foster a positive work environment and enhance productivity. This research aims to develop a robust model for automatic emotion recognition through ensemble learning techniques, leveraging advancements in machine learning and facial expression analysis. The study is divided into three phases. The first phase involves the selection of the top three algorithms by evaluating five different transfer learning models based on their accuracy and processing time in emotion prediction. The second phase compares a custom-built Convolutional Neural Network (CNN) model against the selected transfer learning models from the first phase. The final phase constructs an ensemble model using the best three algorithms identified in the second phase. The dataset comprises 1,500 facial emotion samples from 84 individuals, categorized into positive and negative emotions for training and testing. The comparative analysis reveals that InceptionV3, EfficientNetV2, and MobileNetV2 exhibit superior performance, leading to the exclusion of the custom-built CNN from the ensemble model. The ensemble model achieves an impressive accuracy of 88% as evaluated using a confusion matrix.

Keywords: Emotion Detection, Employees, Facial Expression, Machine Learning, Transfer Learning, Ensemble Learning.

INTRODUCTION

In the dynamic environments of today's fast-paced workplaces, especially within the Information Technology (IT) sector [1], the emotional well-being of employees has become a foundation of organizational success [2]. The demands of heavy workloads, strict deadlines, and continuously changing technology often create a high-pressure environment and lead to emotional challenges that can negatively impact job satisfaction and productivity [3]. The risk of stress and burnout is increasing among IT professionals who must creatively solve problems and have technical expertise. Consequently, prioritizing employees' emotional health has evolved from being a personal concern to a strategic necessity [4] for maintaining a competitive edge and fostering workplace innovation.

Employees who feel emotionally supported and understood are often more motivated, engaged, and collaborative, leading to improved productivity and stronger workplace dynamics. Despite the promise, there are significant challenges associated with the implementation of facial recognition technologies in the workplace. It remains a complex task to translate facial expression analysis results into practical applications that can be easily integrated with the current systems.

Human emotions are complex, and cultural and personal variations in emotional manifestation become major challenges to emotion recognition systems [5].

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Moreover, the ethical aspects of privacy and data safety should be considered to avoid problems with the abuse of employee information or the violation of personal space.

Ensemble learning techniques have gained attention as a viable solution [6] to overcome these challenges. By leveraging the combined strengths of multiple machine learning models [7], ensemble methods enhance the accuracy, reliability, and adaptability of emotion detection systems These approaches work well when dealing with variation and complexities of facial expression so that the models used in emotion recognition can make consistent and reliable predictions. The proposed study seeks to develop and deploy an ensemble model of automatic recognition of emotions using facial expression analysis to suit the IT industry.

METHODOLOGY

In the context of emotion recognition, facial expression is the main principle. This research focuses on facial expression analysis and is considered vital. This research is constructed through an ensemble learning technique using a novel dataset. This chapter details the different analyses carried out to identify the best TL algorithms, implementation of the ensemble model [8], how the different models are evaluated to come up with the best algorithm, and how the ensemble model is constructed and tested.

A. Data Collection

The dataset collected from the real-world is designed to investigate compound emotion recognition. The two categories are positive and negative. All main emotions are compounded in those two categories and contain the dataset. The motivation for creating the dataset is to explore how well the model can perform and as well as a good impression on research topics. For now, data collection consists of 1500 front face images (male and female) with different emotions [9] captured from 84 people. The age range of people who are subject to the data collection is between 25 – 30. Subjects had different appearances such as hair styles, clothes, and accessories. Images were obtained in a controlled environment to overcome problems like background noise, head pose variations, and distance variations. And captured under the same environment. Image resolution 1080 x 1920. Room where images are captured with uniform light and uniform distance. The motivation to use such a controlled environment is to reduce preprocessing steps. High resolution images show detailed information. Each participant displayed six different emotions. The dataset is divided into two groups as a training set and test set. 80% of data is for training and remaining 20% of data for testing. Figure 1 and Figure 2 show two sets of data collection images.

Figure 1: Data collection Images – Set 1

Figure 2: Data collection Images – Set 2

B. Proposed System

This study consists of three phases. The first phase consists of selecting the best three algorithms based on their predictions on emotions by comparing five different transfer learning models according to their learning time and performance accuracy. The next phase consists of comparing one of the own CNN models with built-in transfer learning models that you choose in the first phase. Then the final phase is creating an ensemble model by using the best three algorithms chosen from the second phase. In the initial phase, a preprocessed human emotions dataset is stored in a folder with two

different classes as positive emotions and negative emotions. Classification is performed to help the model uniquely identify features [10] with supervised learning. Next, we import python libraries which require them to carry out the processes. NumPy, matplotlib, and TensorFlow are used within the process. Dataset is used in InceptionV3, EfficientNetV2, ResNet50, MobileNetV2 and MobileNetV3 algorithms to evaluate the best one by comparing the learning time taken by algorithm and based on the performance accuracy shown by each model. Use the same dataset with all algorithms and fixed number of epochs. Finally figure out the best algorithms which have the lowest time taken and have high accuracy.

In the second phase, compares own built CNN model with built-in transfer learning models which were selected in the first phase. Own custom model is created for facial expression analysis and evaluated with transfer learning models according to model accuracy and time. To create this own model, we need to import python libraries. Then split the dataset into training and testing dataset. 80% of data was used for training purposes and the remaining portions used for testing purposes. The computational efficiency of each model will be calculated considering factors like training time, scores of accuracies, and losses. This analysis supports checking model feasibility. Models are evaluated through testing on unseen data samples. That process determines the performance of the model on data outside of the training set.

In the third phase, an ensemble model is constructed in the third stage using the best three algorithms selected in the phase two comparisons. To further boost general performance and resistance, a combination of numerous individual models will be integrated into the ensemble model. The algorithms with the best results are chosen in comparison from the second phase. They are chosen based on specific features of their effectiveness. These include accuracy, computational efficiency, and generalization properties. To decide on the best method that can be used for incorporating these chosen algorithms into one system, different methods for ensemble learning were tried. These include bagging, boosting, and stacking. When numerous models are used during prediction, prediction of an individual model often doesn't provide accurate predictions like what happens in ensemble methods. The integration of Algorithms into the ensemble model works such that the chosen algorithms are connected and their predictions aggregated using methodologies like averaging or weighted voting. Combining the strengths of models gives them better results during emotion recognition tasks. The ensemble model must be validated and optimized to ensure its effectiveness and reliability. This process involves testing the model using datasets, fine-tuning ensemble parameters, and optimizing performance metrics for best results. Figure 3 shows the flow chart of the proposed system.

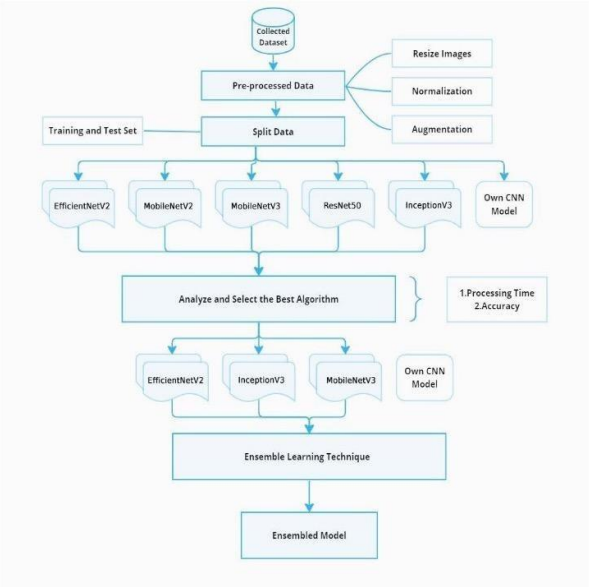

Figure 3: Flow chart of proposed system

C. Model Comparison

After evaluating the performance of each of the five models. Select the most appropriate three models to go. These top three models selected displayed significant precision and efficiency. This comparison shows the merits and shortcomings of each approach, providing useful insights for future optimization. The selected models are EfficientNetV2, InceptionV3, and MobileNetV3. EfficientNetV2 is a model that was discovered to be the most effective in classifying images.

These have been a popular choice for many kinds of applications. InceptionV3 has a complex structure and numerous convolutional layers. And excels in handling complex visual data. MobileNetV3 is designed for mobile and edge devices that provide a lightweight but capable solution for real-time image processing. All these models contribute to different skills and meet various needs in the fields of deep learning and emotional recognition. The three models with the highest accuracy are EfficientNetV2 (0.8333),

MobileNetV3 (0.8367), and InceptionV3 (0.7567). These three models have shown that there are new ways of classifying images, and each one of the models has a balance between accuracy and efficiency.

The performance of MobileNetV3 and EfficientNetV2 is advantageous when it comes to resource-constrained systems, whereas InceptionV3 is a suitable option when more computational units are demanded. MobileNetV3 and EfficientNetV2 could deliver impressive results on devices with limited resources. InceptionV3, on the other hand, is reputed for tasks demanding higher computational power. The versatility of these models allows developers to choose the most suitable option based on the specific requirements of their projects.

The custom CNN [11] was made and applied with the use of the Keras Sequential API to compare directly to the transfer learning models. The model was configured to accept the input of the greyscale image of 48 x 48 x 1. The architecture has been created in three major convolutional blocks; A Conv2D layer (with 32 filters) and a 3 x 3 kernel is successively followed by a MaxPooling2D layer (with 2 x 2 size). Conv2D, which has 64 filters, and 3 x 3 kernel is followed by MaxPooling2D of size 2 x 2. It is followed by a Conv2D layer of 128 filters and 3 x 3 kernel and MaxPooling2D that has a size of 2 x 2. Every convolutional layer in the Rectified Linear Unit (ReLU) activation works.

A Flatten layer was then applied to the convolutional output, creating a fully connected network. In this network, there is a hidden Dense layer of 128 units (ReLU activation), a Dropout layer with a regularization rate of 50%, and a Dense output layer which had a Sigmoid activation function, which was used to classify the binary data. The model was trained during 30 epochs with the help of Adam optimizer and categorical cross-entropy loss function, and the image data were augmented. Figure 4 demonstrates the own built CNN model accuracy and loss changs with epochs.

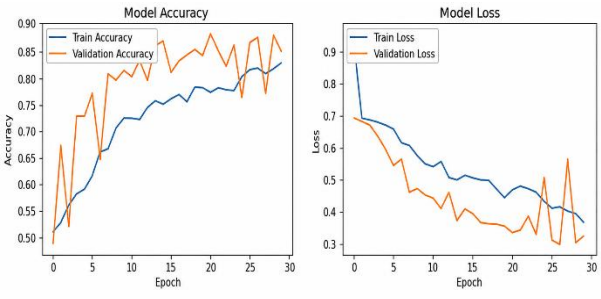

Figure 4: CNN model accuracy and loss changs

4. Accuracy and Loss of own-built CNN model

This own CNN model was found to exceed the three mentioned models in terms of accuracy, boasting an amazing accuracy score of 0.8500. Furthermore, with training times in the 983s, the trade-off between training time and accuracy is critical to consider when comparing these. The Own CNN model achieves the highest accuracy among other three models presented because of the input image sizes we used 48 x 48 pixels. The Custom model exceeds EfficientNetV2 (0.8333), MobileNetV3 (0.8367), and InceptionV3 (0.7567) by a large pixel size of 224 x 224. Therefore, own CNN model takes around 983 seconds to train. This is considerably quicker than training times for more complicated models such as EfficientNetV2, MobileNetV3, and InceptionV3, which are typically longer due to larger architectures and deeper layers. The own model is quicker training period can be useful, particularly in situations where training resources are limited, or rapid prototyping is required. Finally, the custom-created CNN model demonstrates promising performance with high accuracy and a quick training period. Despite reaching an impressive 85% accuracy, the custom-built CNN model was ultimately excluded from the final ensemble.

This choice was made based on technical justifications aimed at increasing the entire system's robustness and efficiency. First and foremost, a lack of feature diversity was a problem. Since the custom CNN was trained just on the relatively short 1500 image dataset, the patterns it caught were regarded inadequately complementary to the huge feature spaces learnt by the pre-trained models (Inception V3, EfficientNetV2, and MobileNetV2). Second, resource constraints encourage exclusion. While the specific CNN trained quicker, EfficientNetV2 and MobileNetV2 are specifically designed for deployment on resource-constrained platforms.

RESULTS

The overall accuracy of each model was measured on the test dataset. Accuracy indicated the proportion of correctly classified images out of the total number of images. The confusion matrix provided insights into the specific strengths and weaknesses of each model in classifying different emotions.

Figure 5, Figure 6, and Figure 7 show the confusion matrices for EfficientNetV2, MobileNetV3, and InceptionV3 respectively.

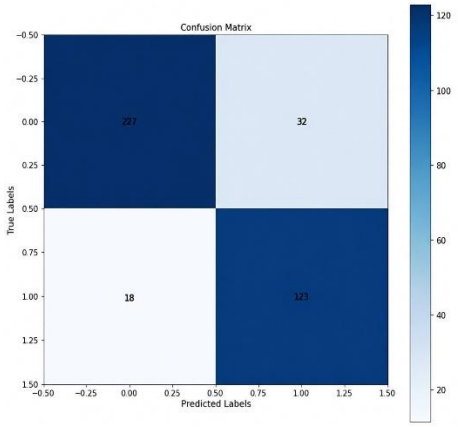

Figure 5: Confusion Matrix of EfficientNetV2

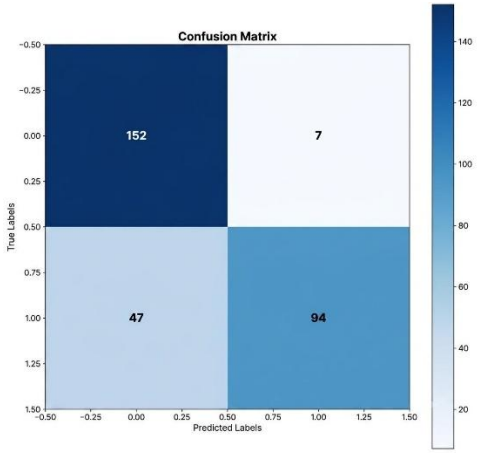

Figure 6: Confusion matrix of MobileNetV3

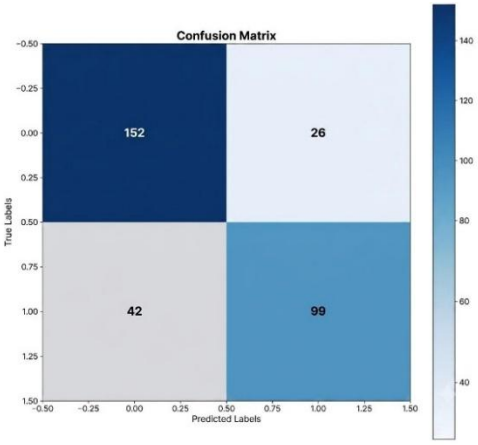

Figure 7: Confusion matrix of InceptionV3

Once the ensemble model has been defined, build it and train it on dataset, noting the training and validation of accuracy and loss. After training, assess the model on a test dataset, create a confusion matrix to analyses its performance, and plot the training and validation metrics to see how the model learns over time. This strategy makes use of the capabilities of various models, potentially improving total performance. With 30 epochs, the ensemble model [12] shows 88% accuracy. This can be compared to a significant improvement than the individual models. The ensemble method utilizes the strengths of each model as well as minimizing its flaws. The predictions of the ensemble model can be used together to come up with more accurate and strong conclusions. Figure 8 presents the ensemble model accuracy and loss variation with epochs.

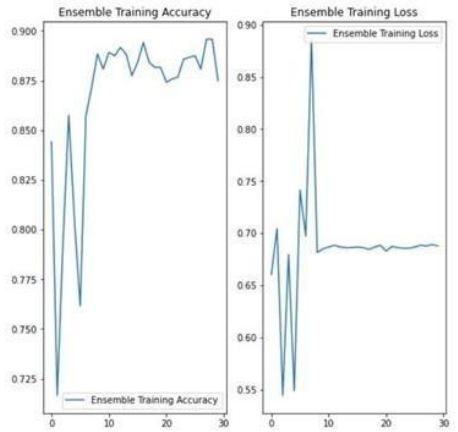

Figure 8: Ensemble model accuracy and loss variation.

The accuracy obtained with ensuing model exhibits a tremendous move towards emotion identification. This technical success is not a measure of the efficiency of algorithms only, but also organizational empathy. The strength of this model was spread in its variety of feature extraction where it managed to merge the intelligence of InceptionV3, EfficientNetV2, and MobileNetV3.

All the models add their own features, which are trained with their own weaknesses, and strike a balance between performance and efficiency. The combination was a strong, generalized classifier. This observation is very influential in automatic identification of emotions of the employees and is useful in enhancing employee health, decreasing stress levels, and consequently increasing productivity at the workplace.

CONCLUSION

This research was able to create a successful emotion recognition system for the IT sector based on an ensemble learning approach on a specifically compiled dataset of 1,500 facial emotion samples. The combination of three progressive models of transfer learning, including Inception V3, EfficientNetV2, and MobileNetV2, and the ultimate ensemble model through the advantages of the complementary learning approaches resulted in an accuracy of 88% in classifications. This result demonstrates better

generalization and classification of employee emotion into positive and negative categories using ensemble methods than using a single model architecture. The system will work well in enabling IT organizations to monitor and control the emotional status of employees automatically, leading to improved work environment and productivity.

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RESEARCH ARTICLE

Multimodal IoT-Based Real-Time Drunk Driver Detection and Reporting System with Intelligent Sensor Fusion and Mobile Law Enforcement App

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Abstract: Drunk driving remains a major factor in severe road accidents and fatalities in the world. In this work we have developed a smart, fully automated system that identifies and reports intoxicated drivers utilizing IoT technology. The system employs a three-layer detection method. Firstly, a voice-activated verification system assesses the driver's alertness prior to starting the vehicle. Additionally, sensors embedded in the steering wheel track the driver's heart rate while gas sensors measure alcohol content. Finally, a webcam captures facial images that are evaluated using a custom-trained CNN model to identify visual indicators of intoxication. All inputs are analyzed with a weighted algorithm. If the assessment indicates that the driver is under the influence, the system transmits a real-time alert, including GPS coordinates, to a mobile application utilized by relevant authorities. This guarantees timely identification and allows for swift action by authorities. The testing of the integrated system demonstrated an overall detection accuracy of 93.5%, with the facial intoxication detection module alone achieving up to 99% classification accuracy and the voice-verification achieving 96% reliability in controlled trials.

Keywords: IoT, Facial Recognition, Pulse Sensor, Gas Sensor, CNN, GPS Tracking

INTRODUCTION

The World Health Organization reports that approximately 1.35 million individuals lose their lives each year due to road traffic accidents, with a staggering 93% of these fatalities occurring in low- and middle-income countries such as Sri Lanka [1]. Among these causes, alcohol-impaired driving stands out as a major contributor, accounting for nearly 30–32% of all traffic-related deaths. This means that nearly one in every three fatal crashes involves a drunk driver. In many cases, intoxicated motorists go undetected until they have already caused significant harm, posing a substantial challenge to law enforcement agencies striving to prevent these incidents before they occur. This underscores a major limitation in current road safety infrastructure: the inability to proactively identify or intercept impaired drivers in real time.

In Sri Lanka, this issue is particularly severe. Police records from January to June 2023 reveal a total of 930 fatal accidents, resulting in 976 deaths and an average of five fatalities each day [2]. Despite the presence of conventional deterrents such as police checkpoints, fines, and public awareness campaigns, the rate of accidents and associated deaths remains alarmingly high.

The persistent occurrence of these tragedies suggests that current strategies are inadequate, as they focus primarily on punitive measures after violations occur, rather than preventing risky behavior beforehand. A key deficiency in existing systems is the absence of real-time, in-vehicle monitoring solutions that can assess and react to the driver's condition before the vehicle is in motion. While a range of road safety technologies have been introduced globally, including speed enforcement

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cameras, breathalyzers, and roadside sobriety checkpoints, these methods are either external to the vehicle or heavily reliant on time-bound, location-specific operations. Furthermore, most of these systems are designed to operate reactively, activating only after a violation or accident has occurred rather than offering continuous, proactive monitoring of the driver's physiological and behavioral state. As a result, intoxicated drivers can frequently evade detection, contributing to avoidable fatalities on the road [3]. This highlights a significant research gap: the lack of an integrated, automated system capable of real-time detection and intervention within the vehicle itself.

To address this challenge, this study proposes a novel drunk driver detection and reporting system powered by Internet of Things (IoT) technologies. The proposed system integrates multiple sensor modalities, including biometric sensors (e.g., heart rate monitors), alcohol gas detectors, voice recognition modules, and facial expression analysis tools, to evaluate the driver's level of alertness and sobriety. If the system determines that the driver is intoxicated, it can autonomously disable the ignition system or send a real-time alert including GPS coordinates and driver status to relevant law enforcement authorities via a custom-developed mobile application. This app enables immediate intervention by police officers, ensuring timely responses that can prevent potential accidents before they occur. Unlike traditional methods, this approach shifts the paradigm from reactive enforcement to proactive prevention through automation, data fusion, and real-time decision-making. By addressing critical shortcomings in existing detection mechanisms, the proposed solution represents a significant advancement in road safety technologies, particularly for countries like Sri Lanka where alcohol-related traffic incidents remain a leading cause of mortality. Through the integration of intelligent sensing, real-time analytics, and law enforcement connectivity, this research offers a robust and scalable model for reducing impaired driving incidents and enhancing public safety on a national scale.

LITERATURE REVIEW

Identifying intoxicated drivers through facial characteristics and image analysis has emerged as a significant focus in road safety research. In their study, Kumar et al. [4] employed a transfer learning strategy to enhance the precision of detecting drunk drivers from facial images. They utilized several pre-trained deep learning models, training them on a publicly available dataset containing faces of both sober and intoxicated individuals. The models were fine-tuned for optimal performance and assessed using metrics such as accuracy and precision. Among the various models evaluated, ResNet101 and DenseNet201 delivered the most promising results, exhibiting great potential for distinguishing between sober and intoxicated drivers. This method underscores the efficiency of transfer learning in accelerating the creation of dependable image-based detection systems by leveraging pre-existing trained networks and modifying them for this application.

The identification of intoxicated drivers through facial characteristics has garnered interest in recent years, particularly with the advancement of deep learning technologies. In research conducted by Chang et al. [5], a two-phase deep neural network system was created to identify signs of alcohol impairment using images of the driver's face. The initial phase utilized a VGG model to estimate the driver's age, while the subsequent phase employed a Dense Net model to assess whether the individual was drunk or sober. Their system achieved an accuracy rate of 89.62% in testing with image datasets.

A recent research effort by Suryawanshi [6] presented a system for alerting alcohol-impaired drivers, aimed at improving road safety through sensor-based monitoring. This system integrates alcohol sensors with vehicle control functions to determine whether a driver is intoxicated. If the system detects alcohol levels exceeding a specific threshold, it activates an alert and takes actions such as disabling the vehicle's ignition. It illustrates how embedded systems and real-time monitoring can be utilized to recognize impaired drivers and initiate suitable safety measures. Sandeep et al. [7] introduced an innovative model aimed at detecting and preventing drunk driving using IoT technology. This system is designed to monitor the driver's blood alcohol concentration using onboard sensors and manage vehicle operation based on the findings. It combines alcohol detection with vehicle access control, ensuring that the engine is automatically disabled if alcohol levels exceed a specified threshold. Additionally, the system features communication capabilities to notify appropriate authorities or contacts in the case of a safety violation. Recognizing patterns in driver behavior has become increasingly essential for promoting road safety and reducing the likelihood of accidents. Shahverdy et al. [8] introduced a technique that employs one-dimensional convolutional neural networks (1D-CNNs) to effectively assess and categorize different types of

driver behavior. The model analyzes time-series data gathered from sensors to identify patterns that indicate risky or distracted driving. By harnessing the capabilities of deep learning, the system achieves a high level of classification accuracy while ensuring computational efficiency. Dairi, Harrou, and Sun [9] presented a sophisticated driver monitoring system that integrates sensor data with manifold learning techniques to recognize unusual behaviors linked to alcohol impairment. Their method utilizes a range of physiological and vehicle signals to identify anomalies in driving patterns, leveraging unsupervised learning algorithms for immediate analysis.

SUMMARY OF THE LITERATURE REVIEW

Table 1: Summary of the Literature Review

Author(s)	Key Technologies Used				
	Facial Recognition	*Alcohol Gas Sensors*	*Heart Rate Monitoring*	*Voice Recognition*	*Mobile App*
Kumar et al. [4]	✓	-	-	-	-
Chang et al. [5]	✓	-	-	-	-
Suryawanshi [6]	-	✓	-	-	-
Sandeep et al. [7]	-	✓	-	-	-
Dairi et al. [9]	-	✓	✓	-	-
Proposed System	✓	✓	✓	✓	✓

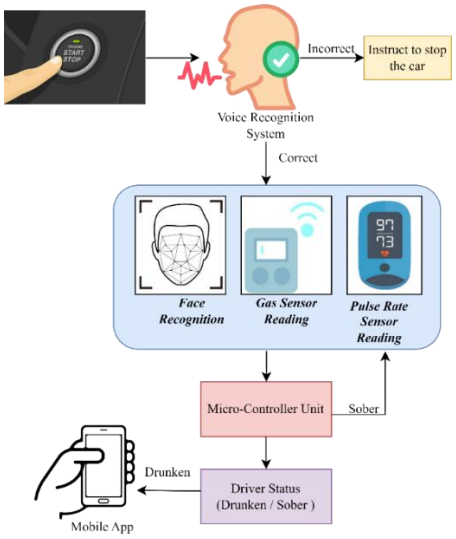

Figure 1: Architecture of the proposed system

Table 1. outlines a comparative summary of key technologies used in intoxication detection systems. Unlike previous approaches, the proposed system integrates all five technologies facial intoxication detection, alcohol gas sensing, heart rate monitoring, voice recognition, and mobile app integration within a single unified framework. This multi-modal approach enhances accuracy, real-time responsiveness, and reliability, making it a novel and comprehensive solution for driver monitoring.

METHODOLOGY

The proposed system architecture for detecting and reporting drunk driving incidents in real time is depicted in Figure 1. This architecture integrates sensor-based monitoring, intelligent data processing, and instant communication with authorities to offer a proactive solution for road safety. The system is embedded within the vehicle and is triggered the moment the driver attempts to start the engine. At this initial point, a voice recognition interface is activated, prompting the driver to speak a predefined phrase. This serves both as a biometric verification step and as a cue to initiate background monitoring procedures.

The system then engages a suite of sensors that operate continuously to monitor the driver's physiological and behavioral parameters. Three primary sensors are involved: a facial intoxication detection module, a gas (alcohol) sensor, and a pulse rate sensor. The facial intoxication detection component, based on deep learning algorithms, evaluates facial cues to detect signs of drowsiness or unusual expressions commonly associated with intoxication. In parallel, the gas sensor captures the driver's breath sample and analyzes it for alcohol content, flagging any readings that exceed the defined safety threshold. Meanwhile, the pulse sensor monitors the driver’s heart rate for abnormal fluctuations that could further indicate impairment.

The data collected from all sensors is transmitted to a central microcontroller embedded in the system. This microcontroller serves as the main processing unit and uses a decision-making algorithm to evaluate the driver's state. The algorithm analyzes the combined data in real time and determines whether the driver is fit to operate the vehicle. If the driver is found to be impaired, the system takes immediate action. It prevents the vehicle from starting, by issuing an audio command instructing the driver to stop the vehicle.

Once intoxication is confirmed, the system transmits the incident data, including driver status and sensor readings, via the MQTT (Message Queuing Telemetry Transport) protocol to a cloud-based web platform. This platform facilitates seamless, real-time communication with relevant authorities. A synchronized mobile application receives the transmitted data and displays the driver's GPS location, status, and a timestamped record of the event. These details assist law enforcement officers in taking swift and appropriate action.

A. Voice-based driver verification system

The initial phase of the proposed system features a voice-based driver verification module that evaluates the driver's alertness prior to allowing the vehicle to start. This process commences when the driver turns on the vehicle. At this moment, the system plays three pre-recorded verbal inquiries through a speaker. These audio questions are created using TTSMaker (Text-to-Speech Maker) and are stored on the Raspberry Pi. A built-in microphone in the system captures the driver's replies in real time.

The replies are then processed with the Vosk offline speech recognition engine (vosk-model-en-us-0.22), which translates the spoken answers into text without needing internet access. The generated text is compared with a set of predetermined correct responses kept in the program. To successfully complete the verification stage, the driver must correctly answer all three questions within a 10 second timeframe. If the driver fails, the system instructs them to retake the test until they provide successful responses.

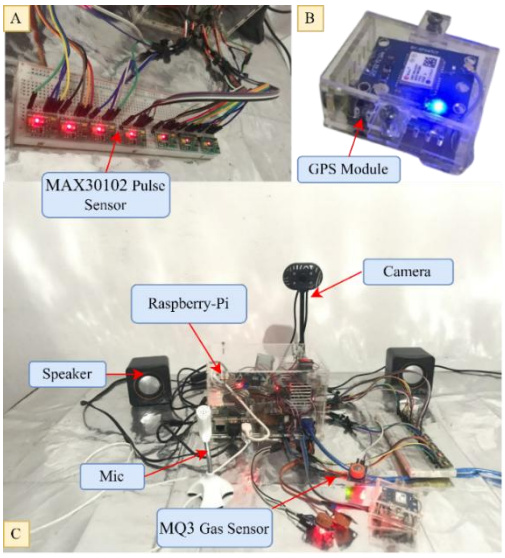

Figure 2: (A) Pulse sensors, (B) GPS module, (C) Sensor unit

This module serves as an initial cognitive filter, verifying that the driver is mentally alert and responsive prior to operating the vehicle. Only after successful verification does the system engage the subsequent detection components, which include pulse monitoring, alcohol vapor detection, and facial expression evaluation. This phase of voice recognition adds a non-contact and user-friendly safety layer, significantly enhancing the overall system's reliability and efficiency.

B. Sensor Calibration and System Integration

The secondary stage of the system is centered on gathering biometric and environmental information through meticulously tuned sensors (Figure 2). This encompasses the MAX30102 pulse sensors and MQ3 gas sensors, both essential in identifying physiological and chemical signs of alcohol impairment. Seven MAX30102 pulse sensors are incorporated into the steering wheel and the area around the push-start button, enabling continuous and non-invasive monitoring of the driver's heart rate. These sensors relay data to the Raspberry Pi using the I2C protocol, ensuring prompt data transmission with minimal lag. The obtained pulse data is evaluated utilizing threshold-based logic to ascertain if the driver's heart rate remains within a safe and anticipated range. Irregular readings such as elevated or inconsistent pulse rates factor into calculating the driver's overall intoxication risk score.

Simultaneously, three MQ3 gas sensors are strategically situated close to the steering column, dashboard, and air vents to assess the air quality inside the cabin for traces of alcohol vapors. These analog sensors are linked to the ESP32 microcontroller, which conducts initial processing of the sensor data. Given that the Raspberry Pi lacks analog input pins, the ESP32 interprets the analog voltage outputs from the MQ3 sensors and sends the digital results to the Raspberry Pi using UART communication.

Extensive calibration tests were performed with actual liquor samples featuring different alcohol-by-volume (ABV) percentages. For instance, a sample with 40% ABV resulted in sensor reading ranging from 3000 to 4000 ADC units, while a sample with 8.8% ABV produced notably lower values, between 1000 and 1500. Based on these experiments, a cutoff value of 3000 was established to effectively differentiate between minimal and substantial alcohol presence, thereby reducing false positives caused by environmental influences.

Together, the calibrated pulse and gas sensors offer two vital layers of intoxication detection. The data acquired from both sources holds a weight of 30% each in the conclusive intoxication assessment. These sensors, combined with the Raspberry Pi and ESP32, create a coordinated sensing framework that supplies real-time physiological and environmental information to the decision-making algorithm.

C. Sensor Fusion Algorithm

A crucial innovation in the proposed system lies in its intelligent data fusion methodology, which integrates inputs from multiple sensing modalities to produce a final intoxication decision. Each sensor facial intoxication detection, voice response accuracy, pulse rate stability, and gas concentration provides a normalized score representing the likelihood of intoxication. These scores are processed through a weighted decision fusion algorithm implemented within the Raspberry Pi controller. The system assigns predefined weights of 0.3 each to the pulse and gas sensors, 0.25 to facial intoxication detection, and 0.15 to voice verification, based on their respective reliability during testing. The fusion function computes a composite intoxication index (I) using the below equation;

$$I = 0.3 \times P + 0.3 \times G + 0.25 \times F + 0.15 \times V$$

where P, G, F, and V represent the normalized outputs of pulse, gas, facial, and voice modules respectively. If the computed index exceeds a predefined threshold (0.5), the system classifies the driver as impaired. This multi-sensor fusion strategy enhances robustness against false positives from individual sensor noise and ensures that decisions reflect a holistic assessment of the driver's physiological and behavioral state. By combining heterogeneous data streams in real time, the proposed approach significantly improves detection accuracy and system reliability, marking it as a key novelty of this research.

D. Deep Learning Models for Facial Intoxication Detection

A key component of the proposed system is the integration of deep learning models for facial intoxication detection. This module was designed to identify visual indicators of alcohol influence, such as drooping eyelids, relaxed facial muscles, and subtle micro-expressions, which can be detected through real-time webcam feeds. To achieve this, a computer vision pipeline was developed that analyzes the driver's face using advanced CNN architecture.

Three CNN-based models were considered during the development phase: a custom lightweight CNN built specifically for real-time inference, EfficientNet B5 for its advanced feature extraction capabilities, and a modified U-Net architecture adapted for classification purposes. A labeled dataset consisting of facial images categorized into "drunk" and "not drunk" classes was prepared. These images were preprocessed through resizing to a standard 224×224 resolution and normalized to facilitate efficient training.

Model development was conducted using Google Colab, taking advantage of GPU acceleration. The custom CNN was trained from scratch, while EfficientNet B5 employed transfer learning using pre-trained weights. The U-Net model, typically used for segmentation tasks, was modified by integrating global average pooling and dense classification layers to suit the intoxication detection objective.

Once trained, the selected CNN model was deployed via a Flask-based API, externally hosted to reduce the computational load on the Raspberry Pi. In real-time operation, the Raspberry Pi captures the driver's facial image and sends it to the predicted image endpoint of the API using HTTP POST. The API responds with a classification label and confidence score, which are then incorporated into the overall decision-making algorithm used to evaluate the driver's condition.

E. Real Time Monitoring Through Mobile Application

To connect in-vehicle intoxication detection with field enforcement, a specialized mobile application was created as shown in Figure 3. to facilitate real-time oversight and action by law enforcement agencies. This app acts as the final user interface within the system's framework, receiving alerts about intoxication, showing driver information, and supporting location tracking. Developed with the Flutter framework, the mobile application delivers a cross-platform solution utilizing a single codebase, optimized for both Android devices and future deployment on iOS. Visual Studio Code served as the main development environment, while Android Studio provided a built-in emulator for testing UI and backend integration. The mobile application is linked to Firebase Firestore NoSQL cloud database that stores streams live data from Raspberry.

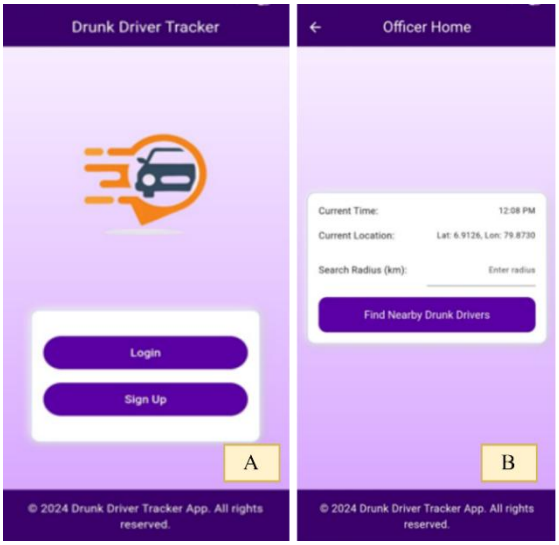

Figure 3: (A) Login page, (B) Select area

Pi, including the driver's sobriety status, GPS location, timestamps, and records of violations. When the system identifies an intoxicated driver, a cloud function within the Firebase database triggers a notification to all registered law enforcement officers through the app. This application incorporates a secure login and registration process, requiring officers to authenticate via encrypted credentials stored in the Firestore's "Officers" collection.

After logging in, the app presents the current time alongside the officer's location. Officers can then choose their monitoring area, and the app automatically filters incidents occurring within that geographical range using distance-based queries. Detected drivers are displayed in a user-friendly, tabulated format featuring essential information such as intoxication level, location, and detection time. Moreover, the app offers access to a driver history section, which shows prior violations, dates, and total counts. The location tracking module integrates with Google Maps API, enabling officers to observe the driver's real-time position and navigate directly to the incident site. This capability is vital for ensuring that authorities can act quickly and effectively.

To streamline the development process, several supporting tools were utilized. Firebase Authentication managed user access control: the Firestore database permitted real-time data synchronization; and the Google Maps SDK was employed for mapping functionalities. During development, debugging and testing were performed using emulated Android environments, ensuring dependable performance across various screen dimensions and network conditions.

This mobile application finalizes the system by linking cloud intelligence with on-the-ground enforcement, equipping authorities with a robust tool to monitor, trace, and immediately respond to drunk driving incidents efficiently and effectively.

RESULTS AND DISCUSSION

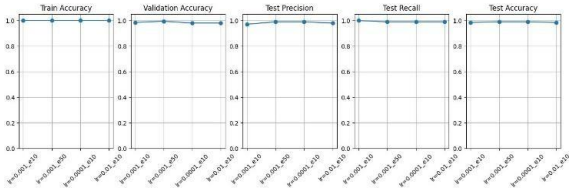

Figure 4: Performance of Custom CNN Model

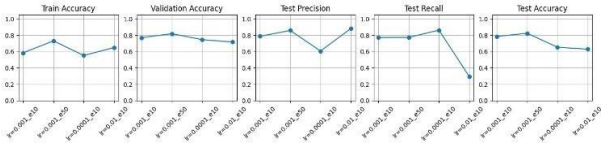

Figure 5: Performance of EfficientNet B5 Model

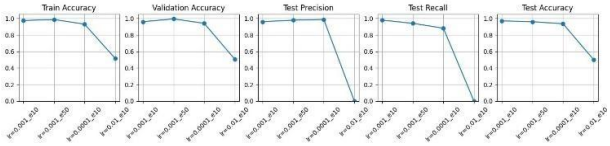

Figure 6: Performance of U-Net Model

Table 2: Performance comparison of deep learning models for facial intoxication detection

Model	Train Accuracy	Val Accuracy	Test Precision	Test Recall	Test Accuracy
Custom CNN	1.0000	0.9951	0.9902	0.9902	0.9902
EfficientNet B5	0.7312	0.8195	0.8587	0.7745	0.8244
U-Net	0.9878	0.9951	0.9796	0.9412	0.9610

The performance of the Custom CNN model for facial intoxication detection is illustrated in Figure 4. The model achieved a consistent 100 % training accuracy across all tested learning rates and epochs, confirming its strong learning capability. The best results were observed at a learning rate of 0.001 with 50 epochs,

where the model reached a validation accuracy of 99.51 %, test accuracy of 99.02 %, and both precision and recall values of 99.02 %. These results highlight the model's robustness and ability to generalize well to unseen data. The consistently high precision and recall indicate effective classification performance with minimal false positives or false negatives, which is essential for safety-critical applications like drunk driving detection. Additionally, the lightweight architecture of the Custom CNN supports fast inference, making it ideal for real-time embedded deployment in vehicles.

EfficientNet B5 demonstrated relatively lower performance across all experimental setups compared to other models in the study. The model achieved its highest test accuracy of 82.44 % when trained with a learning rate of 0.001 over 50 epochs. While EfficientNet B5 was able to attain a notably high precision of 88.24 % using a learning rate of 0.01, this configuration resulted in a sharp decline in recall to 29.41 %, indicating a significant lack of sensitivity in identifying positive cases (Figure 5). This trade-off between precision and recall suggests that the model became overly conservative in its predictions under these training conditions, leading to a high rate of false negatives despite maintaining good specificity for the cases it did classify as positive.

The U-Net architecture demonstrated in Figure 6. shows exceptional performance under optimal training conditions, achieving outstanding results with a learning rate of 0.001 over 50 epochs. Under these conditions, the model attained a validation accuracy of 99.51 % and maintained high precision with a test precision of 97.96 %, indicating robust generalization capabilities and reliable positive case identification. However, the model exhibited significant sensitivity to learning rate selection, as evidenced by its poor performance when trained with a higher learning rate of 0.01. This suboptimal configuration led to training instability and convergence issues, resulting in a dramatic deterioration across all evaluation metrics, with the test accuracy plummeting to just 50.24 %. This stark contrast in performance highlights the critical importance of proper hyperparameter tuning for U-Net architectures, where excessive learning rates can prevent the model from effectively learning the underlying data patterns and lead to essentially random prediction performance.

Table 2 summarizes the evaluation of three deep learning models for facial intoxication detection. Custom CNN outperformed the others, achieving perfect training accuracy and over 99 % validation and test accuracies,with high precision and recall. Its lightweight design and low latency made it ideal for real-time deployment on embedded systems like Raspberry Pi. U-Net also showed strong performance, with high accuracy and precision, but exhibited sensitivity to hyperparameter tuning particularly the learning rate which affected its stability under certain conditions. EfficientNet B5 yielded the weakest results, with lower training and test accuracies and an imbalanced precision-recall profile, making it less effective for consistent intoxication detection. Due to its superior accuracy, generalization, and computational efficiency, Custom CNN was chosen for system integration. These findings emphasize the importance of architecture selection in developing reliable, fast, and accurate real-time detection systems for safety-critical applications like preventing drunk driving.

To contextualize the proposed system's performance, we compare it with recent works. Dairi et al. (2022) used manifold learning with Isolation Forest for anomaly detection, achieving approximately 80 % classification accuracy in specific configurations. Suryawanshi et al. (2023) developed an embedded alcohol-impaired driver alert system but did not report facial-model accuracies exceeding our results. In contrast, our integrated multimodal system achieves 93.5 % overall detection accuracy (face module: 99.0 %) with low inference latency of 300-450 ms, suitable for real-time in-vehicle deployment. These results demonstrate that the proposed multimodal fusion approach improves detection reliability and reduces false alarms compared to single-modality or unsupervised sensor-only methods.

The MQ-3 gas sensor was integrated into the system to capture driver breath samples and analyze alcohol content, automatically flagging readings that exceed predefined safety thresholds. A practical calibration process was conducted using liquor samples with varying Alcohol by Volume (ABV) percentages to establish reliable detection parameters.The calibration results demonstrated in Table 3 show a clear correlation between alcohol concentration and sensor readings. Higher alcohol content samples (40 % ABV) generated readings ranging from 3000 to 4000 ADC values, while 38 % ABV samples produced values between 2800 and 3500. Lower concentration samples (12 % and 8.8 % ABV) yielded significantly reduced readings, typically ranging from 1000 to 2000 ADC values (Figure 7).

Table 3: MQ-3 Sensor Calibration Results

Bottle (ABV %)	Sensor Reading (ADC value)
40%	3000 – 4000
38%	2800 – 3500
33.5%	2500 – 3200
12%	1500 – 2000
8.8%	1000 – 1500

Table 4: Pulse Rate Sensor Module Performance Comparison

Sensor Module	Average reading(bpm)	Stability score (/100)
MAX30100	95	60
MAX30102	78	90
MAX30105	102	55
GY-MAX30102	85	70

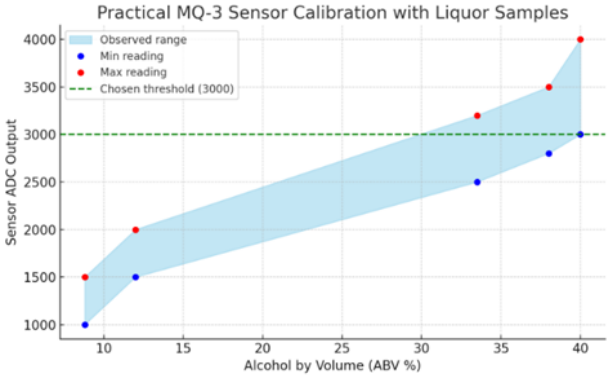

Figure 7: Practical calibration of MQ-3 sensor using liquor samples with different ABV values

During field testing with 50 participants, the system successfully detected alcohol consumption in drivers who had consumed alcoholic beverages within the previous 2 hours, with sensor readings consistently exceeding the established MQ-3 Sensor Calibration Results threshold of 3000 ADC units. Control group participants (34 sober drivers) produced readings below 1500 ADC units, validating the threshold selection. Based on these results, 3000 ADC units were established

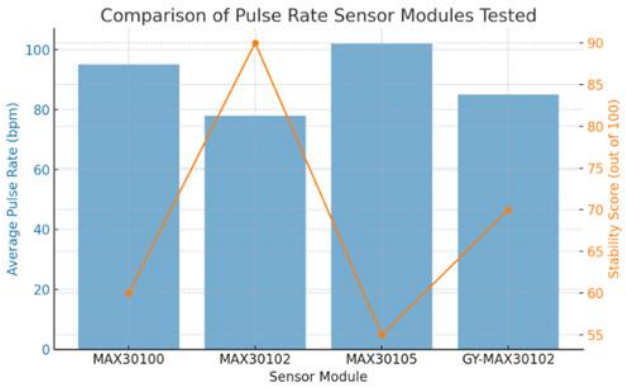

Figure 8: Comparison of pulse rate sensor modules

as the optimal cutoff point, providing balanced detection capability while minimizing false positives from environmental alcohol exposure or residual mouth alcohol.

The pulse rate monitoring component utilized heart rate sensors to detect abnormal cardiovascular fluctuations that may indicate driver impairment as in Table 4. A comparative evaluation of four different pulse rate sensor modules was conducted to identify the most suitable hardware for reliable heart rate detection in automotive environments. The evaluation results demonstrated significant performance variations across sensor modules.

The MAX30102 consistently delivered readings within the normal resting heart rate range (60-100 bpm) with an average of 78 bpm and achieved the highest stability score of 90/100, indicating superior resistance to signal interference and measurement fluctuations (Figure 8).

During field testing with 50 participants, the selected MAX30102 sensor successfully monitored heart rate patterns across different impairment states. Sober participants (n=34) exhibited stable heart rate readings averaging 72±8 bpm, while participants who had consumed alcohol (n=16) showed elevated and more variable heart rates averaging 89±15 bpm.

The sensor maintained consistent performance across the demographic composition of our sample [specify e.g. "predominantly male participants aged 22-35 years"] and various environmental conditions encountered during vehicle operation. While these initial findings demonstrate the technical feasibility of the MAX30102 sensor for real-time physiological monitoring, future studies with larger, more diverse samples stratified by age, gender, and baseline physiological characteristics (e.g. resting heart rate variability, cardiovascular health

status) are needed to establish the system's generalizability across broader populations and validate detection thresholds for different demographic groups.

The results clearly demonstrate that the proposed drunk driver detection and reporting system is both effective and reliable in identifying impaired drivers in real time. By integrating voice-based verification, biometric sensors, gas detection, and advanced facial intoxication detection within a unified IoT framework, the system ensures comprehensive monitoring of the driver's physical and cognitive state. This multi-layered approach significantly enhances the ability to prevent drunk driving incidents before they occur and streamlines the process of alerting authorities for swift intervention.

The practical performance and responsiveness observed during implementation suggest that this solution holds strong potential for reducing road accidents and advancing public safety particularly in regions where alcohol-impaired driving remains a critical issue.

CONCLUSION

This research introduces a comprehensive IoT-based system for real-time drunk driver detection and reporting, integrating voice recognition, biometric sensors, gas detection, and facial intoxication analysis. The system achieved 93.5 % overall detection accuracy, with the automated mobile application enabling swift law enforcement intervention. However, limitations exist. Environmental factors such as temperature and humidity could affect sensor performance, requiring validation under diverse conditions. Cloud dependency introduces concerns regarding network latency, rural coverage gaps, and cybersecurity vulnerabilities. Privacy considerations for continuous biometric monitoring necessitate robust data protection protocols. Future enhancements include incorporating motion sensors for erratic driving detection, advanced machine learning for pattern recognition, direct ignition control, and expanded mobile app features for incident reporting and trend analysis. Despite current limitations, this multimodal system demonstrates substantial promise as a scalable, proactive solution to reduce alcohol-related accidents and enhance road safety.

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RESEARCH ARTICLE

Optimizing The Concepts of Solar Water Distillation System for Rural Communities in Sri Lanka

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Abstract: This study investigates solar water distillation as a sustainable solution for water purity challenges in Sri Lanka. Low production rates and high costs often limit traditional water distillation methods. In Sri Lanka's Northern province, groundwater is the primary source of drinking water, but is often contaminated due to poor sanitation and pollution, making water filtration necessary but expensive. An affordable filtration method could significantly improve access to safe drinking water. The region's ample sunlight offers a cost-effective and sustainable solution through solar water distillation. In this process, unpurified water flows from a tank into a solar distiller's boiling chamber, where solar energy heats the water to produce steam. This steam is captured through a spiral system and directed into a clean container. A heat exchanger between the water tank and the boiling chamber preheats the incoming water. As the distilled water collects in the container, it is further cooled by the heat exchanger. The resulting purified water can be consumed directly or treated with mineral drops to enhance quality. Testing by the National Water Board confirmed that this distilled water had significantly reduced turbidity, chloride levels, hardness, and total dissolved solids, proving its suitability for drinking.

Keywords: Water distillation, Solar Energy, Renewable Energy, Parabolic Reflector, Groundwater, Water Purification.

INTRODUCTION

In an era where the world population is rising exponentially, with growth in industrialization and the approaching challenge of climate change, the need for Conserving and well-manage water on Earth has become most significant. There has now been a critical requirement to win the battle against this scourge as water pollution is no longer a concern of only a few but a concern of every human who is either on water or about to drink, or touch water. There can be waste reduction as well as prevention of unreasonable demand, which is possible by making the conservation of water practices and technology popular among households, organizations, and businesses. Re-using and purifying water are essential elements of sustainable water utilization plans. Repurifying water refers to the process of cleaning wastewater to eliminate impurities and pollutants so that it can be used for industrial processes, household use, and other nonportable uses. But drinking water should meet a higher standard than the water used for simple washing of a car. And converting Unusable water into usable conditions is more critical. For example, seawater, rainwater, brackish water, hard water, and groundwater. The conversion of non-usable water resources into usable or drinkable water must be seen as one of the major solutions for tackling water issues. Many regions around the world are facing the problem of water scarcity, which is manifested in inadequate sources of fresh water like rivers, lakes, and natural groundwater.

The conversion can enlarge the finite water sources and hence relieve the pressure on the nonrenewable waters. Non-usable water resources are condemnable since they contain several pollutants and contaminants, which make them unfit for direct consumption. By applying the distillation, filtration, and disinfection methods, these water sources can be purified up to drinking water standards and ensure people's health and safety.

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In Sri Lanka's Northern Province, safe drinking water has been a perpetual issue, especially in rural as well as remote areas. Most of the communities in the Northern Province do not have the required water supply network, including piped water networks and treatment facilities. Consequently, the community members must depend on shallow wells, rainwater harvesting, or surface water sources, which may be contaminated with pollutants and pathogens. Where water supply infrastructure has been created, water quality might still be degraded because of contamination from various sources such as agricultural runoff, industrial discharge, and inappropriate sanitation practices. Consequently, many individuals opt to purchase water filters for improved filtration, yet cost remains a barrier to widespread adoption. Offering affordable filtration solutions could address this issue and enhance access to safe drinking water for communities in Sri Lanka.

LITERATURE REVIEW

Water is an indispensable basic need in the world, which is necessary for the survival of humans. The sun was always tapped for various purposes in our daily lives, such as a never-ending and costless source of energy. Solar energy technology is crucial for developed and developing countries in the twentieth century, not only to fulfill their energy demands but also to survive. Solar distillation seems to be the perfect match for rural domestic systems with problems of a shortage of fresh drinking water. Simple processes, installations, and low maintenance are the main advantages of solar distillers [1].

Sri Lanka is located within the equatorial belt, a region where considerable solar energy resources are available for most of the year in sufficient quantities, which could be used for solar water heating, solar electricity, and desalination [2].

Northern Province of Sri Lanka, where solar power is significantly higher than the rest of the country, in a sun-hour, an hour during which the intensity of sunlight is 1,000 watts per square meter, and a day becomes a Sunny day if an average of 7 Sun-hours per day is expected. Kilinochchi in Northern Province has the highest sun days and sun hours throughout the year, whereas Vavuniya and Mullaitivu districts have the lowest sun days and sun hours. In contrast to the other provinces of Sri Lanka, the Northern province – Kilinochchi district, with an average monthly sun hour of 289.3 h [3]. In this paper has been highlighted, Jaffna is influenced mainly by two monsoons: the North-east and South-west monsoons.

The average temperature generally reaches highs of around 31 ^{0}C during the day, and at night it reaches a minimum temperature of 20 ^{0}C. In recent years, the maximum sustained wind speed has reached 74 km/h (around 46mph). At the same time, the months of December, January, and February are affected by foggy conditions [4]. The people from the area of Jaffna and Kilinochchi face problems with the flow of clean drinking water services [5]. The findings of this study say that the majority of the houses in the Northern province have toilet pits next to their dug well and about 74% of the selected wells have a minimum distance between the toilet pit and the groundwater source well of 4.6m which is less than the recommended distance of 16m given by the PHI manual, Sri Lanka. While that, pathogenic contamination may take place because of the properties of the soils in the region. Jaffna is also positive for groundwater pollution with limestone, which is the main aquifer that has no purification capacity. Hence, the present study exhibited that 93 % of sampling locations have more than 100 mg / dm^3 hardness waters, amongst which 23 % of wells exceeded the drinking water guideline value (250 mg / dm^3) of SLS [6]. The only freshwater resource in the Jaffna Peninsula is groundwater. Open wells are the common source of domestic water, but these are generally contaminated with pollution from septic tanks and soakage pits located close to wells. In Jaffna District, there are about 53,600 protected wells, around 8,800 unprotected wells, and some 5,100 tube wells. However, the quality of water is generally not satisfactory due to the widespread presence of chlorides and pathogenic organisms [7].

Rural communities in the dry zone of Sri Lanka, which cover two-thirds of the island, have suffered from severe health issues regarding the consumption of groundwater. Introducing by considering the available solar resources in the Northern Province, and the urgent need for clean water, implementing solar-powered water distillers appears as a good solution. This strategy helps in solving the water scarcity issue of the region by utilizing renewable energy, suitably providing safe drinking water to the locals at affordable rates, with a focus on providing aid to lower-income families. Solar distillation is the best solution for small communities that are facing problems in getting fresh water. Solar still is good for operation, maintenance, and repair, and is friendly to human beings in nature [8].

EXISTING SOLAR DISTILLATION UNITS

In the world, there are many different types of water purification processes, such as filtration, reverse osmosis, ultraviolet radiation, carbon absorption, but the most reliable processes are distillation and boiling. Water purification, such as distillation, is especially important in regions where water resources or tap water are not suitable for ingesting without boiling or chemical treatment. Solar distillation systems can be classified as passive and active. Solar radiation is the energy input of the passive solar stills, but the efficiency of the system is low. Attempts have been made to increase efficiency and productivity by preheating the saline water in solar stills. This method is called active solar distillation [9].

The basic principles of solar water distillation are that the solar energy heats water to the point of evaporation. As the water evaporates, water vapor rises, condensing on the glass surface for collection. This process removes impurities such as salt and heavy metals, as well as eliminating microbiological organisms. The result is water cleaner than the purest rainwater [10].

The research team from Sir Syed University of Engineering and Technology, Pakistan, treats the water by combining different methods such as Filtration, Distillation, and a technique called concentrated solar power (CSP). Filtration is done by a sand filter and a carbon filter. Now this is the pre-treatment of water. The filtered water is then collected in a water container at the focus of a parabolic mirror, where the distillation process is done. This project can be easily installed in any remote area where purified water is not easily available [11].

An experimental study of the performance of solar water distillation using a collector box. The results obtained show that the amount of distilled water increased with increasing solar radiation temperature. The results indicated that distilled water can be obtained even if the weather condition is very bad and the very low solar radiation, as well as a higher amount of distilled water can be obtained at higher values of solar radiation intensity [12]. This team from University of Peradeniya, Sri Lanka, conducted a study to design and develop an efficient and cheaper, wick-type solar still, which can be used in tsunami-affected areas. Various wick materials were tested, and it was observed that handloom material gives better results. But to avoid salt building on the wick material, perfect maintenance is necessary. The turbidity, conductivity, and pH values of all the water tested were found to reach the drinkable standards [13].

This team is from Rajarata University of Sri Lanka. This study aimed to address this issue by introducing an advanced basin solar water distillation system by analyzing insights into the effectiveness of different treatment conditions. Such as a basin only (T1), a basin only with the flat-plate solar collector (T2), a basin only with the sand layer (T3), a basin only with sponge cubes (T4), and a basin with all the features(T5). The treatment T5 has recorded the highest distilled output, and it is 4143 ml/m2/day. The distilled water output from this system has a safe pH level, electrical conductivity (EC), and total dissolved solids (TDS), and it contains very low levels of heavy metals, making it suitable for drinking purposes [14].

In this paper, an experiment was carried out to increase the efficiency of the existing single basin solar distillation unit constructed by the NERD center, Sri Lanka, by incorporating a 2cm thick un-sieved river sand layer for heat retention due to its high thermal capacity. The modified solar distillation unit with a 1 m2 area produced about 2100 mL of water per day under the prevailing climatic conditions of Mapalana (6°3'39"N 80°33' 57"E) [15]. The purpose of this project is to fabricate a solar water distillation system that can purify the water, which is impure by using a systematic arrangement, must have a low cost for manufacturing, and work based on renewable energy from solar. In the experiment, it was found that the black coated solar still is more effective when compared with the white coated solar still [9]. Solar energy and seawater are readily available free of cost in the surrounding areas, which makes the whole process Cost-effective. Solar energy from the Sun, in the form of radiation, is focused and concentrated onto the Receiver pipe with the help of a parabolic collector. The water inside the pipes is heated, converted into vapor, and then sprayed on the Designed Distillation system, where it is re-condensed to make portable distilled water, which makes it possible to convert contaminated water into Clean, drinkable water through the Distillation process [16].

By considering all the designed configurations and results obtained from the existing Water distiller units, this paper investigates the optimization of different parameters of the distillation process to improve the overall efficiency and further cost reduction.

METHODOLOGY

A. Experimental apparatus and the operating principle

As the initial step in the design, compare all existing solar water distiller designs from around the world, as shown in Figure 01, to select the most suitable one for this requirement. While choosing the design, the Cost of the product, the size of the parts to be determined at the end of the project, weight, materials, simplicity, fewer maintenance requirements, and the efficiency of water harvesting and solar power collection were considered as key factors. On a global scale, there are two types of solar still: passive and active ones.

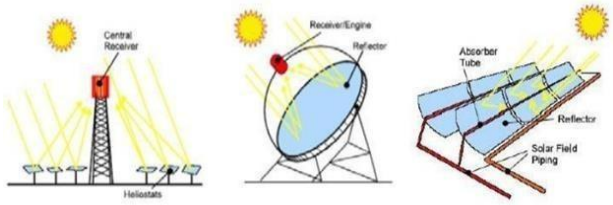

Figure 1: Types of Solar Collectors [18]

This modified solar water distiller could be simplified as a pot-shaped water container (boiler) used to store unpurified water. At the top of the pot, there was a cylindrical container that was used as a condenser, and in the center of this cylinder, a heat exchanger coil was fixed. On the bottom side of the apparatus, the outer surface of the pot is regarded as a focal point to capture the solar power. As illustrated in Figure 2, the solar energy is to be caught by a parabolic satellite dish. When the water flows from the tank or any resources that will be stored in the boiler (pot). To improve the performance of the final product, the water flow is controlled by the level sensor, and a water pump is used to supply water from the water tank. Once the water level is insufficient to continue the distilling process, the water pump will automatically fill the water into water. Owing to the solar heat, the stored water will be heated up inside the boiler. The liquid phase of the water will be transformed into vapor during the boiling process. As these vapors are going through the cylindrical-shaped container, they will be found in these two chambers. One for condensing the steam from the boiler, known as the inner chamber, and one for collecting condensed water from the end of the evaporation, known as the outer chamber.

The water vapors flow inside the cylinder through its hollow pipe and will then be collected in the form of spherical droplet collector. Vapor-to-water drop conversion was carried out by utilizing the heat exchanger mechanism. Next, with the help of the metal frame, the rest of the components are joined together as one product. This was the basis for the design of the solar water distiller. To increase the efficiency of water harvesting using this approach, some more alterations were incorporated. Those things are discussed one by one in a full, detailed way below.

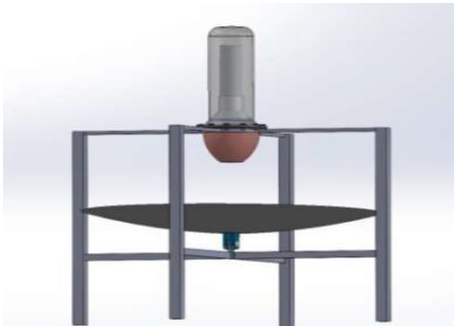

Figure 2: Basic design of the Solar Water Distiller

B. Component Selection and Property Analysis

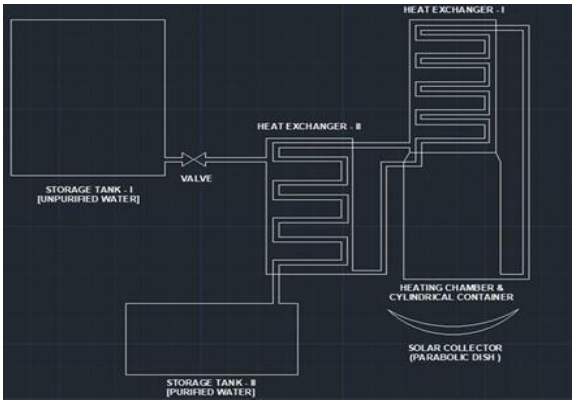

Figure 3: Final Design of the Solar Distiller

To improve the outcomes of the newly designed solar water distiller, the concept of the conventional solar water distiller's design is utilized while comparing each benefit and drawback to find the exact concept for this customized product. Also, a water motor and a set of sensors are used to improve the performance of the overall product with the help of Arduino technology beyond conventional water distiller approaches.

C. Solar Collector

One of the major components can be identified as a solar collector that is used to capture incoming solar radiation. According to the findings of some research, parabolic

collectors are a promising technology for harnessing renewable energy to meet our needs sustainably. They have many advantages, such as high efficiency, minimal environmental impact, and compatibility with existing infrastructure [17]. A parabolic-shaped satellite is selected as a solar collector.

It is referred to as sunlight reflection when a sunlight ray hits a polished, smooth surface and bounces back. The incident of sunlight rays hit the surface and are reflected off it. The beam that returns is referred to as the reflected ray. A parabolic solar ray reflector is fabricated for solar energy gathering and projection onto the heating chamber, and it is fabricated with highly reflective material. During the fabrication, several materials were selected for the surface preparation of the reflector. Those materials provided different reflections. Heat-providing data by reflectors were collected and compared to selecting the proper material for the reflector.

For this approach, a small, parabolic-shaped satellite dish was used, which was painted with Nickel paint as a first attempt, and as a second attempt, the surface was changed to Aluminum paint to improve the reflection. Due to kind of rough surface of the Nickel paint and Aluminum foil, a low range of solar harvesting is recorded. Manufacturing parabolic mirrors is an expensive process [17].

The property of the material that is to be used for coating should be such that it should be able to withstand high temperatures, have better reflectivity, be resistant to corrosion, and have low transitivity and absorptivity. For this purpose, silver seems to be an ideal candidate [18]. Therefore, silver-colored paint is applied to get a smooth surface, as shown in Figure 4.

Figure 4: Solar Collector – Parabolic satellite

D. Heat Exchanger

When the system of distillation proceeds, the water flow begins from the storage tank via a suction water pump to the water distiller. This suction water pump works according to the water level of the distillation chamber with the help of the water flow control valve and level sensor. As shown in Figure 3, the heat exchangers can be found inside the cylindrical container of the boiler, the input water line of the system crosses over the output water line, which is made by using a copper coil. The purpose of the heat exchanger is to increase the efficiency of the system and minimize heat loss. To achieve the objective of the heat exchanger, material selection should be done according to suitable criteria.

The main scenario of a heat exchanger is heat transferring from a high temperature to a low temperature. It can happen by different methods called radiation, convection, and conduction. In this heat-exchanging process, conduction is proceeding. For the conduction process, conductivity is the most crucial property of the material selection for the heat exchanger fabrication. That should come with a higher thermal conductivity as well as being non-toxic for health. This design required two heat exchangers, as shown in Fig03.

The first heat exchanger can be found in the inner evaporating chamber of the cylindric container of the boiler as shown in Figure 7. The boiler is used to store the unpurified water which is going to heat. Usually, the temperature of unpurified water is nearly at room temperature. Once purified hot water passes through this inner evaporate chamber, the heat will dissipate to room temperature. Therefore, output purified water from the product can be provided for direct use. The second heat exchanger can be found in an outer condensation chamber of the cylindrical container, which is placed in the boiler pot, as shown in Figure 7. The operating principle of the second heat exchanger can be expressed as enhancing the speed of change, the form of water into water drops. Unpurified water from the tank flows to the boiler pot through the second heat exchanger, which increases the water temperature a bit higher than the room temperature when entering the boiler by absorbing heat from the outer condensation chamber.

This cylindrical outer chamber is used to collect the evaporated water, and with the help of the second heat exchanger, water vapors speedily change form as water drops.

A cylindrical metal container is used to place the second heat exchanger chamber, which can be highly resistive at high temperatures. The output water line is laid through this cylindrical container using a 1cm diameter copper (Cu) tube. Cu is a strong, reddish-colored

metallic chemical element that ranks among the greatest heat- and electricity-conductors. It is mostly used for heat and electrically conductive purposes because of its material properties. As shown in Figure 5, The cu tube was formed into a helical coil shape to increase the interconnecting area with water. Because it boosts the heat exchange process. When the input water line flows through the heat exchanger, the water fills the chamber and then continues to flow to the evaporation chamber. Output line flow through the cu helical coil when both flows are occurring, the heat is transferring from high temperature to low temperature.

These two heat exchangers are made of copper tubes. Among the different geometrical shapes used in the heat exchangers. It shows that the helical tubes are found better than the straight tubes based on effectiveness and heat transfer rate [3]. When comparing these two helical and straight tubes, the helical shape can hold water vapors for a certain time. Straight tubes tend to sudden action to roll down the evaporated water drops from the top of the heat exchanger.

Figure 5: Inner view of the Heat exchanger

E. Heating Chamber (Boiler)

The heating chamber receives unpurified water through the water storage, as shown in Figure 3. The cylindrical container is placed on top of the heating chamber, which is fabricated with two chambers called the inner evaporating chamber and the outer condensation chamber. This is the part that proceeds with the distillation process of the system. Distillation is the process of turning a liquid into a vapor, which is then condensed back into a liquid state. The simplest illustration of it is when steam from a kettle condenses into drops of distilled water that are left on a cold surface. Water Distillation is the process that separates the freshwater from the contaminants. It evaporates the water molecules and sediment, contaminating the water, and the heat occurring during the evaporation process kills most of the microbial life in the water. Any water, whether it is drawn from a natural spring, an artesian well, or a conventional tap, may contain traces of pesticides, bacteria, minerals, or other impurities. Good heat conductivity, low emissivity, and corrosion resistance make the working fluid ordinary water, which can lead to calcification and rusting. The outer surface being exposed to the atmosphere should also have some kind of protection mechanism [18]. While considering all the required properties of the cylindrical container, stainless steel, copper, and aluminum are selected as the best materials. Among all of them, aluminum is selected due to its low budget, as shown in Figure 6. This cylindrical container and boiler are fixed to a support frame that is made of metal strips. While designing the support frame, the projection focal point of the parabolic solar collector is highly considered. The boiler needs to get sudden and continuous heat from the sun's rays was enhanced by painting the black color on the bottom part of the boiler pot as shown below in Figure 6.

Figure 6: Heating and evaporating unit.

F. Evaporating Chamber and Condensation Chamber

The above-mentioned distillation process in this system uses both the inner evaporating chamber and the outer condensation chamber. The inner chamber was designed to evaporate the water that is produced when the heat is provided to the boiler pot.

The inner chamber consists of a floating level sensor and a temperature sensor for controlling purposes. Usually, the water level is maintained by the controlling system with the help of the water pump according to the signal of the water level sensor. A temperature sensor provides temperature readings using a display. Depending on the supply of heat from the parabolic satellite dish, the water changes from its liquid state to its vapor state. Evaporated vapor from water has been directed into the outer chamber using fabrication methods for the condensate process.

Figure 7: Inner and Outer Chamber View

The outer condensation chamber consists of a helical cu coil, which is included to maximize the condensation process. This helical cu coil is responsible for the input water supply, which is directed into the inner chamber. This helical coil also proceeds with a heat exchanging

task, which is defined as a second heat exchanger. At the outer chamber, the heat of the evaporated gaseous water is absorbed by the input water line, then the vapor phase of the water is again changed into the liquid phase with heat extraction. Condensed water collects in the outer chamber and flows into the outer filtration unit. All this is dependent on the reflection of the parabolic satellite reflector.

G. Suction Water Pump

As the distillation process moves forward, water evaporation causes the water level to drop. Water needs to be replenished in the heating chamber in a continuous operation. The suction pump, which is shown in Figure 8, is operating following the level indication to fully satisfy that demand. Various types of water pumps exist based on the supply voltage and pumping technique. A 12-volt DC motor water pump was utilized for this arrangement. This water pump is powered by an electromotor located inside the waterproof container. When voltage is connected, the immersed pump's spinning component begins to rotate, sucking water from the pump's front side and draining it via a tube above. When the hose is attached to the tube and directed in the desired direction, the pump can discharge 120 liters per hour. This pump has a permanent magnetic rotor and is brushless. If so, there is no need for maintenance on this pump. These 12-volt pumps usually use centrifugal force generated by a fast-rotating impeller to raise, move, or circulate liquids such as water, oil, and coolant for sprayers, automobiles, fountains, showers, gardens, etc. 12V DC water pumps are tiny pumps that run on solar energy, DC power sources, or batteries.

All the controlling parts of this system are based on the Arduino board and the program code. Arduino is a platform that can be used to program according to requirements. When considering this system, all the sensor inputs are interconnected with the Arduino board. According to the requirements of the system, the Arduino code was written. Which considers the conditions given by the programmer and sends the signals to an actuator, like a pump. It provides data to the user by using display equipment. There are differences. Arduino is the most common and widely used for these kinds of applications. Arduino boards can be classified according to technology and size. For this system, an Arduino Uno board has been used.


Figure 8: Experimental Setup

Finally, all the components and parts were assembled as one product, which is shown in Figure 8. presents the circuit of the electrical components. This study builds on a preliminary investigation on solar water distillation conducted at the University of Ruhuna in 2022 [20]. The Experimental Setup shown in Figure 8 was developed, inspired by that foundational work.

Several tastings were conducted as part of this solar water distillation project to choose the best materials and techniques. The chosen material and methods were modified following the results. Increasing productivity and efficiency was the key objective of this project. These goals were taken into consideration during project design, with a primary focus on solar energy. The main objective was to capture more solar energy and use it with the least amount of loss.

RESULTS AND DISCUSSION

This process of solar water distillation included several trials to get the right combination of materials and techniques. The method and materials were altered after the results were obtained. Efficiency and productivity were the main objectives of this project to speed up manufacturing. These aims were involved in the conceptualization of the project, with solar energy being the focus. The most important objective was to catch and deliver as much solar energy to the customers as possible. Through different techniques, one solar collecting technology eventually gained acceptance.

The energy that comes from a distant source is collected by parabolic reflectors. Likewise, a parabolic reflector can convert an isotropic source into a parallel beam, as the laws of reflection can also be reversed. A Metal parabolic unit was the key element for selecting the instrument, and the correctly prepared reflective surface was another important factor to achieve the desired amount of reflection that influenced the thermal flow and the results. By way of the reflective surface preparation, the reflectors can be categorized as nickel-painted reflectors, glass mirror reflectors, polished metal reflectors, and aluminum foil reflectors. This project has used some of the above reflectors for a test. All the different types of reflectors produced different radiating heat at the same time, and similar environmental factors. Table 1 below explains briefly the results of these reflections.

Table 1: Maximum Temperatures obtained by different reflectors.

Image	Surface materials	Maximum temperature
	Nickel painted surface	58.9 ℃
	Aluminum foil coated	79.8 ℃
	Nickle foil sticked	115.8 ℃

To put a summary in a few words of solar collector, and a reflector will be produced following the most appropriate technique, and the projection of solar light to the heating room will be found.

When the solar energy exits the chamber, the heat diminishes because of the absence of solar energy and the heat removal by the air. For this to be solved the evaporating chamber has a black sand layer filled because of its heat- storing ability.

Those implementations were useful for the system because the production rate of the system increased. As the experiment showed, the evaporated water gets out through the inner chamber while the condensate falls into the heating chamber. However, the steam should go out through the outer chamber, and the condensate falls on the outside of it in the initial design.

In the context of this problem, some methods of using steam as shown in Figure 11. Lastly, a cone-shaped reducer on the top of the heating chamber is placed, which has a cone cap to reflect the steam into the other chamber.

The trial-and-error approach is applied in the notable sampling of the wines and the watching of the outcomes caused by the changes in the design. Finally, all the upgrades that were made which are needed were made and the whole system implemented.

The system provided notched in production, and the recorded heat of the inner chamber is reflected in the attached Figure 12 below.

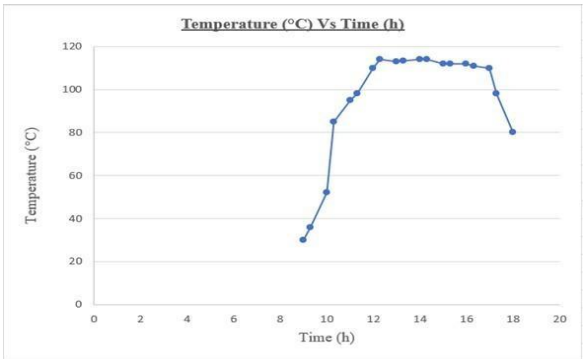

Figure 12: Recorded temperature variations

The following Figure 12 is the plotting of average non-collected within 14 days, and as a result, 02 L and 650 ml of output water were attained after 10 hours as on average, per day under cloudy and windy weather. A daily water intake of 3.7 L for adult men and 2.7 L for

adult women meets the needs of most persons [21]. And finally, a few mineral drops were added as per the required amount to enhance the quality of drinking water.

The Center for Research of the National Water Board carried out a careful assessment of the distillate water outlet to see the difference between samples taken before and after distillation. Originating from the Kilinochchi district of the Northern Province, the water samples were meticulously evaluated against various parameters, including turbidity, total dissolved solids (TDS), and chloride levels.

Turbidity, a crucial indicator of water clarity, experienced a notable reduction through the distillation process. The initial turbidity level of 3.46 Nephelometric Turbidity Units (NTU) decreased to 2.12 NTU post-distillation, aligning closer to the acceptable standard of 1 NTU for drinking water. Moreover, the TDS content, ideally ranging between 100-150, was initially recorded at 217.14 TDS before distillation, subsequently decreasing to 198.23 TDS after the distillation process. Furthermore, the chloride concentration, a significant factor in water safety, exhibited a considerable decrease from 18 mg/L pre-distillation to 12 mg/L post-distillation. While the World Health Organization recommends a chloride level of 4 mg/L for drinking water, the achieved reduction signifies a noteworthy improvement in water quality.

Although the pH values of both samples remained within the standard range for potable water, the comprehensive distillation results demonstrate a marked enhancement in water quality. The system, utilizing a natural, sustainable process powered by renewable solar energy, has consistently yielded healthy and drinkable water outputs. Additionally, the cost-effective production method underscores the system's viability and potential for widespread implementation.

CONCLUSION

Although this general system of distillation is efficient, more purified water can still be produced. Thus, Further modification can lead this product into a high-level product. As discussed in previous chapters, the technology of collecting solar energy can be enhanced. Once the system can keep the temperature more than 100 Celsius continuously, the production rate can be increased. If the surface preparation is equal to that of a mirror there will be some reflection, but it will be improved as the one currently using the reflector gets a temperature around 100 ℃. Hence, solar power extract can be improved to 100 %. While the contemplation of the solar reflector design changed by its shape. If the solar reflector is to be made feasible to use, then it should have a solar tracking system alongside it as well. If the solar redirector can change its reflection direction according to the deflection of the sun it can collect more energy when the sun is low.

ACKNOWLEDGEMENT

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RESEARCH ARTICLE

Vision Based PCB Fault Analyzer with Adaptive Feedback Alignment

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Abstract: This paper presents the development of a Vision Based PCB Fault Analyzer designed primarily for electronics repair centers such as computer and mobile phone service shops, as well as for PCB manufacturing and testing laboratories. The system automates the fault-detection process of Printed Circuit Boards (PCBs) and Printed Circuit Assemblies (PCBAs), reducing manual errors and preventing accidental short circuits common in manual troubleshooting. The proposed system integrates vision-based inspection and electrical testing using a flying-probe mechanism controlled by STM32 and PIC microcontrollers. A YOLOv5 deep learning model is employed to detect visual defects such as missing components, misalignments, and soldering faults, while the probe system verifies parameters like voltage, continuity, and resistor or capacitor conditions. To minimize hardware complexity and cost, an adaptive vision-based feedback mechanism replaces traditional servo feedback, dynamically adjusting camera positioning based on prediction confidence scores to ensure accurate alignment. Experimental results demonstrate that the proposed system provides a reliable, low-cost, and adaptive solution for both repair centers and production-line PCB testing environments.

Keywords: PCB Testing, PCBA, Flying Probe Test, Visual Inspection, Yolov5, Template Matching, Opencv, Pyqt5, STM32, PIC Microcontroller

INTRODUCTION

Printed Circuit Boards (PCBs) form the structural and electrical backbone of nearly all modern electronic devices from mobile phones and computers to automotive controllers and industrial systems. As component density increases, the demand for efficient PCB testing methods has become more critical. Traditional inspection techniques are generally divided into Automated Optical Inspection (AOI) and in Circuit or Flying Probe Testing (FPT), each addressing distinct fault types. However, these systems face challenges when implemented in small-scale production or repair environments.

A. Limitations of Conventional Inspection Systems

Conventional AOI systems employ high-resolution cameras and rule-based algorithms to detect surface defects such as spurs, spurious copper, missing holes, and solder bridges [1]. Although accurate, these systems are highly sensitive to lighting conditions and camera alignment. Moreover, advanced AOI equipment is costly and typically confined to large-scale manufacturing facilities. Flying probe testers and bed-of-nails systems perform electrical validation by measuring parameters such as resistance, continuity, and voltage at test points [2], [3].

These devices rely on servo-driven positioning mechanisms and precision alignment systems, making them expensive and difficult to maintain. As a result, such equipment is not viable for computer and mobile phone repair centers or small-batch PCB producers, where affordability, flexibility, and compactness are vital.

B. Advances in Vision-Based and AI-Assisted PCB Testing

Recent studies have shown that deep learning–based vision systems can overcome many of the limitations of traditional AOI [1]. Convolutional Neural Networks

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(CNNs) and object detection models, such as YOLOv5 and Mask R-CNN, have demonstrated superior accuracy

in identifying missing components, misalignments, and soldering faults under varying illumination and orientation conditions, as shown in Table 1. Some hybrid systems have combined deep learning–based optical inspection with probe-based testing. However, these implementations typically rely on servo motors or laser sensors for feedback and calibration, which increases hardware cost and reduces accessibility for smaller enterprises.

C. Adaptive Vision-Based Feedback and Cost Optimization

Unlike existing systems, the proposed Vision-Based PCB Fault Analyzer with Adaptive Feedback Alignment introduces a camera-driven feedback mechanism that eliminates the need for servo feedback or external sensors. The same inspection camera used for defect detection provides feedback signals by analyzing YOLOv5 confidence scores. During movement, the system continuously adjusts its camera position, advancing, reversing, or stabilizing based on the score variation to achieve optimal focus and alignment. This technique significantly reduces mechanical complexity and cost, making it ideal for small repair shops and testing labs.

D. Hybrid Inspection for Broader Application

Beyond visual fault detection, the system integrates a compact flying probe tester controlled by STM32 and PIC microcontrollers to measure voltage, resistance, and continuity across test points [4]. This allows the system to be applied not only in PCB production but also in component testing, such as verifying resistor or capacitor values during repair. The entire testing process is managed through a PyQt5 graphical interface, enabling real-time video visualization, user interaction, and automatic reporting without the need for expert technical knowledge. The system thus bridges the gap between low-cost manual inspection and high-end industrial platforms. While prior studies have improved PCB defect detection using deep learning and automation, most solutions remain cost-intensive and hardware-dependent. The proposed system provides a low-cost, camera-guided, and adaptive alternative that combines computer vision, deep learning, and intelligent feedback for both visual and electrical inspection. This makes it a scalable, accessible, and reliable testing platform for small-scale repair centers and manufacturing laboratories alike.

Table 1: Comparison of Existing Systems and the Proposed System

Methodology	Technique Used	Key Limitation	Improvement in Proposed System
Automated Optical Inspection (AOI)	Rule-based feature extraction	High cost, poor adaptability to lighting	Deep learning–based real-time detection using YOLOv5
Traditional Flying Probe Tester	Servo-controlled mechanical probes	Requires precise calibration costly hardware	STM32/PIC-controlled Probe system with simpler design
Vision-based Deep Learning	CNN and Mask RCNN	Limited to visual inspection only	Combines visual + elec-trical testing
Hybrid Vision + Servo Feedback	CNN + mechanical servo	Expensive feedback sensors, complex setup	Vision-based adaptive feedback using detection confidence
Industrial AOI and ICT	Fixed test fixtures	Inflexible for small scale repair tasks	Portable, modular, and GUI-controlled PCB/PCBA analyzer

METHODOLOGY

A. General Overview

The PCB Fault Analyzer Figure 1 system follows a structured and modular testing workflow, beginning with system initialization and image capture. The process starts by acquiring real time images of the PCB or PCBA using a mounted camera. In the subsequent PCB Test stage, computer vision techniques are employed to detect visual anomalies such as spurs, spurious copper, mouse bites, missing holes, and short circuits.

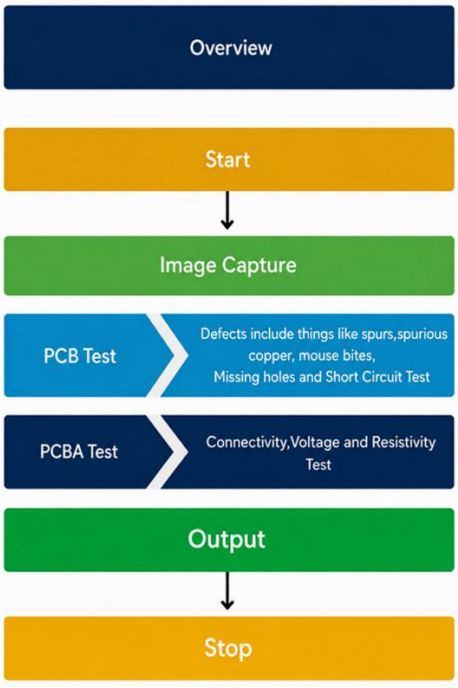

Figure 1: System overview of PCB and PCBA testing workflow

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The PCBA Test then performs physical verification using a flying probe system to measure voltage, connectivity, and resistivity at designated points. Although circuit level testing and thermal camera analysis are planned extensions, they are not yet implemented in the current version. After all, completed tests, results are processed and presented through an output interface.

The system concludes its operation in a controlled stop phase, ensuring the integrity of data and test reports. This streamlined flow allows for flexible integration of future test modules while maintaining an efficient and user-friendly inspection process.

B. Machine Interface

The machine interface Figure 2 consists of various mechanical and electronic components including a camera system, probe drivers, limit switches, and user controls. This subsystem is responsible for executing precise probe movements and capturing visual and electrical test data from the PCB or PCBA under inspection. The following figure illustrates the actual hardware setup and interface layout used in the system.

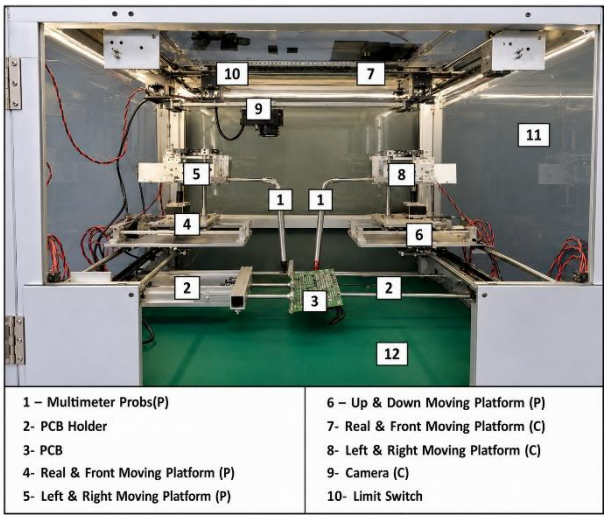

Figure 2: Machine Interface

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The camera platform enables precise two axis movement left – right and front – rear for detailed inspection of PCBs. The left – right motion is driven by a T8 lead screw with an 8 mm pitch, while the front – rear motion is actuated using a GT2 6 mm timing belt and pulley system. Both axes are powered by NEMA 17 stepper motors, which offer reliable torque and fine control for smooth and accurate positioning. The complete platform, including the camera mount, weighs approximately 1 kg and is structurally optimized to minimize vibration and mechanical drift during testing operations.

A standard USB webcam is mounted on the platform to provide real time image capture, with the video feed directly streamed to a host laptop via a USB interface. While a webcam is sufficient for basic testing and prototyping, it is recommended to use a DSLR camera for improved image quality, resolution, and optical performance, especially for applications requiring fine detail analysis or high precision template matching.

C. Machine Structure

The machine Figure 3 has a compact design with dimensions of 72 cm in width, 77 cm in height, and 77 cm in length, making it well suited for users with limited workspace. An aluminum frame is used for the structure to provide both durability and aesthetic appeal, as it supports the attachment of glass panels and enhances the overall professional appearance. The green screen area is constructed using hardboard, while dark tinted glass is used to enclose the system. This not only helps block ambient light from surrounding equipment but also contributes to a cleaner, more refined look. A yellow LED light strip is installed around the system to provide consistent and uniform illumination during testing. Yellow light was specifically chosen because it enhances the camera's ability to detect fine details and small features on the PCB, improving the accuracy of visual inspections. The probe system "Figure 3" is built within a frame measuring 250 cm in length, 160 cm in width, and 200 cm in height. It is capable of multi axis movement to reach designated test points on the PCB. Rear and front movements are driven by a GT2 timing belt mechanism, providing smooth and fast motion over extended distances. Other movements such as vertical (up/down) and lateral (left/right) positioning are actuated using T8 lead screw bars powered by NEMA 17 stepper motors for precise control.

The system currently achieves an approximate positional accuracy of 60 % relative to the intended target, which is sufficient for basic probing tasks but leaves room for further optimization in high precision applications.

D. PCB Design

The system "Appendix 1" utilizes eight DRV8825 stepper motor drivers, corresponding to eight NEMA 17 motors. Each DRV8825 driver supports up to 1/32 micro stepping, enabling high precision movement by dividing a full step into 32 micro steps. For example, with a typical 1.8° stepper motor (200 steps per revolution) 1/32 micro stepping results in 6400.

Micro steps per revolution, significantly enhancing positioning accuracy and smoothness. A PIC16F877A microcontroller is responsible for generating pulse signals to the STEP pins of each driver, with each pulse having an ON duration of approximately 0.2ms. Meanwhile, an STM32 "Blue Pill" microcontroller is used for communication with the host laptop via serial to UART interface. The STM32 receives commands from the laptop and controls the ENABLE and DIR (direction) pins of the DRV8825 drivers, determining motor activation and rotation direction. In terms of protection, the DRV8825 drivers include built in overvoltage and overcurrent protection. The STM32 microcontroller is safeguarded using Zener diodes for voltage clamping. The entire control system is powered by a 24V DC power supply. A 7805-voltage regulator is used to step down the voltage to 5V for logic level components, and capacitors are included for power line filtering and signal smoothing.

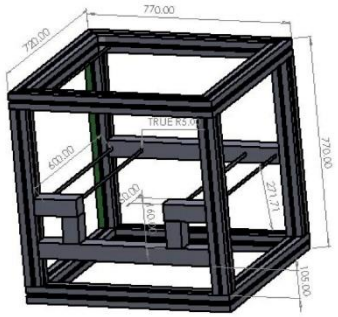

Figure 3: Structure of the machine: Designed using SolidWorks

E. Software Interface

The software for the system is developed using Python with the PyQt5 framework and is currently at version 1.0.0. PyQt5 provides a robust and flexible interface for designing modern graphical user interfaces (GUIs). When the "New" button is pressed within the application "Figure 4", it dynamically loads the menu bar, allowing the user to access various functions such as test configurations, data logging, and hardware controls. This interface is designed to be user friendly, ensuring that even users with limited technical experience can operate the system efficiently.

1. PCB Test: During the testing phase, the system provides real-time camera feedback while enabling the configuration of visual inspection parameters

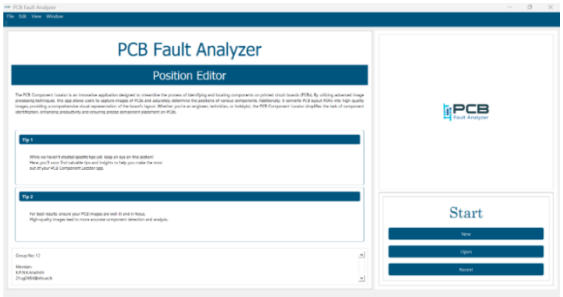

Figure 4: Loading Screen, the internal Interface of the software and the Menu Bar

through the user interface. The inspection process is performed using a YOLOv5-based deep learning model which precisely identifies various PCB defects such as spurs, spurious copper, mouse bites, missing holes, and short circuits. Upon completion of the inspection, the annotated output image is automatically saved to a predefined directory for further analysis, reporting, and documentation.

2. PCBA Test: In this testing phase, users can also upload a PCB image and manually mark specific test points where voltage, current, and continuity measurements are required. For each marked location, the system captures a 400 × 400-pixel image, which is utilized for template matching during the alignment process.

   Once the inspection sequence is initiated, the automated probe system precisely navigates to each designated test point and performs the required physical measurements with high positional accuracy.

F. Yolo Model

Unlike traditional models such as Faster R-CNN or SSD, YOLOv5 provides Figure 5 real-time object detection with high precision, making it ideal for industrial applications like PCB defect inspection where quick and reliable results are critical. Its lightweight architecture allows efficient deployment even on mid-range GPUs or embedded systems and balances detection speed, accuracy, and computational efficiency.

The YOLOv5 model used in this work was trained in a Jupyter Notebook environment using a 1.7 GB custom dataset obtained from Kaggle.com. The dataset was split into 80 % training and 20 % validation to ensure generalization, as indicated in references [5], [6]. Training was performed over 20 epochs with a batch size of 16, optimizing for both accuracy and efficiency. The model learned to detect surface-level PCB defects such as spurious copper, missing drill holes, mouse bites, short circuits, and irregular edges.

G. Algorithm Description

The algorithm powering the PCB Fault Analyzer “Figure 9” is structured to handle multiple inspection modes including PCB testing, PCBA testing, and assembly validation. The workflow begins when PCB enters the system. If PCB testing is selected, the system captures an image and processes it through a YOLOv5 model, which detects potential faults in a single Figure 5. Comparison of frames processed per second (FPS) implementing the Faster R-CNN, R-FCN, SSD and YOLO models. which detects potential faults in a single.

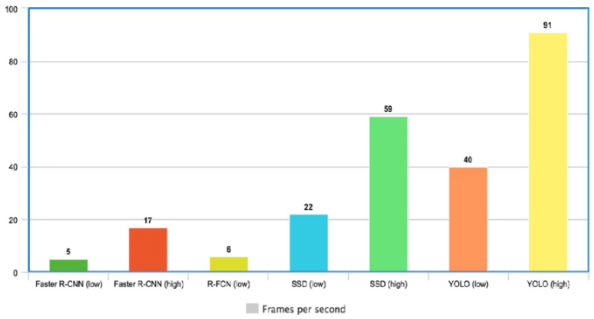

Figure 5: Comparison of frames processed per second (FPS) implementing the Faster R-CNN, R-FCN, SSD and YOLO models. Adapted from [7]

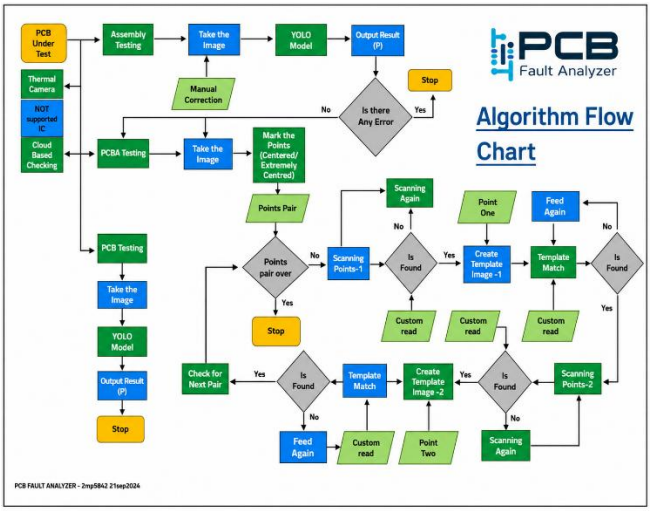

Figure 6: Algorithm Flow Chart

The result is output as a .jpg image, and any errors are flagged for review. For PCBA testing, the user marks inspection points for voltage, resistance, and continuity. The system then pairs the marked points and captures two template images (Point One and Point Two) using the camera feed. These templates are used for matching templates, ensuring accurate positioning of the probes. If the template match fails, the camera repositions and scans again. Once the points are verified, the probes move to the corresponding locations for electrical testing. All data from inspection is stored and compared, and the system checks for the next available PCB. This entire process is managed by a combination of manual control and automated image-based feedback, enabling high accuracy and efficiency in fault detection and analysis.

H. Template Matching Model

The template matching algorithm implemented in this project enables precise and dynamic alignment of the camera view with predefined features on a PCB, facilitating accurate probe positioning. This system operates in real time and is developed using OpenCV for image processing and PyQt5 for GUI integration, with motion commands transmitted via serial communication to a microcontroller. The process begins by capturing a continuous video stream from a high-definition camera (1920×1080).

A vertical strip centered on the frame is extracted to focus alignment along the horizontal axis. Both the live image and the reference template are converted to grayscale, and 1D intensity profiles are generated by averaging pixel intensities column-wise using OpenCV's cv2.reduce() function. These profiles are then compared using OpenCV's cv2.matchTemplate() function with the TM CCOEFF NORMED method, producing a similarity score between 0 and 1. If the score falls below a defined threshold (typically 0.90), movement commands are sent to reposition the camera.

The algorithm monitors these scores, detects peak and decay patterns, and finalizes alignment once the score stabilizes at its optimal value. Throughout the process, the GUI provides visual feedback with a red cross marker for intuitive monitoring. This adaptive, score-based approach ensures robust and accurate alignment without relying on hardcoded parameters, making it highly effective for dynamic PCB inspection scenarios.

RESULTS AND DISCUSSION

A. Performance of the YOLO V5 model

The performance evaluation of the YOLOv5 model is illustrated through the Precision Confidence and Recall Confidence curves Figure 10, which provides a detailed assessment of the model's classification effectiveness across various confidence thresholds. Each curve represents the model's behavior in detecting different types of PCB faults, including missing hole, mouse bite, open circuit, short, spur, and spurious copper. The Precision Confidence curve demonstrates how reliably the model predicts true positives as confidence increases.

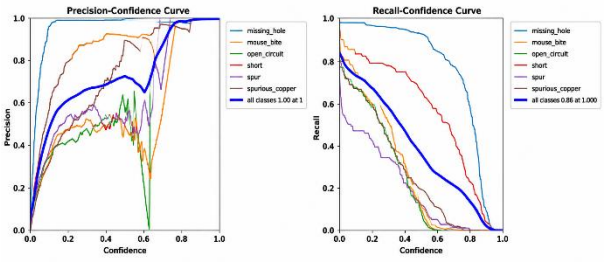

Figure 7: Precision–Confidence and Recall–Confidence Curves 1

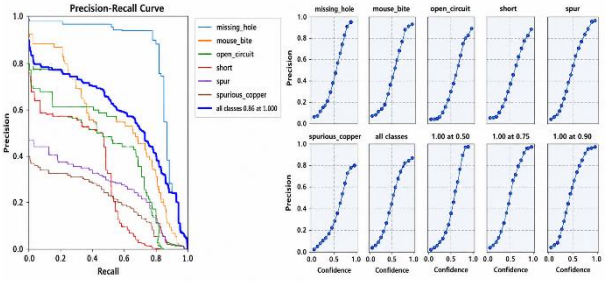

Figure 8: Precision–Recall Curve 1

Confusion Matrix

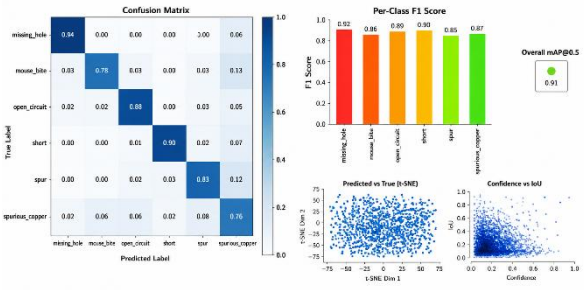

Figure 9: Performance Metrics of the YOLOv5 Model for PCB Fault Detection.

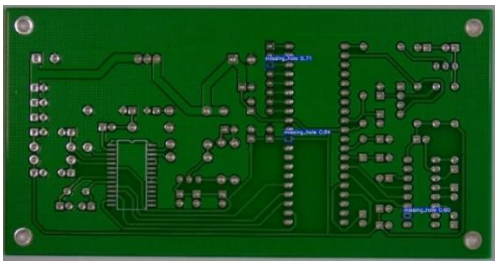

Figure 10: Detected Defects in PCB Using YOLOv5

Notably, the missing hole class achieves consistently high precision across all thresholds, nearing a value of 1.0, indicating excellent defect detection capability with minimal false positives. While other classes like spur and mouse bite show some variability in mid-confidence ranges (0.4 – 0.6), the overall average precision reaches 1.0 at higher thresholds, underscoring the model's robustness when confident.

On the other hand, the Recall Confidence curve reflects the model's sensitivity in identifying all relevant fault instances. As expected, recall is high at low confidence thresholds, capturing most defects but with a potential trade-off in precision. As the threshold tightens, recall gradually decreases, with classes like open circuit and spurious copper experiencing steeper drops. Nevertheless, the missing hole class again stands out with strong recall across all levels, affirming its consistent detectability.

The average recall across all classes begins around 0.84 at the lowest threshold, showcasing balanced performance. Collectively, these results affirm that YOLOv5 provides reliable and efficient defect detection, especially when tuned to higher confidence levels for precision-critical applications in PCB inspection.

B. PCBA Test Result

The output of the defect detection model is illustrated in Figure 11, where the YOLOv5 algorithm successfully identifies multiple instances of the missing hole fault on the PCB. The detected defects are highlighted with bounding boxes and confidence scores. For instance, defects with confidence levels of 0.71, 0.64, and 0.60 are labeled accordingly. Although the model demonstrates the ability to localize and classify missing holes effectively, the relatively moderate confidence scores in some detections suggest that the system's precision could benefit from further refinement.

These results indicate that while the trained model is functional, additional improvements such as increasing dataset diversity, tuning hyperparameters, or incorporating data augmentation may enhance its overall detection accuracy and robustness across different PCB layouts.

Figure 11: Template Matching Score vs variations in template width

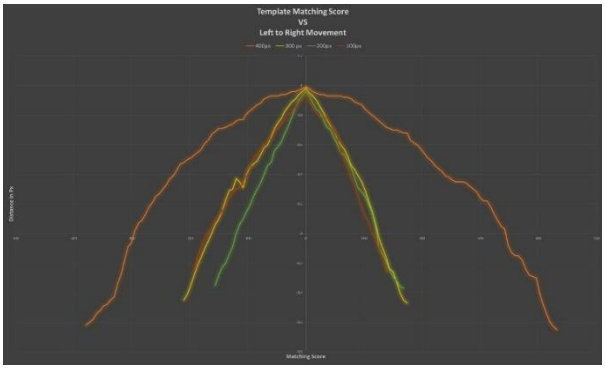

Figure 12: Template Matching Score vs variations in template width

C. PCBA Test Results

In the PCBA testing phase, the template matching algorithm's effectiveness was evaluated by analyzing how the matching score behaves as the camera moves across the target position.

As shown in Figure 12, the template matching score increases progressively as the camera approaches the correct alignment point. Once the camera passes the target, the score begins to decline, albeit slightly indicating a peak score at optimal alignment. This behavior confirms the algorithm's ability to detect alignment through score trends rather than fixed positions. Additionally, a secondary experiment was conducted to assess the algorithm's robustness against variations in template width as indicated in Figure 13.

Starting with a 400-pixel wide template, the width was reduced incrementally by 50 pixels on each side. The results demonstrated that while minor changes in template width slightly influenced the matching score, the overall prediction accuracy remained stable, reinforcing the algorithm's tolerance to template size variation.

This analysis validates the dynamic responsiveness of the system, showing that both motion-based score tracking and adaptive template sizing contribute to reliable visual alignment in real-time PCB testing.

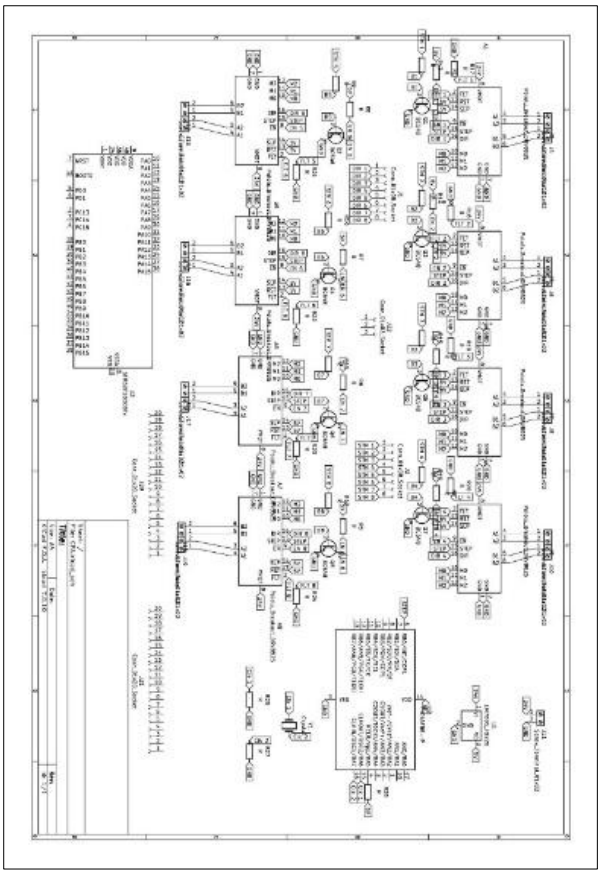

Figure 13: Detailed Schematic of the PCB Fault Analyzer Control Circuit (27 cm × 13 cm)

LIMITATIONS AND FUTURE WORK

While the proposed PCB and PCBA defect detection system show promising results, there are several limitations that need to be addressed in future iterations. One key limitation is the quality and consistency of image data. The current implementation uses a webcam for image capture, which restricts resolution and frame rate, potentially missing fine-grained defects. Upgrading to a high-speed industrial camera or a DSLR would significantly enhance detection accuracy.

Another limitation is the physical construction of the machine, which was manually built. This limits both the precision of movement and long-term durability. A laser-cut chassis with more accurate mechanical alignment could improve the reliability and speed of inspection. The dataset size is also a constraint.

The current training set is approximately 1.7 GB, which restricts the model's ability to generalize to more complex or varied PCBs. Increasing the dataset size to at least 10 GB with diverse defect examples will improve the deep learning model's accuracy and robustness.

Moreover, the current system supports PCB sizes ranging from a minimum of 12 cm to a maximum of 25 cm in length, and from 7 cm to 12 cm in width. This size limitation restricts the machine from inspecting smaller or larger boards used in certain commercial or industrial applications. Extending the mechanical platform and adjusting the vision system accordingly will be essential for handling a broader range of PCB sizes.

In terms of software, while template matching with OpenCV is cost-effective and simple, it has limitations when dealing with rotated or non-uniform PCBs. Future work may integrate feature-based matching or transformer-based object detection models for better flexibility. Additionally, the system currently focuses on visual and structural defects.

Future versions will incorporate thermal imaging to identify overheating components and perform circuit-level analysis to detect electrical failures. Expanding the system's capabilities to test smartphone PCBs, power supply boards, and multi-layered PCBs is also planned.
Overall, while the prototype effectively detects common PCB defects using affordable tools, significant improvements in hardware, dataset size, and algorithmic sophistication will be necessary to meet industrial standards.

CONCLUSION

In conclusion, the developed machine demonstrates promising results in identifying both PCB and PCBA defects, including issues such as spurs, spurious copper, mouse bites, short circuits, and open circuits, as well as performing basic component-level testing. The system effectively leverages template matching techniques using OpenCV in place of more expensive solutions like G-code-controlled systems, significantly reducing cost and simplifying the design.

Although a standard webcam was used for imaging, the overall performance is acceptable; however, integrating a high-frame-rate industrial camera or a DSLR would likely enhance detection precision. Similarly, while the machine was manually constructed, future iterations using laser-cut components could greatly improve speed, stability, and overall performance.

The YOLOv5 model trained on a 1.7 GB dataset performed reasonably well, but expanding the dataset to at least 10 GB would further improve detection accuracy and robustness. Looking ahead, the system could be

extended to support more advanced tests, such as thermal imaging and circuit-level diagnostics. Additionally, upgrading the mechanical platform and incorporating highspeed vision systems would make the machine suitable for testing more complex devices like smartphone PCBs and power supply boards.

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REVIEW ARTICLE

Mini Review on Processed Meat Consumption and the Heart: Risks, Realities and Recommendations

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Abstract: One of the main global health concerns, the burden of cardiovascular illnesses is rising because of aging populations. Strong epidemiological evidence suggests that eating processed meat significantly raises the risk of cardiovascular disease. In contrast, unprocessed red meat has weaker associations with cardiovascular outcomes. This review examines the relationship between consuming processed meat and the risk of cardiovascular disease by examining recent meta-analyses, observational studies, and randomized controlled trials. The increased risk is caused by nitrates, nitrites, polycyclic aromatic hydrocarbons, and high sodium content (four times higher than that of unprocessed meat). These compounds cause systemic inflammation, endothelial dysfunction, hypertension, and the formation of atherosclerotic plaque by interacting with trimethylamine-N-oxide (TMAO) mechanisms. Vulnerable populations, including those with genetic predispositions, diabetes, and the elderly, have higher risk profiles. Substituting processed meat with plant-based proteins, nuts or low-fat dairy products can lower cardiovascular risk by as much as 17%. Current evidence supports recommendations to limit processed meat consumption to 30 –70 g per week while emphasizing the substitution of healthier protein sources for processed meats to reduce the burden of cardiovascular disease.

Keywords: Processed Meat Consumption, Coronary Heart Disease, Cardiovascular Disease, Dietary Guidelines

INTRODUCTION

Dietary meat is a fundamental component of the eating patterns of many populations [1]. In the 1960s, plant-based proteins, particularly those derived from wheat, were the predominant source of dietary protein in many parts of the world. Today, animal-based food accounts for at least 58% of food consumption in many populations.

Meat is the skeletal muscle and associated tissues derived from mammalian, avian, reptilian, amphibian and aquatic species harvested for human consumption [1]. Meat can be categorized into several groups like red, white, process, unprocessed etc. Meat and meat products are rich sources of essential nutrients, including high-quality protein, iron, and vitamins. As part of a balanced diet, meat provides essential micronutrients and amino acids that contribute to the maintenance of overall health**.**

The global increase in meat production across different regions and meat types are shown in Figures 1 and 2. Specifically, the production of chicken, pork, and beef has risen significantly over the past 40 to 50 years. In many developed countries, meat has become the dominant source of dietary protein. For instance, individuals in the European Union consume approximately 28 g of meat-derived protein per capita per day, accounting for around 30% of the total energy intake from animal-derived foods [2]. However, approximately 5% of the world's population identifies as vegetarian.

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In contrast, a much larger proportion of the population (14–60%) reduces meat consumption without eliminating it entirely from their diets; these individuals are commonly referred to as flexitarians [3].

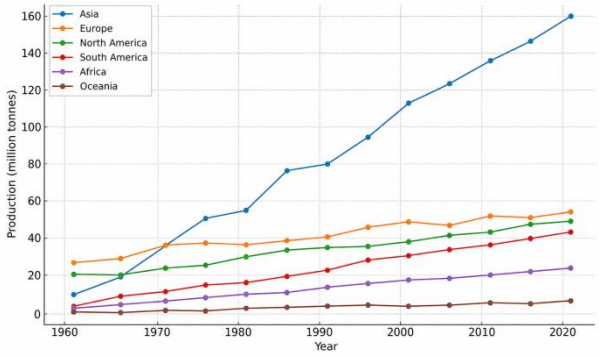

Figure 1: Global meat production during the period of 1961-2023

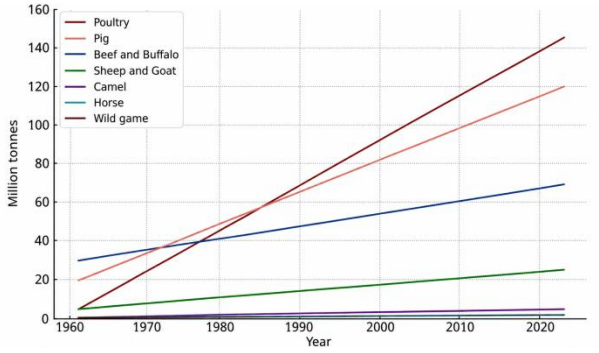

Figure 2: Meat production by livestock type during the period of 1961- 2023

A healthy diet has the potential of reducing the risk of chronic diseases and eating well is of essence especially in critical periods of life such as when one is pregnant, in menopause and in old age [4]. However, the growing consumption of processed meat, including sausages, bacon and canned meat products, has emerged as a significant public health concern due to its established association with cardiovascular disease (CVD) risk. These products, characterized by high levels of sodium, saturated fats and preservatives like nitrates, have been mechanistically linked to endothelial dysfunction, systemic inflammation and oxidative stress.

The main objective of this mini review is to examine the cardiovascular risks associated with processed meat consumption, examine the driving biological mechanisms, and offer certain dietary recommendations to promote heart health.

MECHANISMS AND EVIDENCE LINKING PROCESSED MEAT CONSUMPTION TO HEART DISEASES

There are different categories of meat, such as red meat and white meat. Red meat refers to the muscle tissue derived from mammals, including species such as beef, veal, pork, lamb, and goat, as well as meat obtained from nonbird game animals such as venison, bison, and elk [4] [1]. It can be available in fresh, ground or frozen forms. White meat refers to meat which appears to have a paler color before and after cooking. It also has a lesser amount of myoglobin compared to red meat. Poultry (especially breast muscle) and some aquatic species are known to produce most white meat (e.g. Chicken, turkey and fish and included poultry cold cuts, chicken mixtures, canned tuna, as well as low fat sausages and low-fat hot dogs made from poultry) [5].

Unprocessed meat is the cuts of meat are muscle only, those that have undergone merely cutting, grinding or otherwise standard processes and do not contain any preservatives or other curing agents (e.g. beef fresh cuts, pork chops, lamb chops, chicken breast, fresh fish fillets) [6]. The association between risk of cardiovascular disease and unprocessed red meat is not so robust. Some studies have pointed out the negative effect of unprocessed red meat on cardiovascular health compared with high-quality plant protein sources. A meta-analysis of randomized controlled trials concluded that consuming ≥ 0.5 servings of unprocessed red meat per day does not significantly affect blood lipids, lipoproteins or blood pressure [7]. Moreover, Mendelian randomization studies have not established a causal link between unprocessed red meat consumption and cardiovascular disease risk. Furthermore, some studies have suggested that unprocessed red meat may have a positive impact on cardiovascular health. Because of this disparity of outcomes, several studies have questioned the advisability of limiting unprocessed red meat consumption for cardiometabolic health.

However, scientific evidence supports that the consumption of processed meat is linked to an increased risk of mortality from cardiovascular diseases. Processed meat production undergoes some technical processes such as freezing, salting, smoking, heating, marination or using chemicals to preserve the meat (e.g. Ham, bacon, hamburgers, salami, etc.). Processing involves the addition of extra meat and fat and a lot of ingredients and additives that are not meat-related hence, the result

is unobvious [5]. The potential risk associated with processed meat products may be attributed to the high levels of salt, polycyclic aromatic hydrocarbons, nitrates and nitrites found in processed meat [8]. Industrially processed meat contains preservatives including salts, possibly exerting negative effects on health. During maturation some processed meat products develop a specific microbiota, forming probiotic metabolites with physiological and biological effects yet unidentified, while the concentration of nutrients also increases. Recent meta-analysis of both observational and randomized controlled trials does not support any effect of saturated fat on cardiovascular disease or diabetes. The high contribution of saturated fatty acid (SFA) has been in the spotlight in recent years, as several large observational studies found positive associations between a high intake of red and processed meat and the risk of cardiovascular diseases, cancer and all-cause mortality, as well as type-2 diabetes [9]. Comparatively, studies have shown a weak association between unprocessed red meat consumption and colorectal cancer, breast cancer, type-2 diabetes, and ischemic heart disease. Moreover, there is limited to no evidence of an association between unprocessed red meat and either ischemic or hemorrhagic stroke [10]. While some evidence suggests that eating unprocessed red meat is associated with an increased risk of disease incidence and mortality, it remains weak and insufficient to formulate stronger or more conclusive recommendations [11]. Epidemiological evidence confirms that regular consumption significantly elevates risks for coronary artery disease, stroke and hypertension, even at moderate intake levels [12].

Meta-analysis indicated an increased exposure to coronary heart disease (CHD) due to an increase of 42% with the consumption of processed meat. An example of this includes eating 50 g of processed meat daily and the enhanced risk of CHD of 42 %. Raw red meat in turn did not elevate the risk of CHD. The processed and unprocessed red meat possess approximately equal contents of cholesterol and saturated fats. However, the amount of sodium in processed meats is 4 times higher with approximately 50% more natural nitrate preservatives. The study indicates that the nutrients, as opposed to fat content, could be an explanation why the risk is increased. Sodium in the diet may increase blood pressure, and nitrates may increase atherosclerosis and vascular issues. The risk of CHD across processed meat was 1.42 (95% CI=1.07-1.89) per 50 g portion of processed meat per day. The result remained the same when the only studies included in the review were cohort studies and indicated a 44 % increased risk of CHD per serving consumed. A similar result was yielded by limiting the study to the findings in the U.S with RR of 1.40 (95 % CI 1.03-1.91) [10].

The journal of Nature Medicine has posed the question as to whether consumption of unprocessed red meat is associated with some health conditions. The objective sought to focus on two primary cardiac health indicators; heart disease and stroke (IHD and both ischemic and hemorrhagic). These are the findings on every outcome. The heart disease in the study, there was limited evidence that unprocessed red meat intake increases the risks of IHD. At the dosage of 50 g (50 g d -1), the Relative Risk (RR) was 1.09 and the RR increased to the level of 1.12 at 100 g (100 g d -1). Ischemic stroke in the study, evidence supporting the fact that consumption of unprocessed red meat increases ischemic stroke risks emerging. It received a grade or rating of one star and Risk of Selection or ROS of -0.02. The mean RR was 1.15 at 100 g d-1. Hemorrhagic stroke was also no evidence that intake of unprocessed red meat increases the risk of hemorrhagic stroke. It was ranked as a one star and a ROS as -0.13. The average RR was 0.87, and the Burden of Proof Risk Function (BPRF) value was 1.14 at averaged exposure when the daily intake was 100 g d -1 [13].

Global studies reveal processed meats account for nearly 20% of total meat consumption, with particularly high intake observed in Western nations and rapidly urbanizing regions [13]. Research demonstrated a consistent 12-18% increase in CVD mortality risk per 50 g daily serving [14]. Owing to that, the nutritional transition in South Asia shows traditional plant-based diets being progressively displaced by processed meat products, especially among urban populations and younger demographics [15]. Recent studies indicate processed meat consumption has doubled in urban centers over the past decade, paralleling rising CVD prevalence [16].

Traditional meat processing methods including drying, curing, fermentation, and smoking historically served essential roles in food preservation and flavor enhancement; however, they present significant cardiovascular health implications that require careful examination in contemporary dietary contexts. The high sodium content inherent in curing processes, particularly salt and brine curing methods that utilize sodium nitrate and sodium nitrite, may contribute to hypertension and increased cardiovascular disease risk. Similarly,

smoking techniques, especially hot smoking can generate polycyclic aromatic hydrocarbons (PAHs) and other potentially harmful compounds that may have adverse effects on heart health [17], [18]. However, emerging trends toward natural alternatives such as celery extract instead of synthetic nitrites reduced sodium formulations and controlled fermentation processes using beneficial probiotics suggest opportunities for developing heart-healthier processed meat products [18]. The integration of novel preservation technologies such as high-pressure processing, ultrasound, and cold plasma combined with traditional methods like fat-based preservation, may offer pathways to maintain the cultural and culinary benefits of processed meats while minimizing cardiovascular health risks. Future research should focus on optimizing these processing methods to reduce sodium content, eliminate harmful compounds and potentially incorporate functional ingredients that may provide cardiovascular protective effects thereby bridging the gap between traditional food preservation practices and contemporary health-conscious consumption patterns [17], [19].

Processed meat continues to be consumed for several interconnected reasons. It remains a valuable source of high-quality protein, supplying all essential amino acids with high digestibility and is also rich in critical micronutrients such as iron, zinc, selenium and vitamin B12. Organ meats like liver provide additional benefits, including vitamin A and folic acid. Although fat content varies among products, like fatty bacon, contain up to 90 g/100 g of total fat. Beyond nutrition, factors such as cost, accessibility, convenience and sensory appeal including taste and satisfaction also influence consumption. While some individuals reduce processed meat intake for health (38.2%) or non-health reasons (38.5%) like environmental concerns (22.0%) and animal welfare (20.4%), a smaller portion (4.6%) cite cost. Cultural and social influences, including family practices, personal beliefs about health and sustainability, and enjoyment of eating, further shape dietary habits. Interviews have highlighted that decisions around meat consumption are not solely based on health but also influenced by complex personal and societal factors, as well as uncertainty surrounding the evidence [20], [21].

Several large population-based studies have shown a strong link between processed meat consumption and an increased risk of coronary heart disease (CHD) and heart failure (HF). For CHD, the risk rose by 15% with each additional daily serving of processed red meat. Even total red meat and unprocessed red meat were associated with a 12% and 11% increase in CHD risk per serving, respectively these associations remained statistically significant even after adjusting for various risk factors. The risk was slightly higher in cases of fatal CHD. Notably, substituting processed meat with healthier protein sources such as legumes, nuts, soy, whole grains, dairy products or even eggs was linked to a significant reduction in CHD risk, with a 17% decrease observed when plant-based proteins replaced one daily serving of processed red meat. In the case of heart failure, the high intake of processed meat, especially 75 g or more per day was significantly associated with increased risk [22]. Men consuming more than 75 g/day had a 1.28 times higher incidence and a 2.43 times higher mortality rate from HF compared to those consuming less than 25 g/day. Each 50 g increase in daily processed meat intake was linked to an 8% higher incidence and a 38% higher mortality risk from HF. Potential mechanisms behind these effects include elevated sodium intake and various food additives commonly found in processed meats. These can increase blood pressure and may disrupt cardiovascular function. Nitrites used in meat preservation, though considered cardioprotective in small amounts, have also been associated with endothelial dysfunction at high concentrations. Phosphate-containing additives may lead to phosphate imbalance and contribute to heart failure, while polycyclic aromatic hydrocarbons (PAHs) found in smoked or grilled meats may further raise cardiovascular disease risk. These findings, consistent with previous research, support recommendations to reduce processed red meat consumption due to its contribution to both cardiovascular diseases and cancer [23].

Low-density lipoprotein (LDL) and high-density lipoprotein (HDL) cholesterol levels are critical determinants of cardiovascular health, with elevated LDL and reduced HDL contributing to inflammation, insulin resistance and increased risk of atherosclerotic cardiovascular disease (CVD). Recent studies highlight that the relationship between HDL-C and heart health may not be linear, as both low and very high HDL-C levels (≥80–90 mg/dL) are associated with increased all-cause mortality and CVD risk, suggesting a U-shaped association. Processed meat consumption has been shown to influence these lipid parameters depending on type and frequency. For instance, frequent consumption of frankfurters was significantly associated with elevated LDL-C (2.86 mmol/L) and reduced HDL-C (1.05 mmol/L), while other products like ham and pate

showed no significant changes [24]. These findings indicate that certain processed meats may adversely impact lipid profiles, thereby increasing cardiovascular risk through modulation of LDL and HDL levels.

DOSE-RESPONSE RELATIONSHIP OF PROCESSED MEAT AND CARDIOVASCULAR DISEASES (CVD)

Cardiovascular disease (CVD) is a major global health challenge, contributing significantly to mortality and morbidity. One factor that has received considerable attention is diet, specifically the consumption of red and processed meats. The high content of saturated fats, cholesterol, and heme iron in red meats, such as beef, pork, and mutton, has been hypothesized to contribute to cardiovascular risk. Similarly, processed meats containing preservatives, sodium, and nitrates have been associated with increased CVD risk [24].

Lifestyle modification, especially dietary modification, is a widely accepted cornerstone method for the prevention of CVD and is the first-line strategy for the prevention of Type 2 Diabetes Mellitus (T2DM) and CVD. Excessive intake of saturated fatty acids can significantly increase the concentration of plasma LDL cholesterol, thereby increasing the risk of CVD and coronary heart disease. Reducing the intake of saturated fatty acids can reduce CVD event [25].

Our substitution modeling analyses indicated that replacing red meat with other food sources of protein, such as nuts and skimmed milk, was associated with a lower risk of CVD. Potential mechanisms of detrimental effects of high red meat consumption on cardiovascular health included the high content of saturated fat and heme iron in red meat as well as added sodium in processed red meat, all those factors act on multiple pathways, including hypertension, dyslipidemia and systematic inflammation to an increased CVD risk. In addition, depending on the preparation method of red meat, individuals with a high red meat intake usually had a high intake of nitrite, polycyclic aromatic hydrocarbons and heterocyclic amines that were produced during the cooking process of red meat. These chemicals may increase the risk of diabetes and CVD through pathways of oxidative stress and systemic inflammation. In the liver, TMA is then converted into trimethylamine-N-oxide, which can promote thrombus generation, leading to vulnerable atherosclerotic plaques and eventually, a higher risk of CVD. Red meat consumption is associated with an increased risk of CVD. Our findings support lowering red meat intake and replacing red meat with plant-based protein sources or low-fat dairy foods as a key dietary recommendation for the prevention of CVD [26].

VULNERABLE GROUPS AND RISK FACTORS

A. Diabetes / Metabolic Vulnerability

The susceptibility to diseases such as type-2 diabetes is called metabolic vulnerability. In a mega meta-analysis on all the available studies on about 2 million adults, increased meat, specifically processed and unprocessed red meat intake was associated with the increased prevalence of type-2 diabetes in most of the populations. The research contributes to advising reducing such meat consumption to reduce the likelihood of the condition. Even though some reviews have come up with alternative conclusions concerning the extent to which the evidence is definite, the current analysis presented a positive correlation between the intake of meat and propensity of developing type-2 diabetes [27].

The research there is an evident connection between the consumption of processed red meat with issues that increase the probability of heart diseases. In individuals having diabetes, the analysis finds that consuming processed red meat increases the risk of having uncontrolled blood sugar levels, which are represented using glycated hemoglobin A1c (HbA1c). Individuals with T2DM who consumed processed red meat had an HbA1c value that was 1.76 times more than those who never did. This risk was furthermore intense between two categories of people, namely individuals who did not consume alcohol and individuals who did not use diabetes medicine. The risks were 2.09 and 3.20 times increased in those two groups respectively. A small amount of processed red meat increases the risks of blood sugar, blood pressure and cholesterol levels in individuals with type 2 diabetes. Reducing intakes of processed red meat could reduce heart diseases in individuals that have the same problem [25].

B. Age / Existing Cardiovascular Vulnerability

Consumption of processed meat increases the risk of premature deaths as well as cardiovascular disease deaths among frail elderly people. Consuming greater amounts of processed meat increases the risk of developing cardiovascular mortality. The risks per 25 g/day increment are 1.20 (95% CI 1.02-1.42) with the hazard ratio. Consumption of unprocessed poultry daily

and moderate consumption of unprocessed red hovered down the risk of mortality due to all causes, cancer and cardiovascular deaths [28].

C. Genetic Susceptibility

There was an association between the consumption of meat and death only in older Chinese adults who did not have the APOE-epsilon4 gene. The non-carriers of APOE-e4 and who consumed a lot of meat were at a higher mortality risk. In APOE-e4 carriers, a high consumption of meat did not have a distinct association with death. Only men showed this pattern. Egg consumption was not associated with any mortality in the APOE-e4 carriers or non-carriers [29].

D. Causality, Mechanisms and Broader Context

The authors used a Mendelian randomization perspective in which researchers studied how red and processed meats could increase the risk of four cardiovascular issues: coronary artery disease, atrial fibrillation, heart failure or stroke. Observational studies tend to be inconclusive and demonstrate that the consumption of red or processed meat increases risk. These findings might be conflated with other variables and catalogues might not find a one-to-one correlation between before and after the research. Indeed, genetic variations were used as instrumental variables by the researchers. This method reduces the impacts of other confounding effects that tend to restrict observational studies. They accessed data from the UK Biobank and Finn Gen to conduct their research [24].

PUBLIC HEALTH AND DIETARY GUIDELINES

Processed red meat may play a part in risk factors such blood pressure, obesity and lipid profile, which could explain the positive correlations between red meat and CVD and its subtypes. Furthermore, a high intake of red meat may also be linked to hypertension. Carnitine has also recently been linked to an increased risk of CVD. Carnitine and trimethylamine-N-oxide (TMAO) are elevated in red meat, which may be the cause of the link between red meat consumption and CVD [30]. Due to the addition of flavorings and preservation agents like salt and nitrite, processed red meat may have different health effects than unprocessed red meat. In order to provide evidence regarding alternative protein sources that constitute a healthy dietary pattern in accordance with current dietary guidelines, the reduced risk of incident CVD is by substituting other major protein sources, such as fish, poultry, eggs, dairy products, nuts, legumes and combined plant protein sources (nuts, soy foods and other legumes) for red meat in the diet [26]. Processed meats, including preserved options like bacon, sausage, hot dogs, pepperoni, salami and low-fat deli meats (like chicken, turkey, ham and beef) should only be eaten once a week (about 50 g or 1.75 ounces) due to their high sodium and nitrate content according to Mozaffarian et al [31]. Further, Table 1 depicts Food-Based Dietary Guidelines recommendations for meat for Belgium, Bulgaria, Germany, Estonia and United Kingdom.

The American Heart Association (AHA) states that it's critical to adhere to a heart-healthy eating pattern that can be sustained despite a range of personal and cultural preferences. Two evidence-based diets, the Mediterranean diet and the DASH (Dietary Approaches to Stop Hypertension) diet, reduce processed and red meats, add sugars, sodium and saturated fats while emphasizing fruits, vegetables, whole grains, legumes, nuts and healthy fats like olive oil. These dietary practices have been shown time and time again to improve long-term health overall, lower the risk of cardiovascular disease and maintain normal blood pressure and cholesterol levels [33].

CONCLUSION

This mini review highlights that a high intake of processed meat is strongly linked with an increased risk of heart disease. The findings show that excessive amounts of sodium, saturated fat and chemical preservatives found in processed meat contribute to conditions such as high blood pressure, cholesterol imbalance and other cardiovascular problems. Evidence from global studies confirms that populations with higher processed meat consumption face a greater risk of heart disease compared to those with lower intake. At the same time, the review also points out that adopting balanced diets rich in fruits, vegetables and plant-based protein can help lower this risk and improve overall heart health. From a public health perspective, the growing consumption of processed meat across many countries increases the burden of heart disease and calls for urgent action. Creating awareness, improving consumer education and encouraging healthier food choices are key steps to address this issue. In addition, reducing processed meat intake, promoting safer processing methods and supporting healthier alternatives can make a positive difference.

Future research is essential to develop safer food processing practices and to further study the long-term effects of processed meat on heart health. Overall, this review shows that small but consistent changes in daily diet, along with promoting healthy eating habits can play a powerful role in preventing heart disease in the future.

RECOMMENDATIONS

Studies have revealed that consuming processed meat is linked to increase risk of having heart diseases. These foods may increase blood pressure, worsen cholesterol and injure blood vessels because of the salt, saturated fat and chemical additives these foods contain, (e.g. nitrates). All these are associated with heart attacks and strokes. The evidence here indicates that consumption of processed meat commonly has adverse effects in the heart; therefore, must limit the amount that we consume. This concept has international guidelines to support it. Both WHO and American Heart Association advise reducing the consumption of processed meat as a diet that promotes the health of cardiovascular system.

Similar advice can be equally applied in other places, such as Sri Lanka where traditional diets are predominantly plant based and current trends in changing food preferences and the urban lifestyle are resulting into an increase in the consumption of processed and fast foods. Such a trend might introduce severe long-term impacts on the rate of heart diseases.

Table 1: Food-Based Dietary Guidelines recommendations for meat for Belgium, Bulgaria, Germany, Estonia and United Kingdom [32]

Country	Quantitative recommendations	Qualitative recommendations	Portion size
Belgium	Limit the consumption of processed meat to 30 g per week.	Limit the consumption of red meat, especially processed meat. Red meat can be replaced by e.g. legumes, fish, eggs or poultry.	
Bulgaria		Choose lean meat. Limit the consumption of sausages	1 portion corresponds to 100g
Germany	Eat meat (beef, pork and poultry) once or twice a week and sausage up to 2 portions per week. No more than 300 g of meat and sausage per week	Limit meat and sausage intake (less is more).	Meat:120 g Sausage:30 g
Estonia	Red meat max. 500 g/week (raw weight 700 g).	Processed meat products: as little as possible, prefer with higher meat content, less fat and/or salt.	Red meat products:30 g escalope, rotisserie, Frikandel, etc., 50 g ham, grilled sausage, canned meat, 20 g smoked sausage, salami, 25 g smoked bacon, 10 g fried bacon.
United Kingdom	If you eat more than 90 g of red or processed meat per day, try to cut down to no more than 70 g per day	Eat less red and processed meat.	

The health consequences for the population are very severe. Processed meat intake is already one of the most common causes of illnesses and health in most countries and reducing the per capita consumption of processed meat might mitigate the issue. Nevertheless, it is not simple to change. Processed meat is affordable, readily accessible and frequently involves the cultural food practices. It is for this reason that the changes should engage individuals and governments in the form of food labeling, campaigns and policies to enable people to access healthier food choices. Present studies are limited as well. The largest body of evidence is that of long-term population studies and cannot entirely discount other causes including the overall diet or way of life.

Very little clinical research to determine the direct long-term effects processed meat on heart disease exist. Moreover, the health outcomes of newer products are known to fewer people including low salt or nitrate free meat and plant substitute. Considering what we understand about it; one can suggest several steps. Human beings are urged to reduce their consumption of processed meat and substitute it with alternative dietary sources of protein which include fish, vegetables and legumes or clean breast meat. It would be reasonable that policymakers recommend clear dietary recommendations, organize education efforts and sponsor the food sector to mitigate the hazards of processed meat. Subsequently, it is to be investigated whether the beneficial health outcomes of a low intake of processed meats can be generalized and whether newer options should be investigated.

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