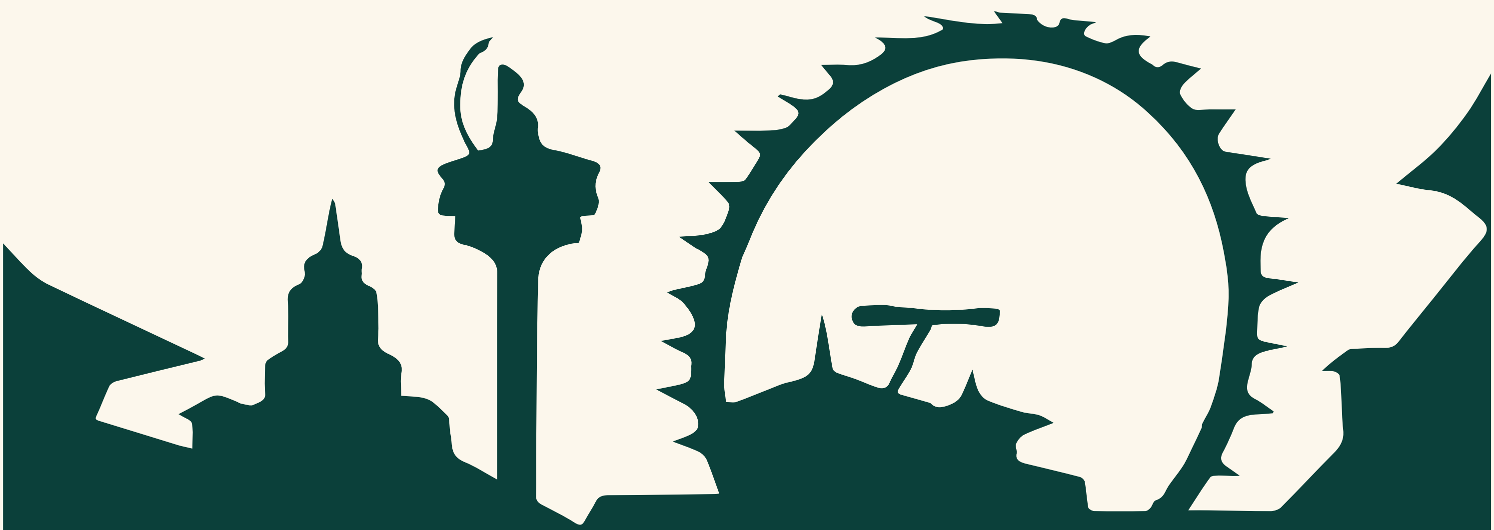
10th SONEUK Conference

on

Science, Engineering and Technology

Cambridge, United Kingdom 28th June 2025



Society of Nepalese Engineers in UK

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Contents

Editorial

Innovation in Science, Engineering, and Technology drives progress, shapes the future, and transforms lives across multiple disciplines. The relentless pursuit of breakthroughs not only accelerates technological advancement but also provides solutions to global challenges. Recognizing this imperative, the Society of Nepalese Engineers in the UK (SONEUK) is proud to present its *10th Annual Conference in Science, Engineering, and Technology to* take place on 28th June 2025 in Cambridge, United Kingdom. This conference features eight peer-reviewed papers, and two poster presentations, each offering unique perspectives on cutting-edge developments in science, engineering and technology. These contributions showcase the transformative power of innovation, addressing critical challenges and opportunities, both for Nepal and the global community.

The integration of Artificial Intelligence (AI) in healthcare systems holds promise for improving patient care and resource optimization, particularly in developing countries like Nepal and Ghana. However, challenges related to data privacy and trust hinder implementation. The paper titled *"Developing a Responsible AI Framework for Healthcare in Low Resource Countries: A Case Study of Nepal and Ghana"* identifies key obstacles and discusses existing AI frameworks from developed nations, proposing a draft Responsible AI Framework tailored for low and middle-income countries.

Natural Language Processing has evolved significantly over the past seventy-five years, with advancements influenced by task complexity, language diversity, and data availability. Machine Translation remains particularly challenging for low-resource languages, exemplified by the case of Nepalbhasa (Newari). Despite the success of platforms like Google Translate for widely spoken languages, Nepalbhasa's inclusion required extensive community collaboration and digitization efforts. This case study presented in the paper *"Challenges in Machine Translation of Nepalbhasa"* not only emphasizes the challenges faced by lesser-known languages but also offers insights into their preservation and technological integration.

This paper titled "*Design of Unmanned Aerial System for RF Source Localization*" presents an autonomous drone system (UAS) for RF source localization, using a MATLAB-based design tool to optimize components like motors and batteries. The system includes a LoRa-based transmitter (ESP8266) and receiver (Arduino with DHT11 sensor) to measure signal strength (RSSI). By applying a path loss model and trilateration, the drone estimates the transmitter's location with an 8.32° angular error and 25-meter accuracy. The study demonstrates a functional approach to autonomous target finding using UAS and RF signals.

The greater Kathmandu Valley requires a comprehensive urban development and integrated transport plan centered around a metro rail system. Current infrastructure projects, including the Kathmandu Metro, have stalled due to a lack of governmental vision regarding the project's potential to regenerate the valley and stimulate economic growth. The proposed framework in the paper *"Framework of Metro Rail Development in the Greater Kathmandu Valley, Nepal"* for metro rail development includes components such as mobility, integrated transport, urban regeneration, and cultural preservation, aiming to maximize the project's benefits for both the capital and the nation.

In Nepal, road tunnels play a crucial role in enhancing transportation infrastructure. The study in the paper *"Ventilation System in Road Tunnel of Nepal"* focuses on ventilation systems, particularly in the Nagdhunga Tunnel, analysing longitudinal and transverse strategies for maintaining air quality and safety. The findings suggest that hybrid ventilation designs tailored to high-altitude conditions are essential for effective operation. The study emphasizes the need for post-construction monitoring and the integration of global best practices to address the challenges faced in Nepal's mountainous terrain.

In the construction industry, the adoption of visualization tools is transforming project management by enhancing efficiency and decision-making. Technologies such as Building Information Modelling (BIM) and AI-powered dashboards facilitate real-time data visualization and collaboration. However, challenges such as interoperability issues and user adoption barriers impede full-scale implementation. The paper titled *"Application of Visualisation Tools in Project Management in Construction Industry: Innovation and Challenges"* reviews the evolution and benefits of these tools, presenting case studies that demonstrate their impact on project efficiency. It also discusses barriers to adoption and suggests future research directions.

Limestone Calcined Clay Cement (LC3) presents a sustainable alternative to traditional Portland cement, significantly reducing CO_2 emissions. Recent advancements in mechanochemical activation (MCA) enhance the performance of LC3 by improving the pozzolanic reactivity of clays, leading to better hydration kinetics and durability. The review in the paper titled *"Synergistic Effects of Mechanochemical Activation and Limestone on Hydration Mechanisms in LC3: A Review"* highlights the environmental benefits of MCA-LC3, particularly in regions with limited access to high-quality materials.

The development of a mass rapid transit system in Kathmandu Valley is essential to meet rising traffic demands. However, rail-soil interactions can generate vibrations that affect nearby structures and residents. This study in *"Kathmandu Metro-Induced Ground Vibrations and Attenuation"* employs numerical modelling to evaluate ground vibrations from a proposed metro train, revealing significant displacement impacts influenced by soil stiffness. Recommendations include soil improvement techniques and the use of lighter trains to mitigate vibrations.

These papers collectively present an in-depth examination of pioneering advancements in engineering and technology, highlighting transformative developments while charting new directions for exploration. This aims to stimulate intellectual discourse, facilitate knowledge sharing, and strengthen collaborative networks across the SONEUK community and wider professional circles. Moreover, the research establishes a robust framework for progressing sustainable engineering practices. We value and encourage your insights and recommendations to guide our future endeavors.

As the editorial team, we are honored to facilitate the publication of these proceedings. We extend our heartfelt thanks to all the authors, reviewers, keynote speakers and SONEUK Executive Committee for their invaluable contributions. It has been a rewarding experience compiling these papers, and we hope you find them as interesting and informative as we do.

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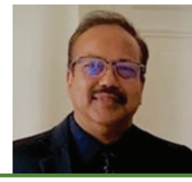
Society of Nepalese Engineers UK



Message from the Chairperson

I am pleased to welcome you to the 10th Annual Conference of the Society of Nepalese Engineers in the UK (SONEUK), held on 28th June 2025, at the historic Madingley Hall, Cambridge, UK.

As your Chairperson, I am honoured to take on this role with a deep sense of purpose and responsibility. Under the guiding theme "Uniting Engineers for Change," we reaffirm our commitment to building a stronger, more connected community of engineers equipped to drive positive and lasting impact both locally and globally.

As we mark a decade of collaboration, innovation, and knowledge-sharing, this year's conference served as a dynamic platform to bring together researchers, engineers and professionals to explore cutting-edge advancements, practical applications, and pressing challenges across a wide range of disciplines under the overarching theme of Science, Technology & Engineering. The selected papers reflected the evolving priorities and challenges in both global and Nepal-specific contexts, with topics spanning from AI in healthcare and machine translation of Nepal Bhasa to sustainable construction materials, visualisation tools in the construction project management, tunnel ventilation systems, and urban metro infrastructure in Kathmandu, the conference fostered interdisciplinary dialogue and collaboration aimed at driving innovation, addressing local and global challenges, and promoting sustainable development through science and technology. I am confident that discussions and ideas exchange during this conference will inspire future research.

First and foremost, I would also like to express our heartfelt gratitude to His Excellency Mr. Chandra Kumar Ghimire, Ambassador of Nepal to the UK, for gracing today's event as a chief guest. His continued support at our past events has greatly encouraged and energised our society, strengthening our mission and outreach.

Sincere thanks Mr Tim Peet, Director, Integrated Project Delivery, Major Projects, WSP for his Key Note Speech title "HS2 Old Oak Common – Largest Interchange Station ever built in the UK". I would also like to thank Er Subash Chandra Baral, President, Nepal Engineers Association (NEA) and Mr Kul Mani Acharya, the Chair, Liaison Committee of the American Nepalese Engineers Society (ASNEgr), for attending the conference in person. Your presence greatly enriched our discussion, and we look forward to the future collaboration and continued exchange of knowledge and expertise.

We will focus on key areas that promote growth, professional development, and meaningful collaboration. Recognising the richness and diversity of the engineering profession, SONEUK will continue to serve as an inclusive platform that supports engineers from all disciplines.

Finally, on behalf of SONEUK, I would like to sincerely thank all authors, reviewers, sponsors, and participants. Your ongoing support makes this conference an invaluable experience for all the attendees, members of SONEUK and engineers around the world.

Subodh Timilsina
Chairperson
SONEUK

नेपाली राजदूतावास

EMBASSY OF NEPAL, LONDON

AMBASSADOR

Message

18 June 2025

It is a privilege to extend my warmest greetings and best wishes to all members of the Society of Nepalese Engineers in the United Kingdom (SONEUK) on its 10th Annual Conference.

It is an honor to convey my warmest greetings and best wishes to all members of the Society of Nepalese Engineers in the United Kingdom (SONEUK) on the occasion of its 10th Annual Conference. I would like to express my sincere gratitude to Chairperson Mr. Subodh Timilsina and the Executive Committee for their exemplary leadership and steadfast dedication to the professional development, unity, and welfare of Nepalese engineers in the UK. I also wish to acknowledge the invaluable contributions of the Founding President and previous leadership, whose vision and actions have laid the solid foundation for the current status of SONEUK, which is recognized as a distinguished, well-organized, and highly esteemed professional platform. This milestone, marking the 10th Conference, serves as a testament to the resilience, adaptability, and growth of the Nepalese engineering community in the UK. It is a source of immense pride that Nepalese engineers in the United Kingdom have not only achieved meaningful employment but have also garnered widespread recognition, respect, and admiration from both British institutions and the broader society. This reflects a new image of the Nepali diaspora, rapidly emerging with a reputation for exceptional competence, dedication, and professionalism in the engineering field. The Embassy of Nepal greatly appreciates SONEUK's proactive involvement in promoting engineering excellence through academic conferences, seminars, and knowledge-sharing forums. Your efforts encompass critical areas of engineering methods, systems, and technologies, with a strong focus on practical application and knowledge transfer. These contributions are highly pertinent to Nepal's national development priorities and can play a crucial role in fostering long-term capacity-building. I am pleased to learn that, in addition to your professional endeavors, SONEUK is also involved in humanitarian and charitable initiatives. The social aspects clearly demonstrate a robust sense of social responsibility and community engagement.

The Embassy anticipates enhancing its partnership with SONEUK as a strategic ally in leveraging the skills, innovation, and experience of Nepalese engineers in the UK to support Nepal's goal of achieving a **Prosperous Nepal and Happy Nepali**.

With heartfelt gratitude and respect, I extend my best wishes for the success of the 10th Conference of SONEUK and for ongoing excellence in all its endeavors.

Best Regards,

Chandra Kumar Ghimire

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ASNEngr
American Society of Nepalese Engineers

Founded in 2007

June 16, 2025

Warm Greetings from American Society of Nepalese Engineers (ASNEngr)

Dear SONEUK Team,

On behalf of the American Society of Nepalese Engineers (ASNEngr) and its members, we would like to extend our warmest greetings and heartfelt congratulations on the occasion of your 10th Annual Conference titled "Science Engineering and Technology"

We sincerely appreciate the immense effort and dedication demonstrated by your organizing committee in ensuring the collective success of this conference. Your commitment to fostering innovation and advancing the field of Science Engineering and Technology is truly commendable.

As fellow engineers, we recognize the importance of collaboration and knowledge sharing in driving progress and innovation. We are excited to see the great strides that will be made during the conference and the valuable insights that will be exchanged among participants.

Ones again, Congratulations to SONEUK on this milestone. We look forward to strengthening our collaborative efforts and exploring opportunities for mutual growth and development in future event.

Wishing you a successful and enriching conference.

Best regards,

Mangal Mahajan
President
American Society of Nepalese Engineers (ASNEngr)
Phone: 202-368-6296

American Society of Nepalese Engineers (ASNEngr) -a non-profit organization with IRS 501(c)(3) tax exempt status – aims at providing a platform for Nepalese, and their friends, in engineering and closely related scientific and technical areas to come together, exchange ideas, and support each other for their and the larger society's common good. The Society also strives at promoting engineering and technological advancement in Nepal.

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Message From the President

On behalf of the Nepal Engineers' Association (NEA) and in my personal capacity as President, I extend my heartfelt congratulations and best wishes to the Society of Nepalese Engineers in UK (SONEUK) on the milestone occasion of your 10th Conference on Science, Engineering, and Technology being held at Madingley Hall, Cambridge.

This remarkable milestone showcases your decade long commitment in uniting Nepalese engineering professionals in the United Kingdom and promoting an environment of academic excellence, professional growth, and collaborative innovation. The theme and structure of this year's conference, with its wide ranging technical sessions, insightful presentations and representation from global engineering communities, reflect SONEUK's continued dedication to advancing engineering discourse and contributing to the global scientific community.

NEA sincerely appreciates the continued collaboration and shared vision between our institutions in promoting the role of engineering in sustainable development, technological innovation, and capacity building, both in Nepal and among our diaspora communities abroad.

May this 10th Conference further strengthen professional networks, inspire new ideas, and empower engineers to take on the challenges and opportunities of the future. We are confident that your efforts will continue to enhance the pride and presence of Nepalese engineers on the international stage.

Wishing the conference grand success and looking forward to greater cooperation in the years ahead.

With warm regards and best wishes.

....
Er. Subash Chandra Baral
President

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Developing a Responsible AI Framework for Healthcare in Low Resource Countries: A Case Study in Nepal and Ghana

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Abstract

The integration of Artificial Intelligence (AI) into healthcare systems in low-resource settings, such as Nepal and Ghana, presents transformative opportunities to improve personalized patient care, optimize resources, and address medical professional shortages. This paper presents a survey-based evaluation and insights from Nepal and Ghana, highlighting major obstacles such as data privacy, reliability, and trust issues. Quantitative and qualitative field studies reveal critical metrics, including 85% of respondents identifying ethical oversight as a key concern, and 72% emphasizing the need for localized governance structures. Building on these findings, we propose a draft Responsible AI (RAI) Framework tailored to resource-constrained environments in these countries. Key elements of the framework include ethical guidelines, regulatory compliance mechanisms, and contextual validation approaches to mitigate bias and ensure equitable healthcare outcomes.

Key Words: Artificial Intelligence, Healthcare, Responsible AI, Low-Resource Settings, Nepal, Ghana, Ethical AI, Low and Middle Income countries (LMICs).

1. Introduction

The adoption of AI in healthcare has brought substantial advancements, improving diagnostic accuracy, treatment personalization, and administrative efficiency. While developed countries have successfully incorporated AI into their healthcare systems, LMICs such as Nepal and Ghana face unique challenges, including a lack of digital infrastructure, policy gaps, and ethical concerns. Despite its potential, AI implementation remains hindered by privacy, liability, and trust issues. This paper aims to evaluate AI healthcare initiatives in Nepal and Ghana, analyse risks and benefits, and propose a Responsible AI Framework draft, tailored to low-resource settings.

The examination of digital health initiatives in Nepal and Ghana has revealed that AI is becoming an integral component of healthcare systems in these nations. However, the widespread use of AI remains largely unregulated, lacking the necessary oversight and ethical safeguards to ensure its responsible application. This absence of a structured AI framework creates uncertainty among patients, regulators, and AI developers, raising concerns regarding safety, fairness, and accountability (Floridi et al., 2020). Without appropriate governance, AI could exacerbate existing healthcare disparities, reinforce biases, and introduce vulnerabilities that compromise patient outcomes (Obermeyer et al., 2019). Hence, there is an urgent need to develop a RAI Framework that provides clear ethical guidelines, regulatory compliance, and localized validation mechanisms to ensure AI adoption aligns with the unique needs of low-resource healthcare settings (WHO, 2021).

1.1 Research Questions

The study aims to address the following research questions, ensuring alignment with the methodology and findings:

- What are the benefits and risks associated with AI healthcare initiatives in low-resource settings such as Nepal and Ghana?
- What are the key challenges hindering the integration of AI in healthcare within these low-resource environments?
- How can a Responsible AI Framework be developed and validated to address the unique socio-economic and technological constraints of low-resource healthcare systems?

1.2 Research Methodology

This study employs a mixed-methods approach, combining qualitative and quantitative fieldwork conducted in Nepal and Ghana. Key methodological elements include:

- Literature review: Combining literature reviews of existing AI frameworks and policies, field studies around developed nations, Nepal and Ghana.
- Sampling: Surveys were distributed to healthcare practitioners, policymakers, and AI developers, with a total of 85 respondents across both nations.
- Survey Design: Questions focused on ethical concerns, trust issues, and governance gaps related to AI deployment.
- Data Collection: Field studies were conducted in urban and rural healthcare facilities, ensuring diverse representation.
- Ethical Approvals: The study adhered to ethical standards approved by the University of Hull, UK.

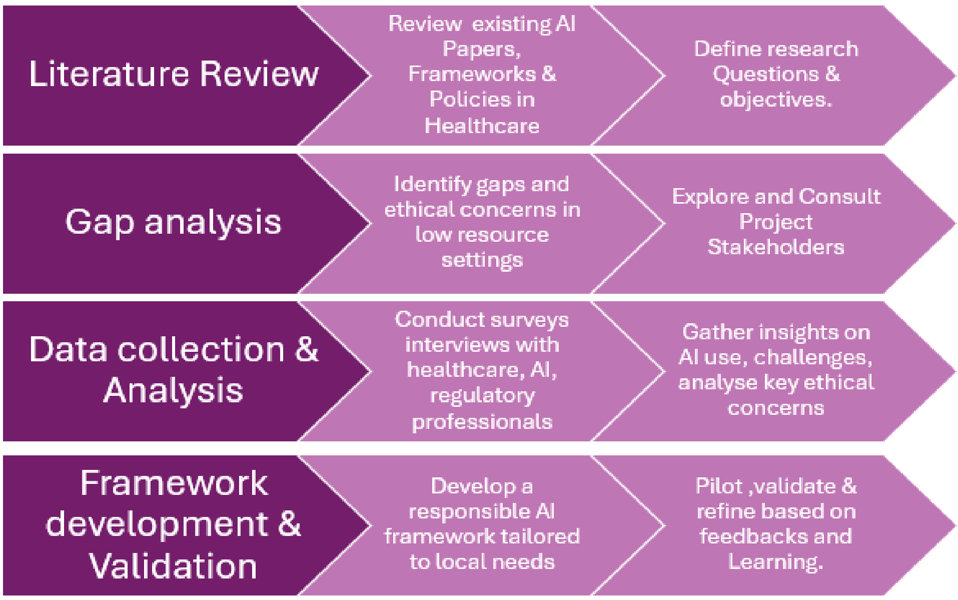

Figure 1: Conceptual flow diagram of adopted methodology.

2. Literature Review

2.1 Existing AI Frameworks in Healthcare

Artificial Intelligence has gained significant traction in healthcare, leading to the development of various ethical and regulatory frameworks to ensure its responsible deployment. The WHO AI4Health Initiative provides guidelines for AI governance in healthcare, emphasizing transparency, safety, and data privacy (WHO, 2021). Similarly, the European AI Ethics Guidelines advocate for human oversight, fairness, and accountability in AI-driven healthcare solutions (European Commission, 2019). In the US, the AI Bill of Rights was introduced to protect patients from algorithmic biases and ensure that AI systems remain interpretable and safe (WhiteHouse, 2022). Despite these initiatives, there is a notable lack of contextual adaptation for LMICs, where data scarcity, infrastructure gaps, and ethical concerns present significant barriers (Rahman et al., 2021).

2.2 AI in the UK's NHS

The National Health Service (NHS) has actively integrated AI in diagnostics, resource management, and predictive analytics to enhance patient care (Topol, 2019). AI-driven imaging tools have improved the early detection of diseases such as cancer, significantly reducing diagnostic errors (Rajpurkar et al., 2018). However, ethical concerns persist, particularly regarding data privacy, algorithmic biases, and regulatory challenges. Studies highlight that while AI adoption enhances efficiency, issues such as transparency and trust among healthcare professionals remain (Holdsworth & Zaghloul, 2022). Recent NHS policies now emphasize the need for explainability and regulatory oversight to ensure that AI complements human decision-making rather than replacing it (UK Government, 2022).

2.3 AI Policies in Developing Nations

AI policies in developing nations remain fragmented and underdeveloped. Countries like India and South Africa have introduced AI ethics guidelines focusing on data privacy, inclusivity, and fairness (NITI Aayog, 2020). India's Responsible AI for Healthcare framework highlights the importance of ethical AI deployment while ensuring compliance with global standards such as the GDPR and WHO's AI guidelines (NITI Aayog, 2020). In contrast, Ghana and Nepal lack formal AI policies, resulting in inconsistent AI adoption and regulatory uncertainty (UNESCO, 2023). Studies suggest that developing nations need tailored AI governance strategies that consider socio-economic factors, healthcare disparities, and technological constraints (Vayena et al., 2018).

A systematic review by Obermeyer et al. (2019) identified that most AI-driven healthcare solutions in LMICs fail due to data bias and inadequate validation of local populations. Similarly, research by Ting et al. (2020) emphasizes the need for clinical trials and real-world validation before AI tools are deployed in resource-limited healthcare settings. Further, studies by Panch et al. (2019) and Beauchamp & Childress (2019) stress the importance of ethical considerations, highlighting the need for frameworks that ensure fairness, transparency, and accountability in AI-driven healthcare systems. These findings collectively indicate that while AI presents immense potential, its deployment in LMICs must be accompanied by robust policies, regulatory oversight, and ethical considerations to maximize its benefits while mitigating risks.

3. Challenges in AI Implementation in Developing Countries

3.1 Data Privacy and Security

One of the primary concerns in AI deployment in healthcare is data privacy and security. Many developing countries lack robust data governance frameworks, increasing the risk of patient data breaches due to inadequate cybersecurity measures. Studies indicate that without proper regulatory oversight, AI-driven healthcare applications may inadvertently expose sensitive patient information, leading to ethical and legal challenges (Ting et al., 2020). The absence of standardized encryption protocols and weak cybersecurity measures exacerbates vulnerabilities, making AI systems prime targets for cyber threats (Rahman et al., 2021). Ensuring compliance with international data protection laws, such as the General Data Protection Regulation (GDPR), remains a significant challenge in LMICs (Vayena et al., 2018).

3.2 Algorithmic Bias and Trust Issues

AI models trained on Western datasets often fail to generalize in LMICs healthcare settings, leading to skewed results and potential misdiagnoses. The lack of diverse, region-specific datasets results in biased predictions that disproportionately affect underserved populations (Obermeyer et al., 2019). Studies highlight that healthcare professionals in LMICs exhibit skepticism toward AI recommendations due to a lack of transparency and explainability in AI decision-making processes (Panch et al., 2019). To build trust in AI systems, healthcare institutions must ensure contextual validation and algorithmic fairness, reduce biases and improve AI interpretability (Beauchamp & Childress, 2019).

3.3 Infrastructure and Workforce Limitations

The successful deployment of AI in healthcare requires robust digital infrastructure and a well-trained workforce. However, many LMICs face challenges such as limited internet connectivity, outdated hospital IT systems, and a shortage of AI-trained medical professionals and data scientists (WHO, 2021). A lack of continuous professional development programs for clinicians further hampers AI adoption, as many healthcare workers are unfamiliar with AI-based decision support tools (Ting et al., 2020). Moreover, inadequate funding for AI research and implementation restricts the scalability of AI-driven solutions in LMICs. Addressing these challenges requires investment in digital infrastructure, workforce training, and cross-sector collaboration to bridge the AI readiness gap in healthcare systems (Rahman et al., 2021).

4. Understanding Healthcare Ecosystem in Nepal and Ghana: Field Study and Survey

4.1 Healthcare Ecosystem in Nepal

Nepal's healthcare system has made significant progress in recent years, yet it continues to face challenges in adopting digital health technologies and AI integration. Through discussions with digital health experts, healthcare professionals, and policy regulators, it has been observed that Nepal is gradually adopting Electronic Health Record (EHR) systems and Hospital Management Information Systems (HMIS) to improve patient data management. However, these systems remain fragmented due to a lack of interoperability across public and private healthcare sectors. The inconsistency in data standardization poses a critical challenge, as healthcare providers struggle to maintain well-defined patient records. Furthermore, regulatory gaps and weak data privacy policies raise concerns about ethical AI adoption in healthcare. Although there is an increasing interest in AI-driven healthcare solutions, the country lacks a comprehensive framework to guide responsible AI deployment. There is an urgent need for AI governance policies, role-based data security, and collaboration between policymakers, AI developers, and healthcare institutions to ensure ethical, effective, and secure AI integration in Nepal.

4.2 Healthcare Ecosystem in Ghana

Ghana's healthcare system is supported by multiple digital health initiatives, including the District Health Information Management System (DHIMS2) and Lightwave Health Information Management System (LHIMS), which aid in patient records management and health service delivery. Additionally, the National Health Insurance Authority (NHIA) system plays a crucial role in claims processing and healthcare financing. The E-Pharmacy project is another government initiative aimed at providing telehealth and remote prescription services, enhancing accessibility to medical consultations. However, Ghana's healthcare digitalization faces substantial hurdles, such as fragmented health data systems, connectivity issues, and inadequate AI policy frameworks. Stakeholder discussions indicate a pressing need for AI-driven data analytics, predictive modelling for disease surveillance, and AI-based decision-support systems. Survey findings reveal that although healthcare professionals acknowledge AI's potential in improving patient care, they also express concerns about bias in AI models, lack of transparency, and low AI literacy among medical practitioners. Therefore, structured AI training programs, regulatory oversight, and strategic public-private partnerships are essential to facilitate responsible AI integration in Ghana's healthcare sector.

4.3 Data Collection and Analysis: Survey

We gathered important insights and feedback from an initial survey conducted among 85 respondents, including healthcare professionals, IT experts, and regulatory personnel in Nepal and Ghana. The survey aimed to assess AI awareness, usage, perceived risks, and local mitigation strategies. Below is a statistical summary of the key findings, followed by a critical analysis of how these findings influence the proposed Responsible AI (RAI) framework.

5. Survey Findings and Statistical Summaries:

5.1 Professional Diversity: Work Domain and Job Titles

The majority of respondents (53%) were healthcare professionals, while IT experts and regulatory personnel constituted 15% and academia 12%, respectively. This distribution highlights the multidisciplinary involvement required for AI adoption in healthcare (Figure 2).

Figure 2: Professional diversity of the survey participants.

5.2 Perception of AI's Impact on Patient Care

The majority opinion is that AI integration will improve the quality of patient care, as presented in Figure 3.

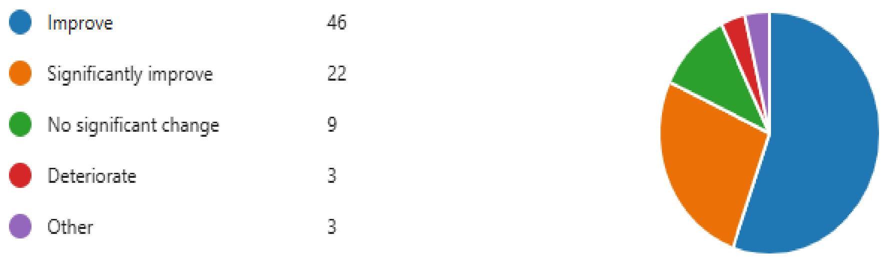

Figure 3: Participants' opinions on the impact of AI integration into healthcare.

5.3 Necessity of a Responsible AI Framework

A strong consensus emerged on the importance of enforcing a Responsible AI framework. Key recommendations included:

- Strict guidelines and regulations (61%)

- Moderate regulation (15%)

- No regulation (0%)

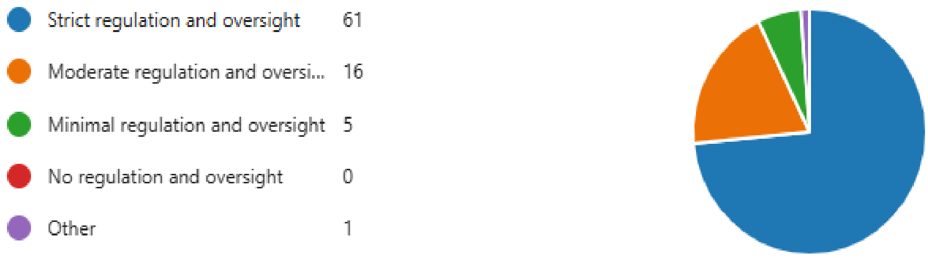

Figure 4: Participants' opinions on the necessity of a Responsible AI Framework.

5.4 Challenges Identified

Low AI literacy among healthcare workers (65%), lack of robust infrastructure (58%), and limited funding for AI research (52%) were the most frequently cited challenges.

5.5 Critical Analysis

The survey findings emphasize the need for a localized and context-sensitive approach to integrating AI into healthcare in developing countries, such as Nepal and Ghana. Below is an analysis of how the results shape the proposed RAI framework:

6. Implementation Strategies & Draft Framework

Effective Implementation of Responsible AI in the healthcare sector of developing countries has got many challenges and needs to be done with careful consideration. To integrate AI efficiently into healthcare in developing nations, digital capacity building is a fundamental necessity. Training healthcare workers in AI literacy and ethical guidelines is a critical first step, ensuring that professionals understand how to interpret AI-generated insights and integrate them into clinical workflows (Ting et al., 2020). Educational initiatives should focus on developing digital competencies, enabling clinicians to critically assess AI recommendations and intervene when necessary (Beauchamp & Childress, 2019). Public-private partnerships (PPPs) can play a pivotal role in fostering collaborations between governments, technology firms, and healthcare providers. PPPs facilitate resource sharing, reducing the financial burden on governments while promoting AI research and innovation in LMICs (Rahman et al., 2021). These partnerships can also aid in creating AI solutions that are tailored to local needs, ensuring that technology adoption aligns with regional healthcare priorities (NITI Aayog, 2020).

Conducting pilot studies is necessary to test AI deployments on a small scale before national implementation. Pilot programs provide empirical data on AI performance in real-world settings, highlighting areas for improvement before large-scale rollout (Panch et al., 2019). These trials should assess the accuracy, fairness, and usability of AI applications, ensuring that models function optimally across diverse patient populations (WHO, 2021). Furthermore, continuous monitoring and evaluation mechanisms must be established to ensure AI-driven healthcare applications remain effective and aligned with ethical standards. Developing real-time feedback loops, where AI-generated outcomes are routinely assessed and refined, will help maintain system reliability and mitigate unintended biases (Obermeyer et al., 2019). By prioritizing ongoing assessment, LMICs can ensure that AI remains a tool for enhancing, rather than compromising, healthcare quality and accessibility.

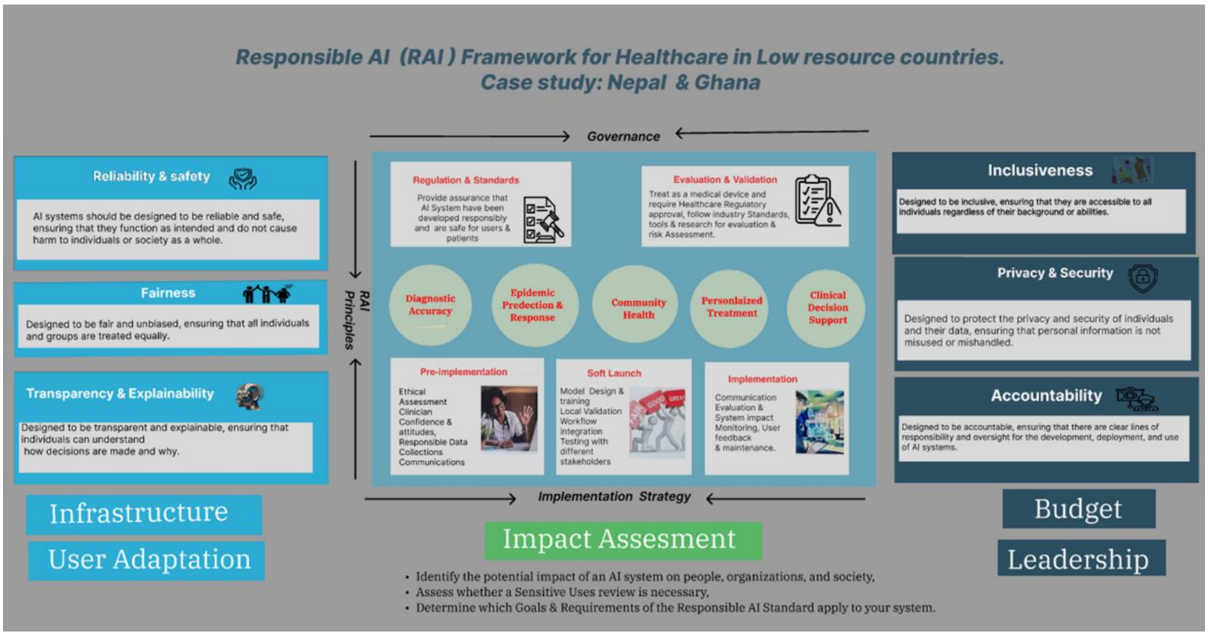

Figure 5: Draft Responsible AI Framework for Low-Resource Countries.

The insights gained from this study reinforce the necessity of establishing the RAI Framework, as presented in Figure 5 that fosters trust, compliance, and equitable access to AI-driven healthcare innovations. The draft RAI Framework is designed to ensure ethical and effective AI implementation. It is built around key RAI principles: Reliability & Safety, Fairness, Transparency & Explainability, Inclusiveness, Privacy & Security, and Accountability.

The framework integrates governance through regulatory standards and validation processes while ensuring smooth Implementation via ethical assessment, stakeholder engagement, and monitoring systems. It follows a structured approach—beginning with a literature review to identify gaps, followed by issue identification through surveys and interviews. The framework is then tailored to local needs, piloted, and refined based on stakeholder feedback. A strong emphasis is placed on infrastructure, user adaptation, budget, and leadership to ensure a sustainable and impactful AI-driven healthcare system. This is a draft framework under review from different stakeholders and has not been tested and validated yet. After having a through review this will be tested and validated.

7. Conclusion and Future Work

In summary, this study examined the benefits and risks of AI in healthcare for low-resource settings, identifying key challenges such as limited digital literacy, infrastructure and lack of leadership commitment. Addressing these, we are trying to develop a Responsible AI Framework tailored to local socio-economic and technological realities and outlined steps for its validation. These findings directly address the research questions and demonstrate how ethical AI can improve healthcare in places like Nepal and Ghana, supporting equitable, effective solutions.

Field studies highlighted the importance of localised governance, collaboration with stakeholders, and strengthening AI literacy among healthcare professionals and policymakers. Addressing infrastructural gaps and establishing robust regulatory mechanisms are vital to ensure transparency, accountability, and equitable access. By adopting a Responsible AI framework, healthcare systems in these regions can reduce disparities and promote equitable, patient-centric outcomes.

Future work will focus on the need to strengthen AI literacy and awareness programs among healthcare professionals, policymakers, and AI practitioners, equipping them with the necessary knowledge to integrate AI effectively into healthcare systems (Ting et al., 2020). Additionally, field assessments will be conducted to evaluate the digital readiness of healthcare facilities, identifying infrastructural gaps and capacity-building opportunities (Rahman et al., 2021). Collaboration with health ministries, AI researchers, and regulatory bodies will be prioritized to develop context-specific AI policies that align with national healthcare objectives (Beauchamp & Childress, 2019). Furthermore, advocacy efforts will aim to establish robust legal and regulatory mechanisms, ensuring that AI implementation remains transparent, accountable, and ethically aligned with patient-centric healthcare. Through a multi-stakeholder approach, draft RAI framework will be validated with some use cases and harnessed to enhance healthcare delivery, reduce disparities, and promote long-term sustainability in LMIC healthcare ecosystems. Future research should also focus on pilot testing the framework and expanding its applicability to other LMICs and as per the local contexts of developing countries.

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Challenges in Machine Translation of Nepalbhasa

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Abstract

Over the past seventy-five years, *Natural Language Processing* (NLP) has made significant advancements in the field of *Artificial Intelligence* (AI), with progress largely dependent on the task, language, and availability of data. Within NLP, *Machine Translation* (MT) remains a major challenge, particularly for low-resource languages. While services like *Google Translate* and *DeepL* have achieved near-human translation quality for widely spoken languages with extensive literary corpora, lesser-known languages, such as Nepalbhasa (Newari), continue to face hurdles. This paper presents a case study of Nepalbhasa, detailing the processes and methodologies undertaken by my team at the World Newah Organisation to have the language included in *Google Translate*. It documents the painstaking efforts to digitise Nepalbhasa, which UNESCO classified as endangered nearly twenty-five years ago. Over three years, hundreds of community members worldwide contributed daily to training *Google Translate* in Nepalbhasa. Drawing from this experience, the paper analyses the linguistic complexities where machine translation still struggles and requires further refinement. Additionally, this case study of Nepalbhasa sheds light on broader challenges faced by other national and regional languages in Nepal, offering insights into their preservation and technological integration. *Keywords:* Machine Translation, Google Translate, Nepalbhasa, Community.

Key Words: Natural Language Processing, Nepalbhasa, Neural Machine Translation.

1 Introduction

1.1 Machine Translation

Natural Language Processing (NLP) is a branch of artificial intelligence that focuses on enabling machines to understand, interpret, and generate human language meaningfully (Jurafsky and Martin, 2021). It combines linguistics, computer science, and machine learning to process large volumes of natural language data. NLP originated in the 1950s with early machine translation projects (Weaver, 1955). Rule-based systems dominated until statistical methods gained prominence in the 1980s, supported by larger corpora and computing power (Church and Mercer, 1993). The 2000s saw a shift to machine learning, while deep learning transformed the field in the 2010s with models like Bidirectional Encoder Representations from Transformers or *BERT* (Devlin et al., 2018) and Generative Pre-Training Transformer or *GPT* (Radford et al., 2018). NLP now underpins applications from chatbots to automated translation with remarkable accuracy.

Over the past seventy-five years, NLP has made significant advancements, with progress largely dependent on the task, language, and availability of data. Within NLP, Machine Translation (MT) remains a major challenge, particularly for low-resource languages. MT is a subfield of Natural Language Processing that focuses on automatically converting text or speech from one language to another. Early MT efforts began in the 1950s, driven by rule-based systems (Weaver, 1955). These evolved into statistical approaches in the 1990s, improving translation quality by learning from bilingual corpora (Koehn, 2010). More recently, neural machine translation (NMT) has become the dominant approach, using deep learning models to produce more fluent and accurate translations (Bahdanau et al., 2015). Today, MT plays a crucial role in global communication, powering tools like Google Translate and real-time multilingual systems. While services like Google Translate and DeepL have achieved near-human translation quality for widely spoken languages with extensive literary corpora, lesser-known languages such as Nepalbhasa (Newari) continue to face hurdles.

1.2 Introduction to Nepalbhasa

Nepalbhasa, also known as Newar or Newari, is the language of the Newar people, the indigenous inhabitants of the Kathmandu Valley in Nepal. It belongs to the Sino-Tibetan language family and has a rich literary history dating back to the 12th century (Glover, 1974). The language is tonal, with a complex system of honorifics and verb conjugations, reflecting Newar social and cultural structures. Historically used in administration, literature, and religious texts, Nepalbhasa experienced a decline after the 18th century but has seen revitalisation efforts in recent decades. With only 8,46,557 active speakers at present (GoN, 2012), UNESCO has listed Nepalbhasa in the “Definitely Endangered” category.

The early 20th century, particularly from the 1920s to the 1950s, is considered the Renaissance of Nepalbhasa. This period saw a revival in literature, journalism, and cultural expression despite political suppression under the Rana regime. Prominent figures such as *Siddhidas Mahaju*, *Jagat Sundar Malla*, and *Nisthananda Bajracharya* played key roles in revitalising the language through education, publishing, and literary works (Shrestha, 2000). During this period, conscious efforts were made by the literate Newar community in the Valley to revive Nepalbhasa through public events and wider publications. Today, Nepalbhasa is recognised as one of the national languages of Nepal, and from around 2010 onwards, various attempts have been made by members of the Newar community to bring Nepalbhasa to new technological platforms such as digital content creation, e-learning, gaming, and animation. The following sections of this paper will focus on machine translation in Nepalbhasa.

2. Nepalbhasa in Google Translate

The project to include Nepalbhasa in Google Translate started on 5th December 2020. Hundreds of contributors from all over the world came together to contribute training data to the Google Translate engine. It took them three and a half years to reach a stage when the engine was ready to include Nepalbhasa in the list of languages it could translate successfully. The contributors from Nepal, USA, UK, Canada, UAE, and several other countries joined a video conference every single day for three and a half years, leading to the completion of the project on 27th June 2024. For the World Newah Organization, the author of this paper led this project along with the then Google Engineer Ujjwal Rajbhandari from the USA, and two other community leaders, including Season Shrestha from the USA and Deepesh Man Shakya from Ireland (Onta, 2025). In the following section, various stages of this project will be explained with their problems and solutions.

2.1 Phase 1 - Digitisation

Digitisation means developing digital copies of physical objects. This first phase aimed to collect as much published material as possible in Nepalbhasa. Fulfilling such a need was not an easy task for a historically marginalised language like Nepalbhasa. As introduced in section 1.2, during the Rana regime, handwritten books in Nepalbhasa were searched and burned. Only after the restoration of democracy in Nepal did the people regain the right to write and speak in their mother tongue openly. After almost a century of linguistic oppression, with the development of Devanagari Unicode at the beginning of the twenty-first century, it was not difficult to bring Nepalbhasa into use through information technology. As a result, various digital magazines were born, and the general public made the most of this technology.

In the digitisation stage, the project made use of the digital Nepalbhasa content generated over a decade by active publishers like Eloham Prakashan and Jhigu Swaniga Dainik. This, however, was not sufficient in quantity as required for training the translation engine. Finally, to overcome the challenge of quantity, we started scanning physically published books and digitising them in large numbers. This was possible through the tireless efforts of Ravi Shakya, Associate Professor of the Central Department of Nepalbhasa, Tribhuwan University. A special task force was also created to overcome the challenges of various file formats and typesetting. As a result of this first phase, the Google Translate engine could recognise Nepalbhasa as a distinct language among the thousands of languages found on the Internet. The accuracy of language identification was 75%, which was termed by Google as ‘very encouraging’ compared to other languages.

2.2 Phase 2 - Collection of Translations

The second phase was the collection of materials translated from Nepalbhasa into other languages. The project prioritised English translation as it would be easier for the Google Translate engine as compared to translation from other languages. This is because Google's artificial intelligence system would first translate any language into English. It was hence clear that the linguistic gap would be overcome step by step by re-translating it into other languages. Based on this strategy, the project emphasised the collection of as many English translations as possible. Another option was to translate materials into Nepali.

Among the organisations born abroad for the preservation and promotion of culture, the Newah Organisation of America and the Pasa Puchah Guthi UK have been translating numerous press releases and news articles into English in the past two decades. Most of the materials were directly useful for this phase. Even the English subtitles of dialogues in Nepalbhasa films proved useful. Moreover, by providing a digital version of their commercially published books, eminent writers like Bal Gopal Shrestha and Mathura Sayami also gave unique examples of love for the language. Finally, after about a month of tireless efforts, satisfactory results were obtained in terms of quantity, and the project entered the third and more challenging phase.

2.3 Phase 3 - Evaluation Sheet

In the third phase, new content was created specifically for this project. On January 19, 2021, I signed an agreement with Susan Chan from Google's Partnership Team on behalf of the World

Newah Organization. According to the agreement, Google had to translate 1,200 English sentences into Nepalbhasa as needed. These sentences were not only used in general conversation but also mostly of technical and scientific interest. They ranged from academic subjects such as sociology and politics to geometric mathematics and physics. Again, the context would change if one sentence had no connection with another. This phase was like a test of whether one could write and speak in Nepali as competitively as English, even in difficult topics and contexts. Even after spending an hour or two, it would be difficult to translate ten such sentences. The task was completed by sharing the workload amongst experts from the USA, UK, and the Netherlands.

These 1,200 sentences were entered into an evaluation sheet. This evaluation sheet was developed to test Google's translations. Its accuracy was expected to determine the standard of Nepalbhasa translations made by Google's system in the future. After this phase, Nepalbhasa was listed as a Google community-enabled language. Although more than 200 languages from around the world were listed for translation by Google, only two languages, Nepali and Icelandic, had made it through to the fourth stage.

2.4 Phase 4 - Community Enablement

In April 2021, the journey of the Nepalbhasa translation with Google reached its ultimate phase with the commencement of community enablement. This involved the availability of an entry form for anyone with a Gmail account, allowing them to type in their best effort to translate any sentence randomly generated by Google. A sample screenshot from the input panel is shown in Figure 1 below.

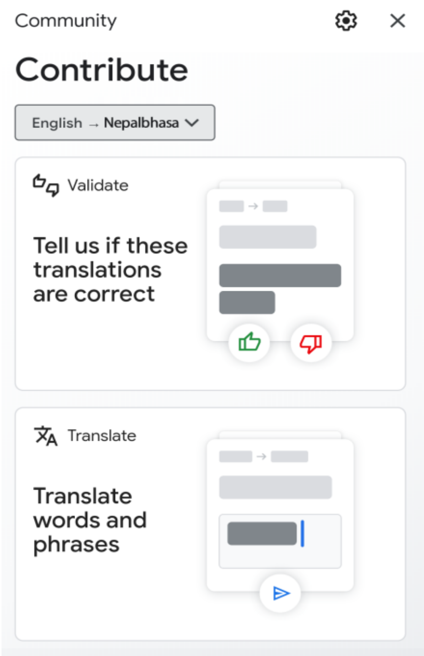

Figure 1: Community Enablement panel in Google Translate

The initial goal for the entire Newah community was to work together to get 12,000 English sentences translated into Nepalbhasa. While the global Newar community had achieved a total of 10,000 Translations by June 2021, it took them hours of video conferencing daily until

February 2024 to reach the milestone of 5,00,000 contributions. This was the longest phase, and its progression in the last month of the project is recorded in the table below.

Date	Total	English-Nepalbhasa		
		Contribution	Validation	Translation
31 Jan	494,400	480,100	436,300	43,800
30 Jan	493,800	479,500	435,700	43,800
29 Jan	493,100	478,800	435,100	43,700
28 Jan	493,100	478,800	435,100	43,700
27 Jan	492,500	478,200	434,500	43,700
26 Jan	492,200	477,900	434,300	43,700
25 Jan	491,300	477,000	433,300	43,600
24 Jan	490,100	475,800	432,300	43,600
23 Jan	489,800	475,500	432,000	43,500
22 Jan	489,400	475,100	431,600	43,500
21 Jan	489,100	474,800	431,300	43,500
20 Jan	488,600	474,300	430,900	43,300

Table 1: The last month's record from the three years of contributions to Google Translate.

2.5 Phase 5 - Machine Translation and Improvement

With the adequate quantity of translation data entered through the community enablement stage, on 27th June 2024, Nepalbhasa was listed as one of those languages that can be translated into 247 other languages of the world using the Google Translate platform. With a commendable accuracy rate, especially for longer sentences and paragraphs that provide the context effectively, the remaining task in the project has been identified as the continuous use and improvement of the existing platform. The more people use it, the engine improves with iterations. Users can also suggest corrections which directly influence future translations.

From the planning to the eventual launch of Nepalbhasa in Google Translate, the project timeline spanning the various stages of the project, as covered under section 2, is shown below.

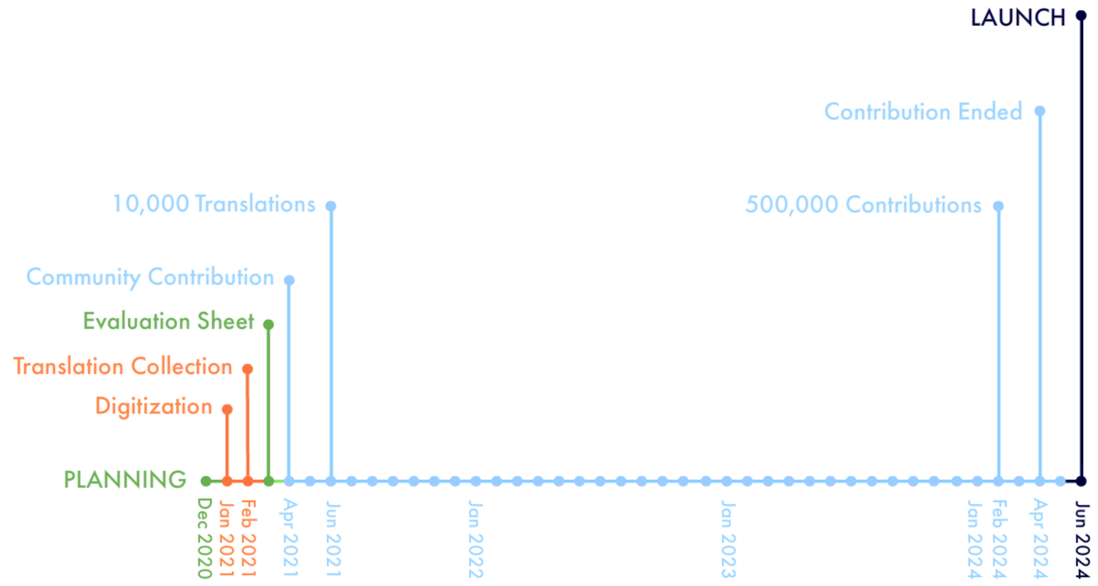

Figure 2: Project Timeline

The percentage distribution of the project stages is shown in the pie chart below.

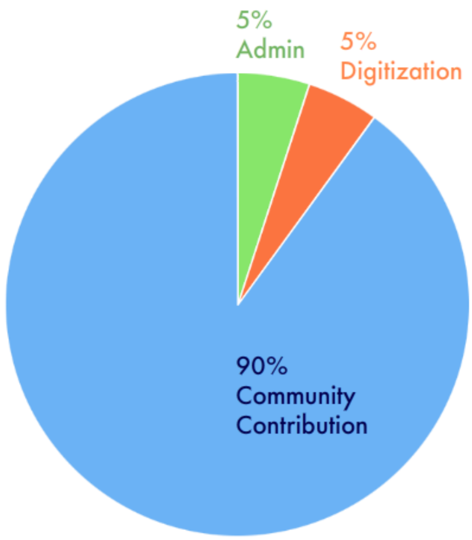

Figure 3: Percentage share of project stages over the timeline

The chart below shows the size of teams involved in each of the stages of the project.

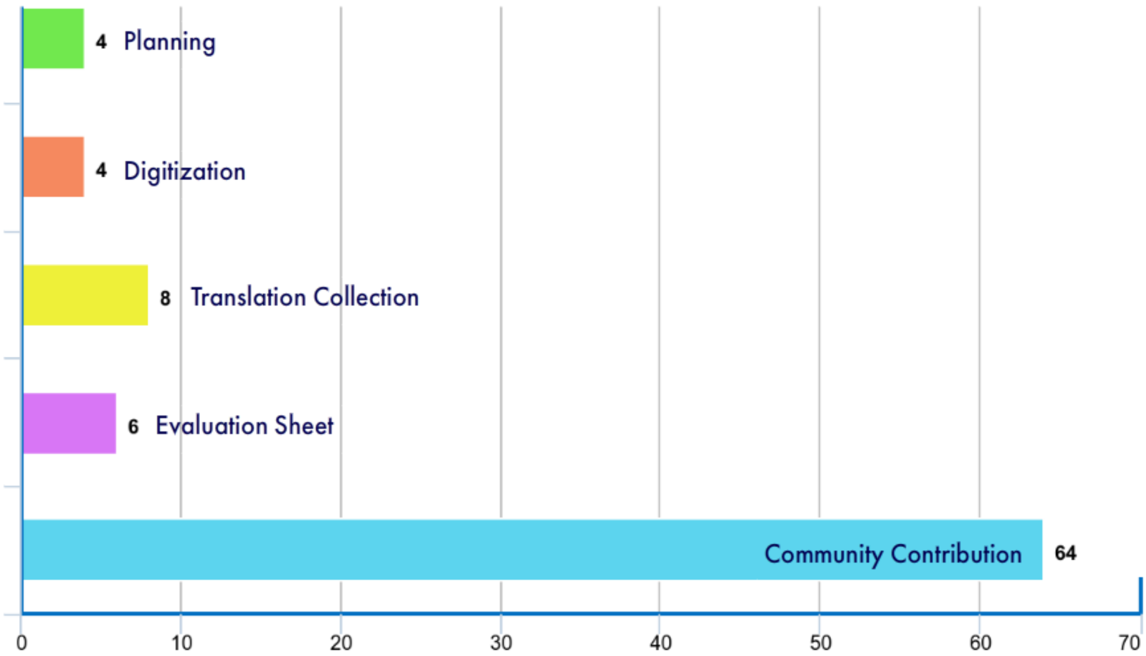

Figure 4: Team size in various stages of the project

3 Challenges in the Machine Translation of Nepalbhasa

The more general challenges with machine translation continue to apply in the case of Nepalbhasa. Nepalbhasa also offers domain-specific issues that extend the list of challenges faced. Like most other languages, Nepalbhasa consists of words that can have more than one meaning. It has words with multiple meanings that cannot be translated correctly without the availability of sufficient context. An example can be the word *'Waa',* which could mean come, teeth, or hay. Besides a single word with multiple meanings, a sentence made up of words that have singular meanings only can also be resolved to mean something beyond their literal meaning.

3.1 Idioms

One example of this case can be cultural traditions or social beliefs that lend an inherent context to the sentence that is different from what it means in a literal sense, e.g., idioms. It has been argued that a deep understanding of both source and target languages and cultures is what remains missing from current translation models (Li et al, 2023). In Nepalbhasa, the phrase *'Woya pwathay du'* literally means that there is (something) in the tummy. However, a native speaker of Nepalbhasa would understand the phrase as 'She is pregnant'. The social knowledge implies that the person is a woman, and something that is in her tummy is nothing but a child to be born. While the non-literal and culturally embedded nature of human expressions like idioms remains a huge challenge for machine translation, the integration of idiom-specific knowledge bases and the advancement of evaluation metrics are promising steps toward more accurate and culturally sensitive translations.

3.2 Proverbs

Another example can be proverbs. Proverbs cannot be understood as such without living the social and cultural life of the region where the language is rooted. One can read the book of Proverbs, but its usage cannot be perfected without bringing it to practice within the sensibilities of the native speakers. The inherent challenge of understanding proverbs is yet an underdeveloped area of research even for English (Romaniuk, 2024; Wang et al, 2025). A specific issue with languages like Nepalbhasa is the dearth of training data due to a limited number of speakers. Out of the existing number of speakers, the next level of challenge is to have them contribute to the training data. The current level of accuracy in the machine translation of Nepalbhasa is owed to the hardcore lovers of Nepalbhasa who have dedicated their lives to its preservation, which is a fortunate case.

3.3 Composite Verbs

Much like with idioms, it can be argued that the transformer's tendency to process compositional expressions contributes to erratic literal translations (Dankers et al, 2022). This is also true for various other composite elements of a general sentence. For instance, it has been noted that composite verbs in Nepalbhasa are not yet correctly translated by *Google Translate*, e.g, the sentence *'Dakwo pasapinta napa lana woye'* has two verbs occurring together – *'napa laye'* (meet) and *'woye'* (come). Their composite meaning here in this sentence would be 'I will come after meeting all of my friends'. However, a simple translation by *Google Translate* is given as 'See you all friends'.

3.4 Confusion with Nepali or Other Similar Languages

Closely related South Asian languages have been a known challenge for translation models. While the inclusion of Nepalbhasa is due to the research of known language clusters with high confusion rates, such as Gujarati, Kutchi, and Bhilori; and Koda, Bengali, and Assamese, misidentifications are attributed to the lexical and structural similarities among these languages, which can lead to errors in both language identification and translation processes (Tadimeti et al, 2023). However, research has shown that such a scenario can also offer opportunities to improve translation quality by leveraging these similarities (Doddapaneni et al, 2020). Although Google Translate identifies Nepalbhasa with a high level of accuracy, words that are common to both Nepali and Nepalbhasa but can have different meanings in either language add to the inaccuracy. This can be true with other languages besides Nepali as well. An example is the word Nepalbhasa itself. Google Translate translates Nepalbhasa as 'Nepali Language' since the term Nepalbhasa can be separately understood as 'Nepal or Nepali' and *'bhasa'* (language), instead of the uniquely different language that is Nepalbhasa.

3.5 Standardisation of Nepalbhasa

Unlike Nepali, Nepalbhasa does not have a long history of systematic education, which makes its standardisation efforts equally less popular. As a result, less of native speakers can write Nepalbhasa correctly. Besides, it has a variety of dialects that come from various regions in and around the Kathmandu Valley, like *Khwopa* dialect (Bhaktapur), and *Dwalkha* dialect (Dolakha), among others. Preliminary research has been carried out on the differences between Dolakha and Kathmandu dialects, which focuses on phonological, morphological, and syntactic differences (Genetti, 1988; Genetti, 2007). On the other hand, the Bhaktapur dialect presents variations in phonology, morphology, syntax, and lexicon (Joshi, 1984). Much like the Dwakha dialect, the Bhaktapur dialect has different words and pronunciations for the same thing, e.g., water is called *'La'* (Kathmandu) and *'Naa'* (Bhaktapur). Variations are not only limited to words but also to their grammar (Regmi, 2012). The presence of multiple dialects is yet another challenge to be addressed in the machine translation of Nepalbhasa.

4. Further Work

While the challenges listed under section 3 need further addressing in the learning model, there are three distinct levels at which further work can be carried out in improving the current rate of accuracy in the machine translation of Nepalbhasa, which are enumerated below.

4.1 Continuous Editing and Feedback

Even after the inclusion of Nepalbhasa in *Google Translate*, the Nepalbhasa community volunteers continued to meet online for an hour every day since June 2022. In these sessions, they generate new translations and conduct short brainstorming rounds within the team of experts to improve the result and feed it back to the system. This is a continuous process and should be continued with the same spirit in the future.

4.2 Identification of Common Issues and Error Patterns

Further and in-depth work is needed to identify common issues at the current stage of the project output. This study should make use of linguists, translators and expert users of *Google Translate* to deduce a list of error patterns. Such patterns can be utilised by the editing and feedback team (see 4.1) as their sample inputs, which will help improve the target patterns through continuous feedback.

4.3 Utilisation of Known Research on Common Machine Translation Issues

Identification of issues with machine translation is not a new task and has been carried out for several other languages in the past, which have a longer history of machine translation. The teams involved in the machine translation of Nepalbhasa are yet to make use of the known research works and the solutions they devise. It can be argued that the research outcomes have sole relevance to the engineering of the translation model. Since the model is capable of correcting itself, the use of strategic datasets by the end users can contribute directly to the improvement in results. This can be particularly effective when deployed by the dedicated editing and feedback teams of community volunteers. The specially designed datasets can focus on various challenges listed in Section 3.

5. Conclusion

Nepal is a multi-ethnic, multicultural and multilingual country with a total of 124 languages according to the 2021 census. While globalisation has imposed English on every part of the world, including Nepal, the one-nation-one-language policy of the Panchayat era unfortunately contributed to the decline of many of the languages from a culturally rich Nepal. Less can be done to correct past mistakes, but technology can be a tool to improve the situation with cultural assets that need preservation, which includes our languages. Machine translation can help us learn languages that have fewer speakers and trainers left in this world.

The community project to include Nepalbhasa in Google Translate proved a rewarding experience due to a large number of community volunteers making it possible to gather the required amount of training data and a consistent attempt to improve the results. However, the project continues to face further challenges due to social, cultural, historical and other technical aspects of Nepalbhasa, which has laid the ground for further improvement through manual correction and continued retraining of the model.

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Design of Unmanned Aerial System for RF Source Localization

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Abstract

An unmanned aerial system (UAS) capable of radio frequency (RF) source localization is developed and tested to localize the LoRa transmitter. The proposed method employs a UAS equipped with RF receiver to obtain Received Signal Strength Indication (RSSI) readings from the RF source. The log-distance path loss model with Gaussian noise correctly models the distance variation in the observed RSSI readings. On a test domain of 100 meters radius, a trilateration-based localization algorithm executed on-board the microcomputer determines the position of the radio transmitter with an angular accuracy of 97.6 % and a distance error of 25 m. Achieving this directional accuracy at a single iteration is promising and paves the way for a practically realizable UAS-based autonomous solution for real-time localization of radio transmitters.

Key Words: RF source localization, Unmanned Aerial System, RSSI, Trilateration.

1. Introduction

The effectiveness of Unmanned Aerial Systems (UAS) has led to their applications in diverse fields. Notably, they have gained significant traction in search and rescue operations due to their ability to efficiently access remote and hard-to-reach locations that would otherwise be inaccessible or unidentified to immediate human responders. Radio-based localization proves advantageous in power consumption when compared to GPS in this regard since the radio signal source can operate for several months with minimal power consumption. Consequently, the work presented here focuses on localizing the target by utilizing the Radio Frequency (RF) localization technique, under the condition that the subject in search is equipped with an RF-transmitting device. The technique involves equipping the subject with an RF source, the strength of which is then utilized by the localization algorithm to determine the location of the subject. This paper employs a range-based technique that utilizes Received Signal Strength Indication (RSSI) measurements.

The process of localization relies on filtered RSSI values owing to its acceptable degree of accuracy and relatively lower complexity compared to other techniques. Furthermore, the RSSI-based method is regarded as the most cost-effective means of localization in outdoor settings. However, in indoor conditions, the performance of this technique is somewhat limited (Alippi, 2006). The practice of target localization has been extensively studied and applied using fixed reference nodes (Alippi, 2006). However, the current research seeks to extend the same methodology to UAS for enhanced target-tracking capabilities.

The UAS designed for this purpose has the following potential applications.

I. Search and rescue operations.
II. Emergency response for hazardous incidents.
III. Security and surveillance.
IV. Environmental monitoring and research.
V. Wildlife tracking and monitoring.

1.1 Localization Modality

RF based localization has a rich history, dating back to World War II when it was used to locate soldiers in emergency situations (Stella, 2012). Earlier approaches to sensing the RF signal were based on creating maps of the signal strength over the area by using mobile robots (Bahl, 2000). Different RF localization techniques have been studied including angle of arrival (AOA) (Hou, 2018), time of arrival (TOA) (He, 2014), time difference of arrival (TDOA) (Quitin), and received signal strength indication (RSSI) (Ismail, 2019), (Heurtefeux, 2012), (Jondhale, 2016). The accuracy of these methods depends on the target source being under the line of sight of the localizing system (Stella, 2012). This paper dives into RSSI-based target localization method.

RSSI is the cheapest and simplest technique for localization. While it can suffer from inaccuracy due to the reflection and attenuation of signals when impacted by the environment, the issue can be mitigated by implementing a more detailed physical model of the environment (Whitehouse, 2007).

1.2 UAS Development

1.2.1. Software Development

A MATLAB-based application is created to select drone components by taking input for the drone's weight, number of motors, and drone range required. The application is designed to provide the necessary propeller, motor, ESC and battery capacity for drone building. A database of motor static thrust ratings is kept, providing the necessary information on the propeller's pitch, and motor's KV rating. Using the input weight of the drone, the thrust per motor is calculated and then compared with the database's thrust values to select the appropriate motor and propeller. The database is created with the motors and propellers that are available in Nepal.

1.2.2. CAD Geometry

The drone proposed to be assembled is designed in CAD software CATIA V5 to understand the overall design and architecture.

Figure 1: CAD model of the drone

1.2.3. UAS Hardware

An X-type drone configuration consisting of four 980kv DC brushless motors is used. To vary the speed, four electronic speed controllers are present. Pixhawk 4 and Arduino Uno are used as the flight controller and the flight computer respectively. Other peripheral components and sensors include PM07, SX1278 LoRa transceiver, etc. To power all the components a 3-cell Li-Po battery is used. 10*4.5 propellers are used during the mission. GPS module and telemetry are connected to Pixhawk to provide the necessary data to control and perform the mission.

Figure 2: Developed UAS (Quad)

To perform the localization mission, an antenna and sensors are attached to the drone. After the assembly of the drone, control, stability as well as the performance of the drone are tested and the necessary modifications are done accordingly.

1.3 Hardware for Localization

1.3.1. LORA-ESP 8266 Transmitter

A prototype transmitting device was made with an SX1278 LoRa module, using ESP 8266 as a microcontroller. When the switch is turned on, the device starts transmitting “Help! Help!!” packets on the frequency band of 433 MHz, which is a license-free RF band for Asia. Despite a higher latency (of the order of seconds), the LoRa module is selected owing to its potential in large-range communication, which can particularly be helpful during search and rescue missions. It was tested for distances as large as 5 km, and still showed promise, though further investigation for localization was not undertaken (Poudel, Regmi, & Parajuli, 2023).

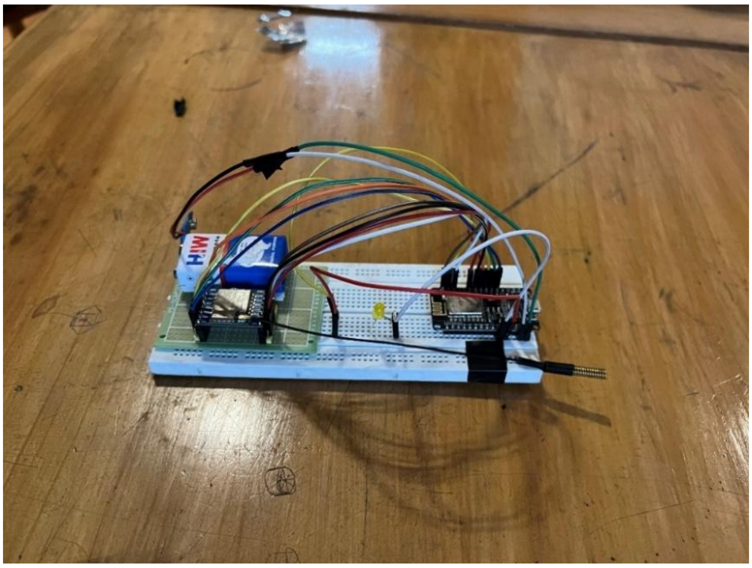

Figure 3: LoRa transmitter

1.3.2. LoRa-Arduino Receiver

It is a prototype receiving device with Arduino as a microcontroller. It is programmed to continuously receive the transmitted signals along with their RSSI, after syncing with the transmitter. Other peripheral sensors and devices like DHT 11 Temperature and Humidity sensor, and micro SD card module are also interfaced with Arduino.

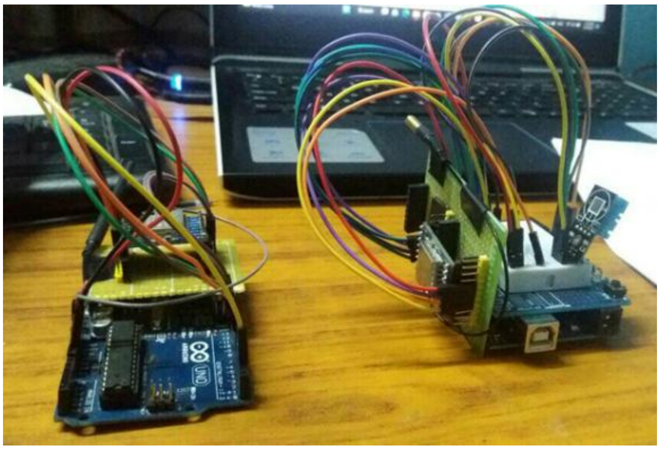

Figure 4: LoRa receivers

1.3.3. Sensing Modality

The sensing modality for 433 MHz radio signals consists of two modules:

1. The first module is an SX1278 LoRa transceiver which is connected to the antenna and can measure the RSSI of RF source. It communicates with the microcontroller module with a Serial Peripheral Interface (SPI).
2. The second module is the microcontroller module, which is the Arduino. It reads the values of RSSI from the RF module, processes them, and runs the localization calculation, and sends the localized coordinates to the ground station. The ground station then gives the coordinates to the Pixhawk through Ground station controlling software. The proposed sensing modality is shown in
3. Figure 5.

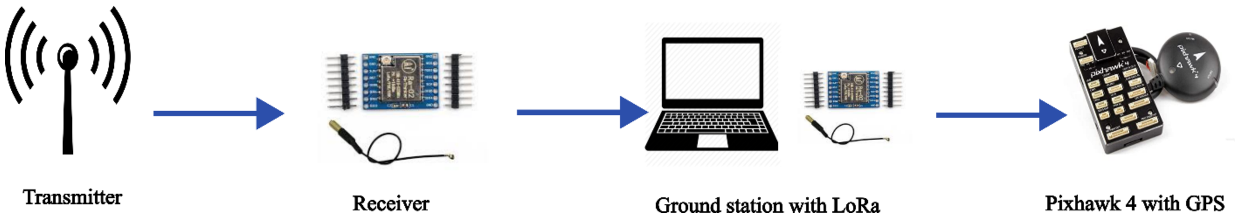

Figure 5: Sensing modality for 433 MHz

1.4 Localization Modelling

The objective of this work is to use a UAS to localize a stationary RF transmitter to the best possible accuracy. It aspires to attain reliable positioning accuracy with a single UAS by discarding inaccurate RSSI measurements and identifying the most accurate ones. RSSI measurements in UASs vary due to various elements such as structures, trees, wind, speed of the vehicle, etc.

As a result, a localization technique based on several sample measurements is required. As the position of the UAS in space will be known, a model is necessary to obtain the distance of the UAS from the transmitter to further proceed with localization. As we will be receiving radio frequency signals, a distance conversion model based on the Received Signal Strength Indicator (RSSI) values is selected.

1.4.1. RSSI Based Localization

RSSI values are the measure of the power of received radio signals measured in dBm. In RSSI-based localization, a receiver will measure the RSSI values of the signal transmitted by the transmitter. When RSSI values are measured at three known locations, those values can be translated into the distance values based on some signal propagation model. Then, we will have a system of three non-linear equations, which are linearized and solved to obtain the transmitter coordinates. The flowchart for RSSI-based localization is shown in Figure 6.

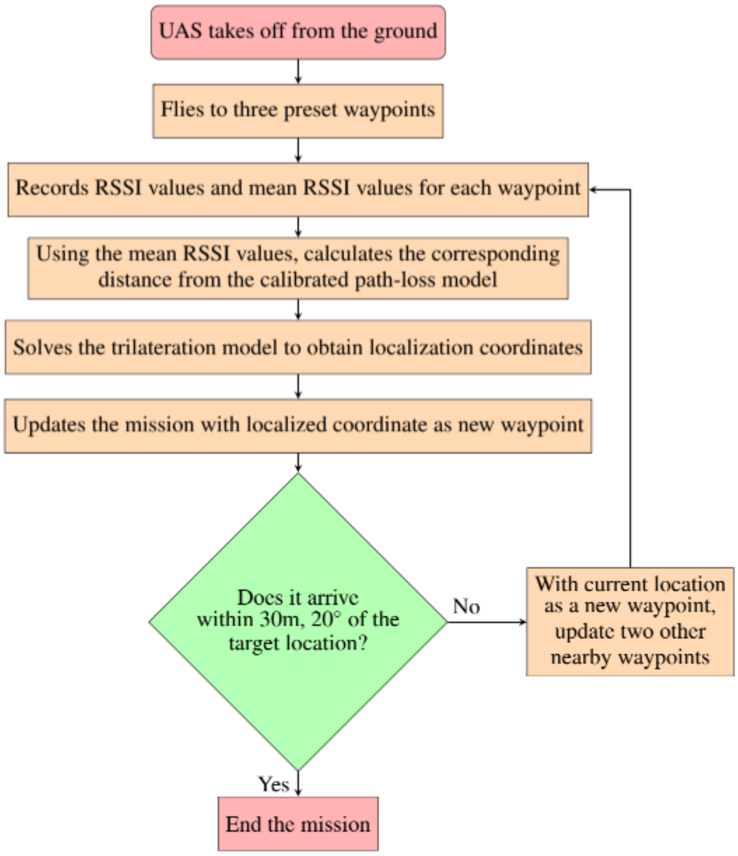

Figure 6: RSSI based Localization

1.4.2. Distance Estimation Model.

RSSI values, which are measured in dBm, give the power of the received signals as the signal propagates from transmitter to receiver. As the signal power decays with distance, RSSI values can be used to infer the proximity between the receiver and transmitter by approximating the distance between them. One of the most widely used distance estimation models for radio wave propagation is the log-normal model (Rappaport, 2002) given by the equation as:

$$PL(d) = PLd_0 + 10n\log_{10}\frac{d}{d0} + X_\sigma$$

Here, PL(d) is the path loss at a distance d, d0 is the reference distance, PLd0 is the experimentally measured average path loss at d0, and n is the path loss index. X(σ) is the Gaussian distributed random variable with mean, μ = 0, and some finite value of the standard deviation, σ.

The equation in terms of RSSI can be written as:

$$RSSI = RSSI_0 - 10n\log_{10}\frac{d}{d0} - X_\sigma$$

The effect of X(σ) can be removed to some extent by filtering. If we neglect X(σ), and take the reference distance d0 equal to 1 meters then, equation becomes.

$$RSSI = RSSI_0 - 10n\log_{10}(d)$$

RSSI0 can be experimentally determined and the value of n can be computed by minimizing the sum of squares.

$$f = \sum (RSSI - RSSI_0 + 10n\log_{10}(d))\hat{}2$$

Here, f is the function to minimize. Then, the distance between the receiver and the transmitter can be approximated by

$$d = 10^{\frac{RSSI_0 - RSSI}{10n}}$$

1.4.3. Trilateration Model

The trilateration model aims to calculate the localized transmitter coordinates based on three known measurement coordinates and the approximated distances of those coordinates from the transmitter.

$$(x - x_1)^2 - (y - y_1)^2 = {d_1}^2$$
$$(x - x_2)^2 - (y - y_2)^2 = {d_2}^2$$
$$(x - x_3)^2 - (y - y_3)^2 = {d_3}^2$$
$$Ax = B$$
$$x = A^{-1}B$$

Where,

$$A = \begin{bmatrix} 2(x_1 - x_2) & 2(y_1 - y_2) \\ 2(x_1 - x_3) & 2(y_1 - y_3) \end{bmatrix}$$

$$B = \begin{bmatrix} r_2^2 - r_1^2 + x_1^2 - x_2^2 + y_1^2 - y_2^2 \\ r_3^2 - r_1^2 + x_1^2 - x_3^2 + y_1^2 - y_3^2 \end{bmatrix}$$

$$x = \begin{bmatrix} x \\ y \end{bmatrix}$$

It is based on simple matrix operations and is basically converting a system of three non-linear circle equations into a linear form as in the equation (Ax=B) and solving for matrix, x, which contains the co-ordinates of the localized transmitter. Note that due to the presence of measurement noise and the inherent uncertainty in real-world data, there is often no solution that satisfies all three equations simultaneously. Therefore, the solution is obtained by computing pseudo-inverse which provides a best fit solution by minimizing the sum of squared residuals.

1.4.4. Conversion to Geographical Coordinates

Conversion of the localized Cartesian coordinates into geographical coordinates is necessary in order to command the UAS to fly to the localized GPS location. Calculation of the latitude and longitude of the localized coordinate given the latitude and longitude of the reference point and the distances east and north of the reference point is given by:

$$latitude = latitude_{ref} + \frac{y}{earth'sradius} \times \frac{180}{\pi}$$

$$longitude = longitude_{ref} + \frac{y}{earth'sradius} \times \frac{180}{\pi} \times \frac{1}{\cos(latitude_{ref})}$$

The formula is based on the principles of spherical trigonometry. It assumes a spherical Earth, which is an approximation that works well for small distances. It is commonly used in geodesy and navigation and is often implemented in software libraries and programming languages. The Cartesian coordinate system is fixed in such a way that the X-axis and Y-axis are directed towards east and north respectively, such that when localized Cartesian point (x,y) is obtained with respect to the reference point (0,0), values of x and y can be directly implemented in the coordinate transformation formula.

2. Results

2.1 Experimental Setup

An experiment was conducted using a drone equipped with the localization algorithm hardware at Pulchowk Cricket Ground. The mission involved creating axes for target localization. To conduct the mission, the creation of a coordinate system, calibration of RSSI value with distance and the mission flight itself was required.

2.1.1 Coordinate System

The coordinate system used for the mission was different than that of the algorithm verification. To find the coordinates of the three positions, they were marked. The origin was placed at the geographic coordinates of (27.6831534, 85.3221424) which was also the starting point of the mission flight path. The other two positions were kept at the north and east axis with coordinates of (27.6836279, 85.3221545) and (27.683138, 85.3224484) respectively. The geographical coordinate system was converted to a Cartesian Coordinate system, where the north point and the east point had the coordinates of (0,50) and (30,0) respectively.

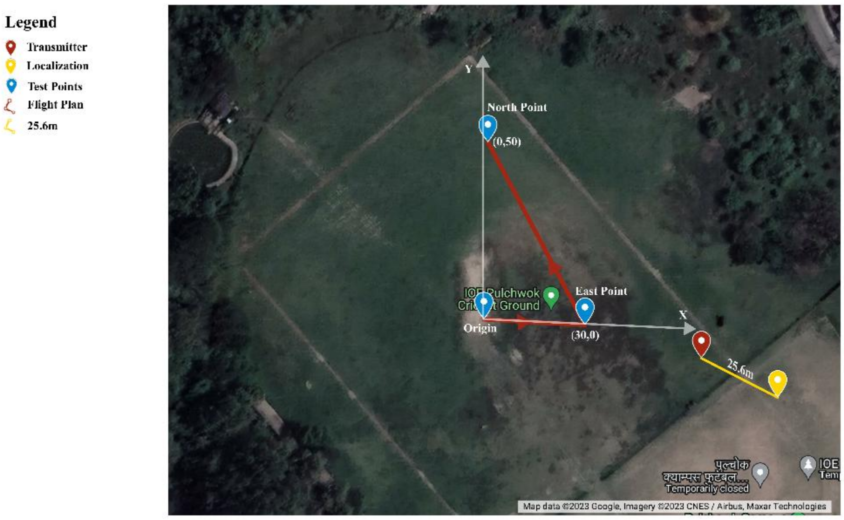

Figure 7: Coordinate System

2.1.2 Calibration

To accurately fit the log-distance path loss model for the testing environment, calibration flight was carried out by continuously measuring RSSI values at different distances from the transmitter. The measured values were extremely noisy ($\sigma \approx 5$), so the noisy signals were filtered using the Kalman filter. For the comparative results between using simple moving average (SMA), exponential moving average (EMA) and Kalman filter, see (Poudel, Regmi, & Parajuli, 2023). It was observed that the Kalman filter has low responsiveness to fluctuations and gives a smooth fit to the noisy signal data and was used for signal filtering.

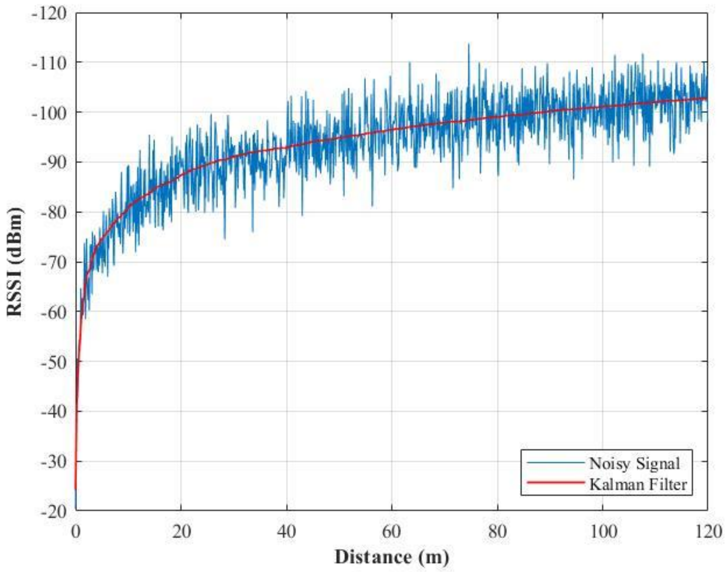

Figure 8: Noisy signal filtered out for calibration

The log-distance path loss model is then fitted to the filtered values. It shows that the model almost perfectly fits the filtered values, with RSSI0 = -59.1 and n = 2.1.

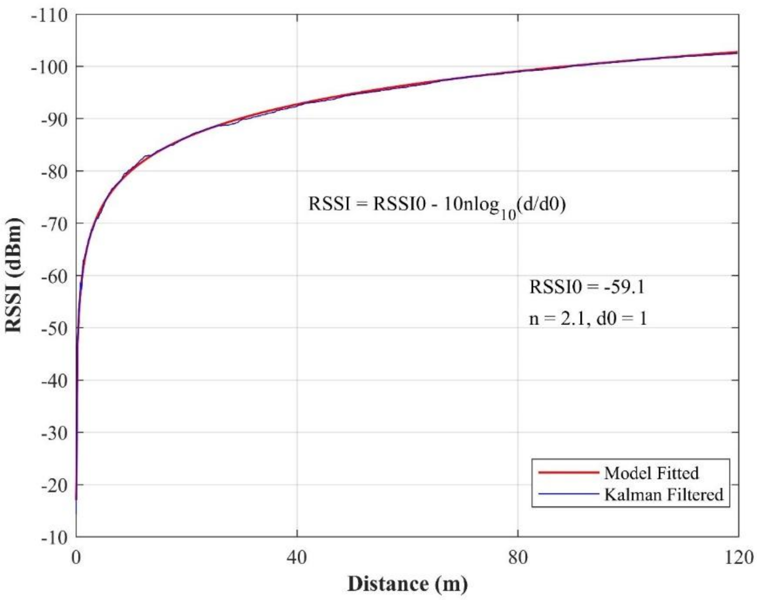

Figure 9: Fitted log-distance path loss model

2.1.3 Mission Flight

The mission flight was planned in the QGroundControl application using the three positions as waypoints in the coordinate system. The flight altitude was set to 3 m from the ground, and the flight speed was selected as 5 m/s. At each waypoint, the drone hovered for 25 seconds to acquire data on RSSI values. After obtaining the mean RSSI value at 63 the third position, the drone landed there, and the localized coordinates were provided to the ground station. Another mission was then planned to the localized position using the obtained geographical coordinates.

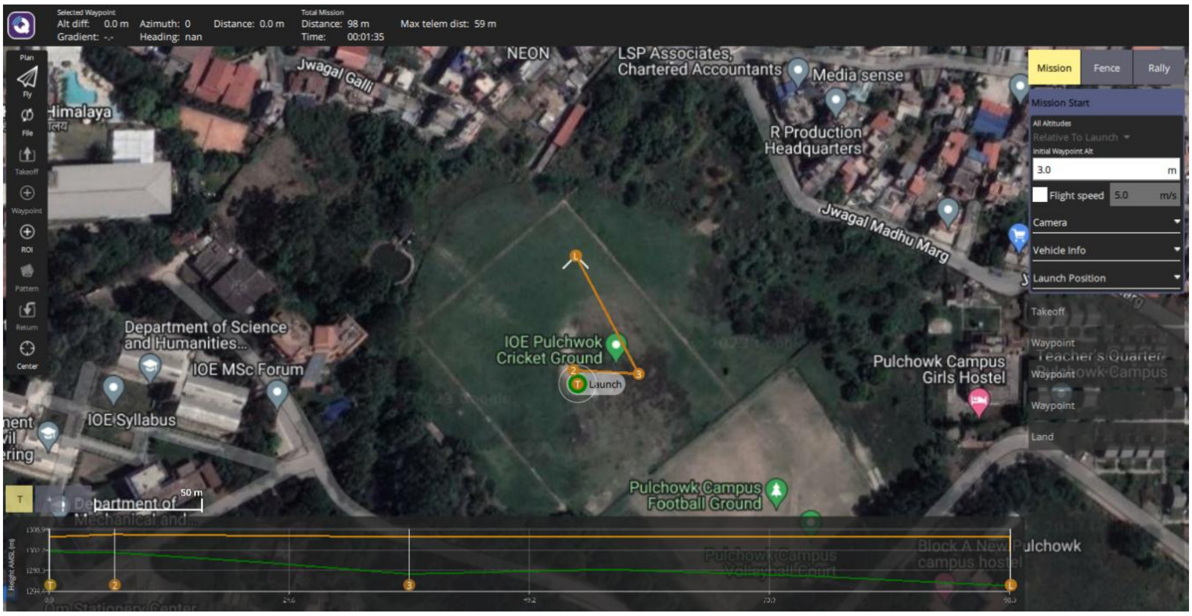

Figure 10: Main Mission flight plan

2.2 Result and Analysis

The mean RSSI values received at the three waypoints are shown in Table 1. Using the calibration of RSSI values with distance, the corresponding distance for each RSSI value was calculated by the on-board computer, which then performed the trilateration calculations, and provided the localized latitude and longitude to be (27.682944, 85.323031). The localized point was 25.6 m from the target source, but the angular error was only 8.32 degrees with respect to the origin. This translates to a remarkable angular accuracy of 97.6 %.

Table 1: Mean RSSI received at different co-ordinates

Coordinate	RSSI (dBm)
(0,0)	-97.93
(30,0)	-88.51
(0,50)	-101.02

Table 2: Localization results obtained from the experiment

Test	Localized Cartesian X	Localized Cartesian Y	Localized Geographical (°) Latitude	Localized Geographical (°) Longitude	Distance Error (m)	Angle Error (°)
1	87.62	-23.36	27.682944	85.323031	25.6	8.32

The results from the main mission show that the transmitter is localized within the desired minimum distance error of 30 meters with respect to its actual position and 20◦ with respect to the origin. The results could have been even better if not for the GPS offset at measurement locations, which was showing errors as high as 5 meters.

2.3 Limitation

Considering the primitive level of the system developed with its research and development at Pulchowk Campus being at an early phase, the acceptable error tolerance was set as 30 meters within an angular accuracy of 15 degrees for the test domain of 100 meters radius. Given this, the developed system localized the transmitter to an acceptable level of accuracy. However, the system has some important limitations offering a scope for future enhancement. The limitations of the developed system are listed below:

- It will only be capable of locating a stationary transmitter source that emits radio signals with constant power.
- The proposed localization modality is affected by multi-path and signal fading.
- It is based on the assumption that the transmitter is perfectly omnidirectional.

2.4 Future Improvements

The project offers several rooms for enhancements in the future. One of the immediate actions would be to incorporate the directional antenna into the system and develop a corresponding localization algorithm based on RSSI and Angle of Arrival data. This will increase the accuracy, as well as reduce the localization time. If accuracy becomes the major concern, and not the resources, then employing multiple UAS systems that communicate with each other in real-time, instead of just one, will help develop a high fidelity localization scheme. The project, currently, employs the deterministic model for localization purposes, i.e., you measure the RSSI, translate to distance, use trilateration and locate the source. In the bigger picture, it can be enhanced into the probabilistic model in the near future, which, contrary to what the name suggests, is expected to be more accurate, as it will be based on real-time iterative path planning.

3. Conclusions

UAS system, with underlying tools, techniques, and capabilities for the localization of radio frequency sources for outdoor environments, is presented. Using mean RSSI values at each measurement point, the UAS, in its final test mission, localized the transmitter with a distance error of 25 meters, and an angle error of 8 degrees. As the acceptable level of accuracy was set at 30 meters within the angular accuracy of 15 meters, the results are accepted. It is clearly understood that RSSI-based localization, despite being simple, is highly affected by weather conditions and environmental dynamics. Therefore, it is prone to inaccuracy and requires extensive testing for calibration. Therefore, it is recommended to measure the reference values before each flight.

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The Framework of Metro Rail Development in the Greater Kathmandu Valley, Nepal

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Abstract

The greater Kathmandu Valley is in urgent need of comprehensive urban development and an integrated transport plan with a metro rail system at its core. The infrastructure development projects in Nepal, such as the Kathmandu Metro rail, have been stalled for years and have not progressed beyond a few feasibility studies. These studies are also confined to the core city areas. Such slowness and confinement are due to the government's lack of vision and understanding of the metro rail project's capability to regenerate the valley and drive the nation's economy. In this paper, a framework of metro rail development in the greater Kathmandu Valley is presented. Such a framework would help maximise the benefit of the project for both the capital and the country. A framework comprising of the following components is proposed: (a) mobility and connectivity, (b) Integrated transport, (c) open space, green space and underground space, (d) urban regeneration and creation, (e) economic growth, (f) culture and heritage. These components are elaborated upon in detail, along with examples, in this paper.

Key Words: Kathmandu valley, metro rail, urban development, development framework.

1. Introduction

Greater Kathmandu Valley is among the most rapidly urbanising agglomerations in South Asia. The current population of the GKV, including the floating figure, is estimated to be about 5 million. The valley is the country's prominent economic hub. It contributes about one-fourth of the national GDP (JICA, 2016). According to the Economic Survey Report of the Ministry of Finance, it is forecasted that by 2030, the KV will contribute one-third of the national GDP.

Urban planning in the Kathmandu Valley has suffered from haphazard development over the last 70 years. This has resulted in the depletion of fertile land and public open spaces, an increase in air pollution, and a lack of transport connectivity and mobility. The valley's public transports are left unmanaged. All urban roads are heavily congested. In 2012, the government conducted a feasibility study on the metro rail within the Ring Road, with support from the Korean government (Gov 2012). There were a few other transport studies carried out by the institution, such as those by ADB and the World Bank, including 'KSUTP 2018'. However, neither of these studies materialised to introduce a mass transit system in the valley, nor did they look into a holistic urban development perspective of the region, including transport measures. In 2021, approximately 1.5 million vehicles were expected to be on the roads of the valley, and data shows that about 200,000 vehicles are added to the region every year. The valley has become one of the most polluted cities in Asia. The transport sector is a major contributor to air pollution (Regmi et al., 2022).

Many monuments and historical settlements have been defaced, degraded, and lost their charm due to disregard for cultural and heritage values during the planning and construction of new infrastructure and haphazard urban sprawl.

To enhance mobility and connectivity in the region, decrease air pollution, rehabilitate the historic value, drive economic prosperity of the nation, and keep the valley and capital city fit for the 21st century, the region needs regeneration through the introduction of a mass rapid transport system, such as a modern electrified metro rail.

2. Metro Rail Development Framework

Metro rail is not only a means of transportation but also a tool of urban planning. Integrated transport, with metro rail at its core, could transform connectivity and mobility in the region. This will drive economic prosperity by unlocking homes, jobs, skills and a better community and environment. Therefore, the development of metro rail needs a framework to maximise its benefits. A framework comprising the following components is proposed:

- Mobility and connectivity
- Integrated transport
- Open and green space and underground space
- Urban regeneration and creation
- Economic growth
- Culture and heritage

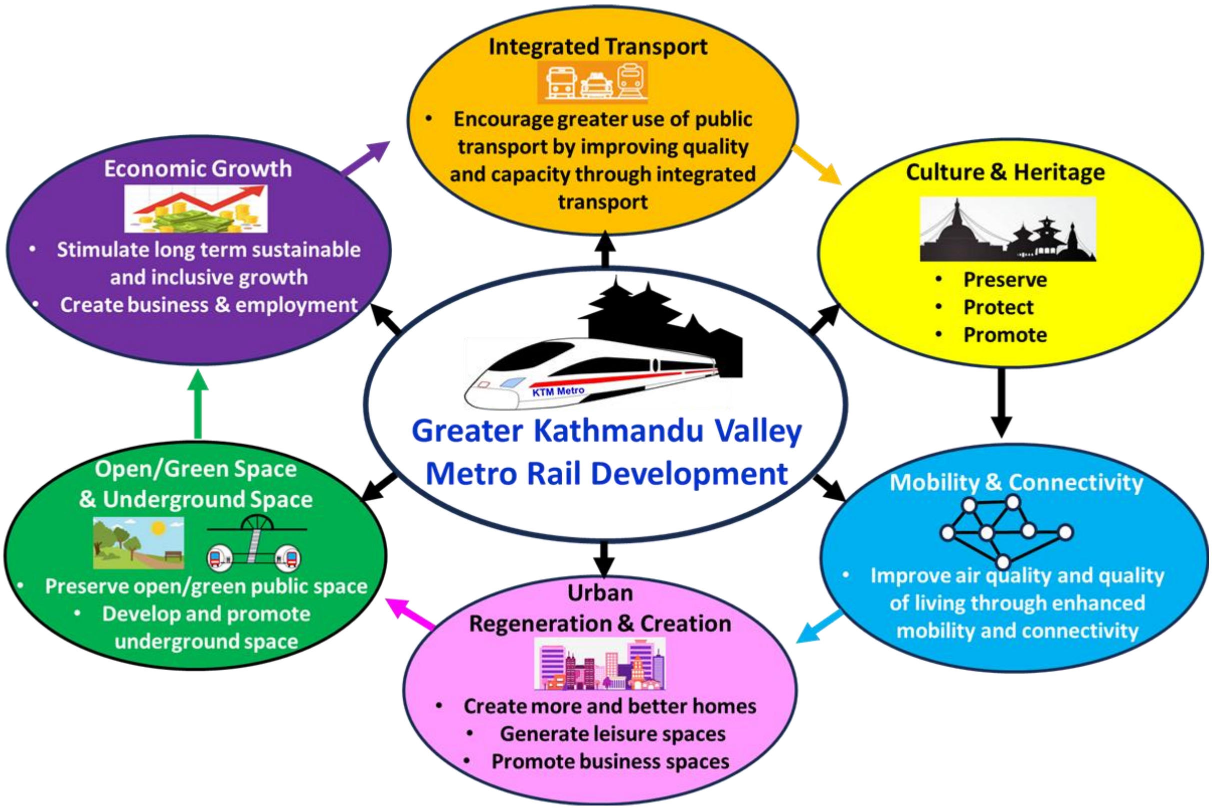

Figure 1: Greater Kathmandu Valley Metro Rail Development Framework

2.1 Mobility and Connectivity

The author dreamt of modern KV along with metro rail and published his proposal of metro rail development in the KV region for the first time in 2012, which was published in the Kathmandu Post entitled ' Kathmandu's metro dream (Amatya, 2012). His study of metro development continued. A revised version of the metro network with additional connectivity was published in 2017 (Amatya 2017) as a conceptual plan for the metro rail in the valley. In this paper, the proposed network is presented as a guiding framework (a Yantra) for mobility and connectivity of the valley and beyond. Refer to Figure 2. A proposed rail network with a total length of 192.5km and comprised of the following five lines:

- Kathmandu line (East-West line/Blue line)
- Patan line (North-South line/Green line)
- Bishnumati line(North-South line/Black line)
- Chakrapath line (Inner orbital line)
- Valley line (Outer orbital line)

Such a network would integrate 18 municipalities in the valley, providing easy connectivity to all municipalities of the GKV, core areas, important tourism destinations, pilgrimage sites, economic hubs, and satellite cities. A study conducted by ADB in 2018 revealed that introducing a metro rail in the KV would absorb approximately 25% of total trips (KSUTP, 2018). That means more mobility on existing surface modes of transport, such as buses and taxis, while offering mass transit facilities. A comparison of travel time with and without metro rail is shown in Figure 3. In addition to improved mobility, such development would also lead to enhanced air quality and a higher quality of life in the region.

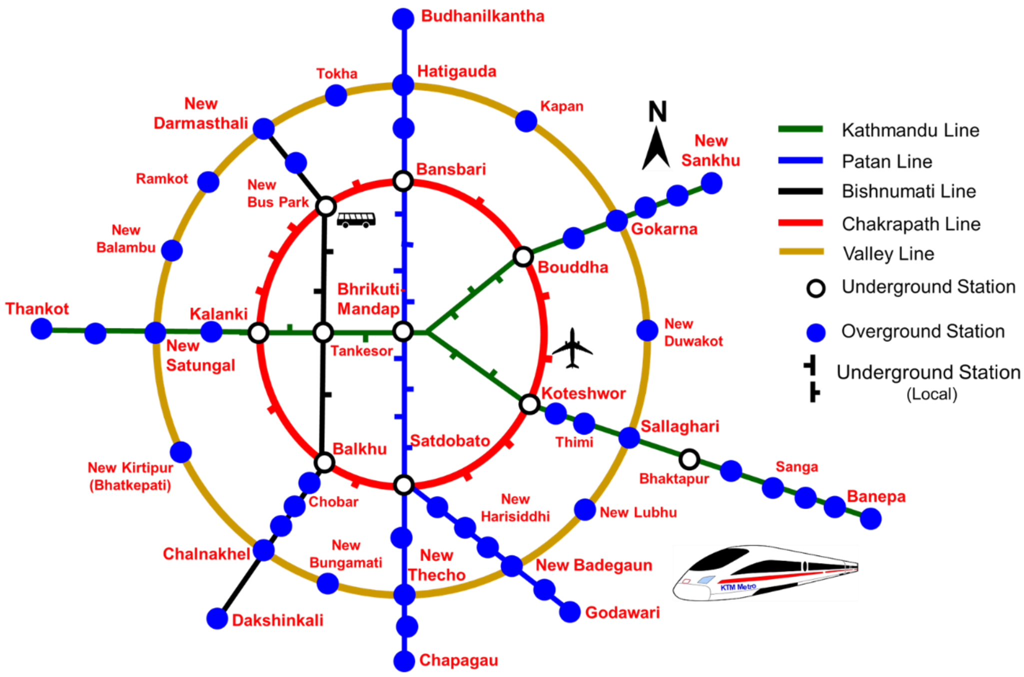

Figure 2: Proposed Idealised Kathmandu Valley Metro Rail Network (Amatya, 2017)

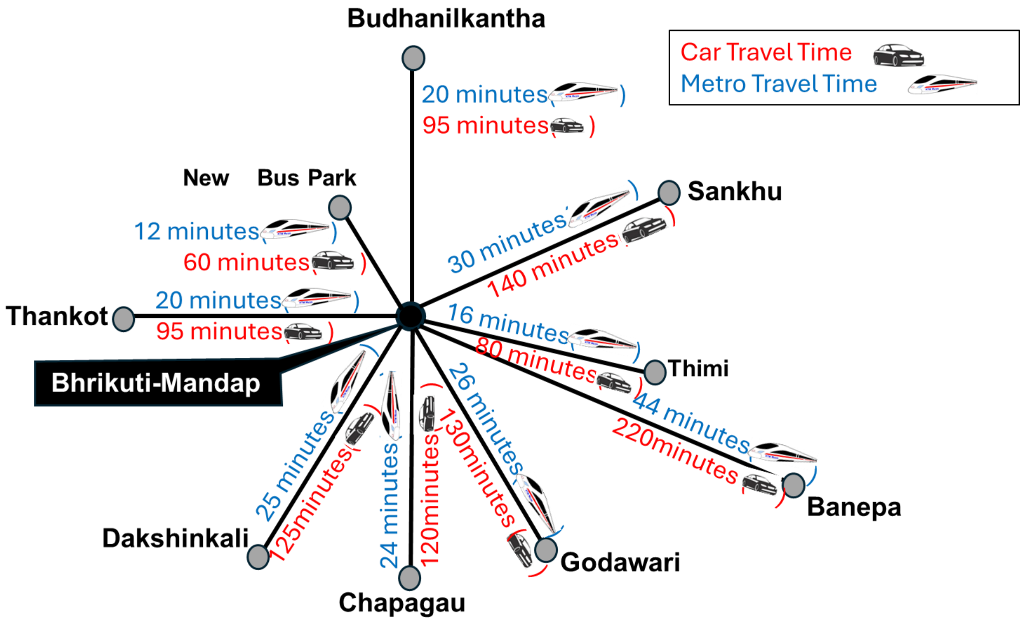

Figure 3: Comparison of estimated travel time with and without metro

2.2 Integrated Transport

An integrated transport network with a metro rail system at the core is proposed. It will create the option of last-mile connectivity from and to the metro station, thereby generating more metro users. Such a network will encourage greater use of public transport by improving quality and capacity, utilising various transport modes as feeders to each other. An ideal integrated transport system combines the following modes, as illustrated in Figure 4.

- Walking
- Cable car/ Podway
- National Rail
- Airport
- Bus
- Taxi
- Cycling
- Wheel chair

For integrated transport, following initiatives are recommended:

- Park and ride facilities
- Bike ride scheme
- Cable car/podway at the outskirts of the KV
- Single transport authority

Integrated metro stations offer a range of services, including ATM facilities, food outlets, cafes, hotels, apartments, and convenience stores. An integrated transport network would provide easy access to urban utility facilities, including hospitals, colleges, schools, museums, stadiums, hotels, tourism spots, cultural and natural heritage sites, and other key destinations. It would also bring more regional connectivity through transport corridors.

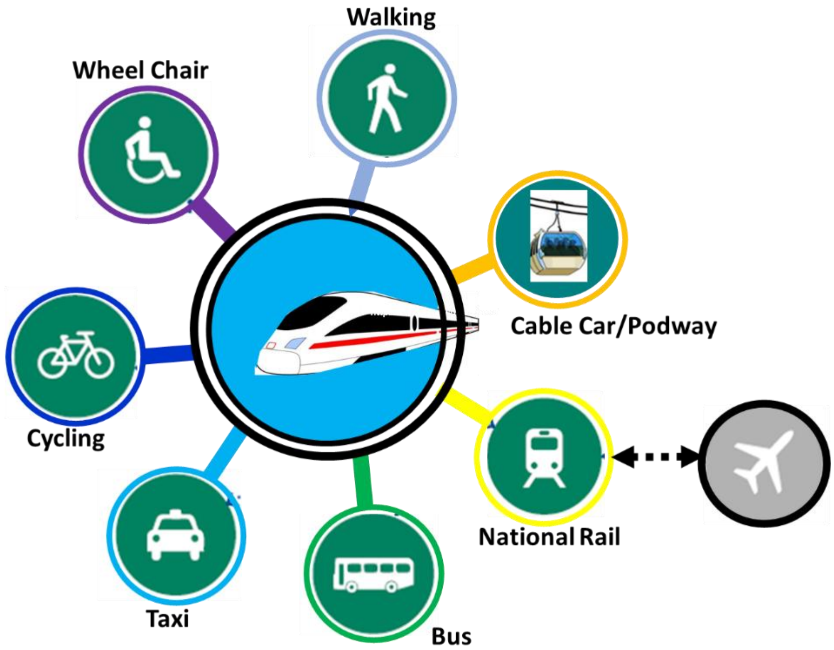

Figure 4: Integrated transport with metro rail at the core

2.3 Open and Green Space and Underground Space

Land use change and metro rail transport planning must work together. While introducing metro rail infrastructure in the valley, the following fundamental guiding principles are proposed:

- Preserve existing open/green public space, fertile land
- Create new open, free and green spaces and
- Develop and promote the use of underground space for metro routes, stations and car parking

The author proposed a major underground metro rail junction at Bhrikuti Mandap Park in Central Kathmandu City. Such imagination is illustrated in Figures 5 and 6. The proposed network, as shown in Figure 2, comprises an 85 km tunnel network and 39 underground stations to connect core urban spaces effectively.

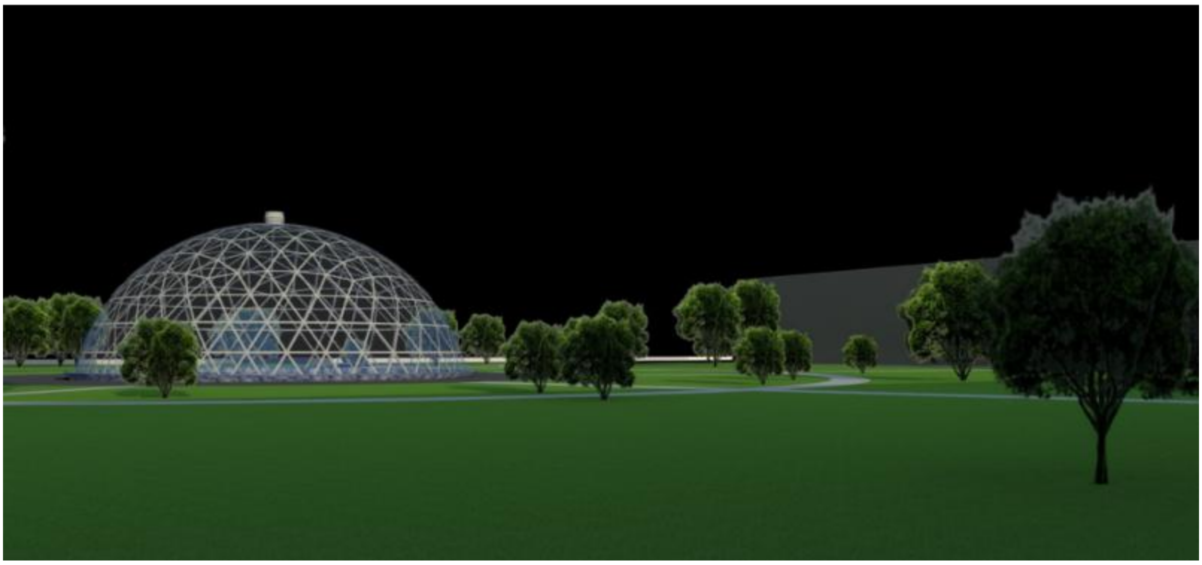

Figure 5: Imagination of underground metro station in Bhrikuti-Mandap park (Sharma 2019)

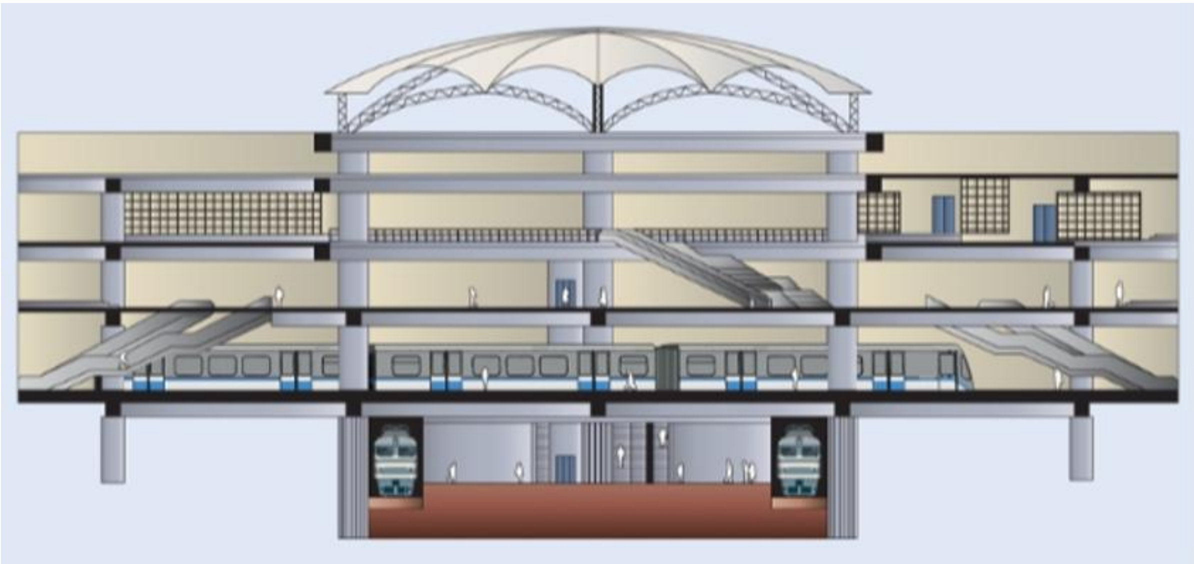

Figure 6: Imagination of Underground Bhrikuti-Mandap Junction (Sharma 2019)

2.4 Urban Regeneration and Creation

Metro rail development should be coupled with an urban regeneration program to unlock additional value in the already-built environment. Stations could work as multimodal nodes, which could boost the local economy by bringing together retail, leisure, and commercial activities in one place, as well as promoting the regeneration of the larger area. For regeneration, the following interventions are proposed:

- Maximise the use of land by high-rises, house pooling
- Create a mini-business hub around the metro station
- Provide easy access to prominent spots in the area
- Develop underground parking facilities
- Integrate metro stations with other modes of transportation
- Protect, preserve and promote religious/cultural site

The connection of future smart cities with a metro rail network would help tremendously in the success of such town planning efforts, creating more and better homes. This will generate a good traffic volume for the metro line to run sustainably as well. It is proposed to develop urban amenities, such as international exhibition and convention centres, sports hubs, IT parks/Industrial zones, and amusement parks, in the outskirts of the valley. These amenities are to be connected to central Kathmandu and other hubs by metro lines.

Metro rail development should be strategic and coordinated with a comprehensive urban planning and design process to maximise benefits and steer sustainable change in land use. The author's imagination of how the Lagankhel area of Patan could be regenerated with the arrival of an underground metro station is presented in Figure 7.

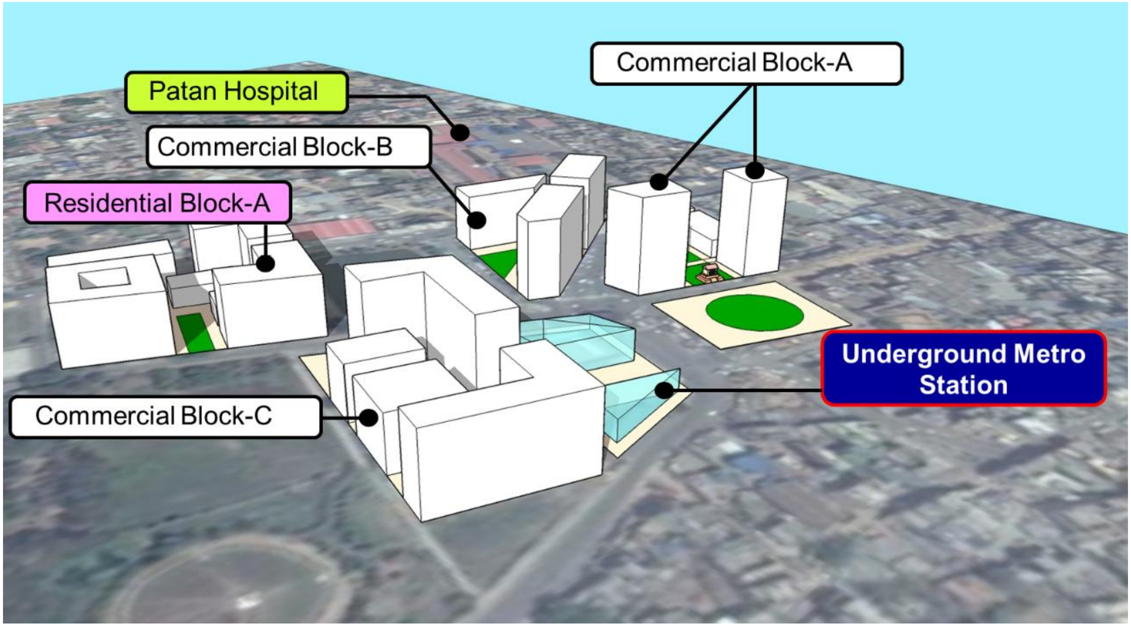

Figure 7: Urban regeneration (Amatya 2017)

2.5 Economic Growth

Kathmandu Metro rail project should be planned and developed in such a way that it:

- Stimulates long-term sustainable and inclusive growth and
- Creates business and employment opportunities.

Carrying out urban regeneration and urban design while planning metro rail routes and metro stations could unlock thousands of homes and hundreds of commercial units. It will create thousands of jobs during the design, construction and operation stages. For example, it is estimated that operating a 62.5km long metro line (Kathmandu Line and Patan Line) alone could generate 3,500 new railway operation jobs. In addition, it will create thousands of other jobs through the supply chain and growth around stations and regeneration. This will give people opportunities to upgrade or enhance their skills and workmanship.

Connectivity will offer the distribution of opportunity to a broader area and community. Better homes, jobs and skills mean a better community and environment. A cleaner environment means a healthy society and a healthy workforce.

2.6 Culture and Heritage

The World Heritage sites are scattered throughout the KV, and there are numerous monumental heritage sites and venues for cultural and art shows and festivals. Therefore, planning modern urban infrastructure and urban regeneration programmes such as metro rail needs advanced planning and needs to adopt the following principles:

- preservation
- protection and
- promotion of culture and heritage, as well as ancient settlements and monuments along the route and within the development zone of influence.

For example, while carrying out urban regeneration programmes in the Lagankhel area, shown in Figure 7, the importance of protecting, preserving, and promoting the heritage sites in the area, such as the Sapta-Patal area and Ashok Stupa, is highlighted. Refer to Figure 8.

Therefore, it is recommended to investigate the following types of heritage along the proposed routes, around the proposed metro stations and proposed regeneration areas:

- Intangible heritage
- Historical landscapes
- Historical buildings
- Archaeology
- Natural heritage

Figure 8: Presevation and promotion of Saptapatal Pokhari and Ashok stupa while regenerating Logankhel (Manandhar 2023)

3. Conclusions and Recommendations

The urban landscape of Kathmandu Valley has suffered from haphazard development for decades. Public transport in the region is left unmanaged. The valley is in urgent need of an electrified metro rail system to improve public transport, regenerate the area, and keep the valley fit for the 21st century. Metro rail is not only a means of transportation but also a tool for urban planning and design.

Integrated transport with metro rail at the core could transform the connectivity and mobility in the region. This will drive economic prosperity by unlocking homes, jobs, skills and a better community and environment. To maximise the benefits of such a transport system, a framework for metro rail development is recommended. A framework comprising the following components is proposed (a) mobility and connectivity, (b) Integrated transport, (c) open space, green space and underground space, (d) urban regeneration and creation, (e) economic growth, (f) culture and heritage.

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Ventilation System in Road Tunnel of Nepal

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Abstract

Road tunnels are integral to Nepal's evolving transportation infrastructure, enhancing connectivity across its mountainous terrain. This study examines the critical role of ventilation systems in ensuring air quality, safety, and visibility within tunnels, with a focus on Nepal's pioneering Nagdhunga Tunnel. Ventilation strategies longitudinal and transverse systems are analysed for their efficacy in mitigating pollutants and managing emergencies. Longitudinal ventilation, utilizing jet fans, is highlighted for its cost-effectiveness and adaptability, particularly in high-altitude environments like the Nagdhunga road tunnel, where reduced air density impacts fan performance. Transverse systems, while effective in smoke extraction during fires, face constraints in Nepal's space-limited, ecologically sensitive regions. The Nagdhunga case study reveals that hybrid or adaptive designs, informed by altitude-specific engineering, are vital for balancing safety, cost, and environmental compliance. However, the study's reliance on pre-construction data and geographic specificity limits broader applicability, underscoring the need for post-construction monitoring. As Nepal expands its tunnel network, integrating global best practices with localized solutions such as portal air management and stack emissions will be pivotal. This paper contributes to the discourse on sustainable tunnel ventilation in high-altitude regions, offering insights for future projects facing similar climatic, topographic, and regulatory challenges.

Key Words: Tunnel safety, Ventilation system, Jet Fan, Air Quality.

1. Introduction

Road tunnels are enclosed vehicular pathways designed with controlled entry and exit points. In Nepal, such tunnels enhance transportation efficiency by facilitating seamless connectivity between major urban centres (Joshi, 2000). To ensure safety, these tunnels incorporate ventilation, lighting, and interior finish systems, considering factors like tunnel length, traffic volume, and design speed (Bassan, 2016). Among these, ventilation systems play a critical role in mitigating pollutants from vehicle emissions, safeguarding users and maintenance staff from health risks, and preserving visibility within the tunnel environment (Mashimo, 2002). By effectively dispersing toxic gases and particulate matter, these systems ensure both air quality and driver safety are maintained throughout the tunnel's operation.

1.1 Ventilation during Normal Condition

In normal traffic conditions, maintaining air quality standards in tunnels requires the dilution of vehicle-generated pollutants with fresh air. The volume of pollutants produced depends on individual vehicle emission rates, which are influenced by factors such as vehicle type, age, driving patterns, e.g., acceleration, idling, and road slope. Modern vehicles, benefiting from advanced emission-control technologies, generally emit fewer pollutants per kilometre travelled.

Global initiatives to decarbonize transportation have accelerated the adoption of vehicles using alternative energy sources, such as electric, hydrogen fuel cell, and hybrid systems, as well as alternative fossil fuels like compressed natural gas (CNG) and liquefied natural gas (LNG) (PICAO, 2012). Despite this progress, these low-emission vehicles currently represent a small proportion of total traffic. Consequently, their impact on reducing in-tunnel pollution levels remains marginal, with conventional internal combustion engines still dominating emissions contributions (Wang *et al.,* 2020).

1.2 Ventilation during Incidents

During fire incidents involving smoke, tunnel ventilation systems are critical for mitigating risks to occupants and responders (Ren *et al.,* 2019). Their operational goals evolve across two key phases:
Initial Fire Stage (Self-Rescue Phase):
The primary focus is maintaining smoke-free escape routes to enable safe self-evacuation. Ventilation strategies aim to limit smoke infiltration into exit pathways.
Emergency Response Phase:
Once professional responders arrive, the system transitions to supporting firefighting and rescue operations, e.g., controlling smoke spread to protect evacuation corridors or creating safe zones for intervention (Barbato *et al.,* 2014).
Detailed design criteria (e.g., airflow rates, fan configurations) and incident-specific operational protocols (e.g., smoke extraction sequences) fall outside the scope of this analysis.

2. Tunnel Ventilation Systems

Ventilation systems are typically defined by the method of air movement within the tunnel and the direction in which the air is directed concerning the tunnel's axis. Longitudinal ventilation, in its most basic form, involves the introduction of fresh air at the entrance portal and the expulsion of exhaust air at the exit portal. In contrast, transverse ventilation operates on a similar principle of dilution and removal as longitudinal ventilation; however, it facilitates the supply of fresh air and the extraction of exhaust air across the width of the tunnel (i.e., transversely) *(*ACTAQ, 2014*).*

2.1 Longitudinal Ventilation System

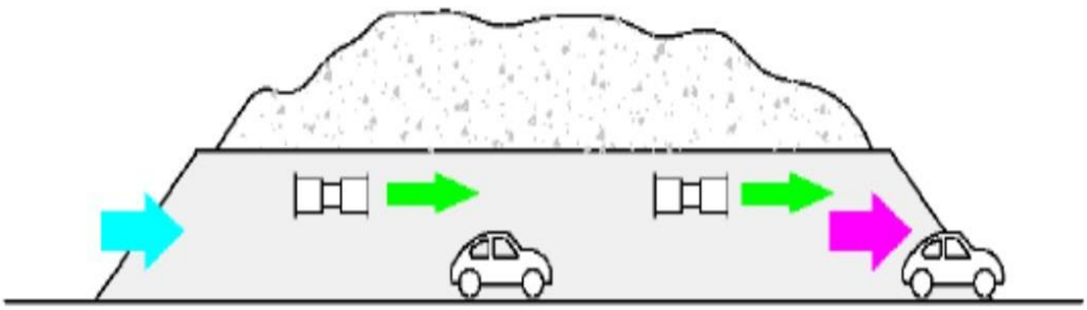

Figure 1: Longitudinal ventilation with jet fans (PIARC, 2011)

*Table 1: Comparison between Longitudinal Ventilation (*ACTAQ, 2014*)*

Aspect	Standard Longitudinal Ventilation	Longitudinal Ventilation with Portal Air Extraction
Airflow Mechanism	Air flows from entry to exit portals via jet fans and piston effect (strong in unidirectional traffic).	Adds **stacks** to extract air partially or fully, reducing reliance on exit portals.
Pollutant Distribution	Pollutants peak at exit portal, increasing from inlet to outlet.	Pollutants diverted to stacks, reducing emissions at portals. Full extraction eliminates portal emissions.
Emissions Control	Emissions exit through portals, affecting air quality within 100–200 meters.	Stacks reduce/eliminate portal emissions, ideal for urban areas with strict air quality standards.
Fire Safety & Smoke Management	Smoke travels to exit portal; requires short evacuation routes and speed limits (8–10 m/s).	Similar smoke behavior (exits via portals unless stacks are retrofitted for emergencies). No inherent smoke extraction.
Infrastructure Complexity	Simple: relies on jet fans, portals, and natural piston effect.	More complex: requires stacks, ducts, and additional equipment for air extraction.
Energy Consumption	Moderate: depends on jet fan usage and traffic-driven piston effect.	Higher: stacks require constant energy, especially during full extraction. Inefficient in low-traffic conditions.
Typical Applications	Shorter tunnels or those with moderate traffic (constrained by velocity limits).	Urban tunnels where portal emissions are unacceptable. Suitable for projects prioritizing local air quality.
Regulatory Compliance	Complies with velocity limits (8–10 m/s) for fire safety.	Meets stricter urban emission regulations but may face energy efficiency challenges.
Cost Implications	Lower initial and operational costs.	Higher upfront (stack infrastructure) and operational costs (energy-intensive extraction).

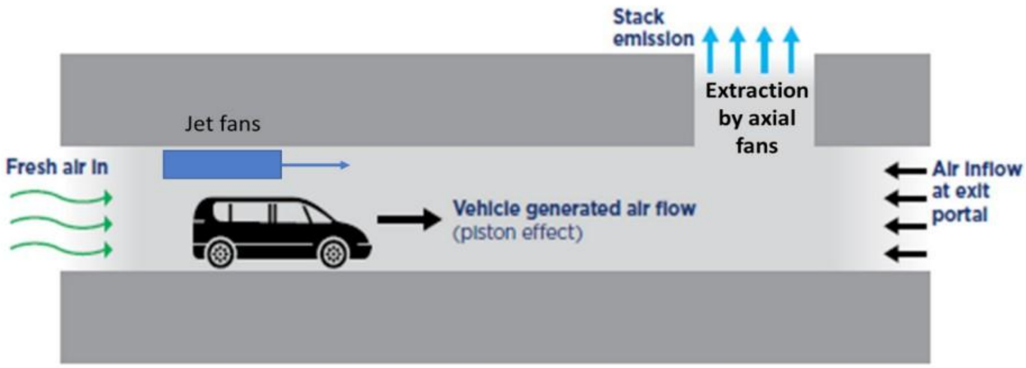

*Figure 2: Longitudinal ventilation with portal air extraction and zero portal emissions (*ACTAQ, 2014*)*

2.2 Transverse Ventilation System

An alternative approach to ventilation is the transverse ventilation system. These systems are divided into two categories: full transverse, which facilitates a complete air exchange within a designated section of the tunnel, and semi-transverse, where only a portion of the air is exchanged. Traditionally, full transverse ventilation systems have been utilized in older, long, or heavily trafficked tunnels; however, contemporary applications are increasingly favouring semi-transverse systems, particularly those that incorporate air extraction. The benefits and drawbacks, along with the operational strategies of these systems, have been thoroughly discussed and documented in numerous publications (PIARC, 2011).

*Table 2: Comparison between Transverse Ventilation Systems (*ACTAQ, 2014*)*

Aspect	**Full Transverse Ventilation System**	**Semi Transverse Ventilation System**
Airflow Mechanism	Simultaneous supply (injection) and exhaust (extraction) via dedicated ducts, perpendicular to the tunnel.	Operates in **one mode at a time**: either injects *or* extracts air (not both simultaneously).
Normal Operation	- Continuously dilutes pollutants with uniform airflow. - Maintains stable air quality.	- **Injection mode**: Dilutes pollutants effectively. - **Extraction mode**: Less effective during high pollution.
Fire Emergency	- Directly extracts smoke at the fire source. - Prevents longitudinal smoke spread (PIARC 2011).	- **Injection mode**: Must shut down; relies on jet fans for smoke control. - **Extraction mode**: Similar to full transverse (localized smoke removal).
Modes of Operation	Fixed simultaneous supply/exhaust.	Single mode (injection/extraction). Reversible systems can switch modes but with delays.
Smoke Management	Immediate, localized extraction without disrupting airflow.	- Requires mode switching or external fans. - Reversible systems face delays during fan reversal.
Infrastructure	Complex ductwork for separate supply/exhaust ducts; higher installation/maintenance costs.	Simpler ductwork (single-purpose or reversible ducts); lower complexity than full transverse.
Flexibility	Optimized for both normal and emergency use.	Limited flexibility: trade-off between pollution control (injection) and fire safety (extraction).
Response Time	Instantaneous smoke extraction during fires.	Delays in emergencies if reversing from injection to extraction mode.
Regulatory Compliance	Aligns with PIARC (2011) fire safety standards.	Some countries restrict semi-transverse systems to **extraction mode only** due to reversal delays.
Cost	Higher initial and maintenance costs due to dual duct systems.	Lower costs than full transverse, but reversible systems may incur added expenses.
Typical Applications	Long tunnels, heavy traffic (e.g., urban subways, highways).	Shorter tunnels or where fire safety prioritizes extraction mode; reversible systems in adaptable designs.

3. Design of Tunnel Ventilation System

Tunnel ventilation systems are designed to meet air quality benchmarks defined by regulatory bodies, balancing in-tunnel pollutant control, ambient air protection, and operational safety during incidents *(*ACTAQ, 2014*).* The key air quality performance requirements for tunnel ventilation systems are as below.

3.1 In-tunnel Air Quality

The main pollutants of concern are CO, particulate matter (PM) and in some countries, NO2 (PIARC, 2000). While in-tunnel air quality threshold values are commonly in use for CO and visibility (PM), the situation for NO2 differs (PIARC, 2012). In many countries, NO2 is currently not controlled; however, the World Road Association (PIARC) recommends the application of 1 ppm, based on the US National Institute for Occupational Safety and Health (NIOSH) short term exposure limit.

3.2 Ambient Air Quality

Ambient air quality guidelines provide a reference point for evaluating pollution concentrations related to human health. The threshold values defined in the guidelines are related to certain exposure times, generally using a one-hour average as a minimum time period and a yearly average as a maximum. The focus of air quality standards is on the protection of humans and ecosystems. Assessment of the contribution of tunnel air to local air quality with respect to air quality guidelines is required to inform decision making regarding the choice of tunnel ventilation system (PIARC, 2008).

3.3 Portal Air Management

Internationally, many tunnels are vented via portals; however, tunnels in urban areas pose an increased risk of elevated pollution levels in proximity to the portal and management of portal emissions may be required to meet environment and health based regulatory requirements. This might consist of releasing the tunnel air (either fully or partially) via a stack into the atmosphere. Portal air management is mostly carried out in sensitive regions in urban areas. The decision on whether portal air management is necessary or not is based on the legal, regulatory and policy framework and air quality standards in place (PIARC, 2008).

4. Results and Discussion

As Nepal advances its transportation networks, road tunnels like the Nagdhunga Tunnel—the country's first—are critical for efficient mobility. Central to its operation are 15 jet fans, strategically positioned at 160-meter intervals from the tunnel portal, which ensure robust ventilation and smoke control. Situated at an elevation of 1,292–1,385 meters (averaging 1,339 meters), this tunnel's high-altitude environment introduces unique engineering considerations, particularly for ventilation systems designed under standard sea-level conditions.

Jet fans are typically engineered for altitudes below 1,000 meters, where air density (ρ) is assumed to be 1.2 kg/m³. At Nagdhunga's elevation, reduced atmospheric pressure lowers air density to approximately 85% of sea-level values (calculated as a factor of 0.85). This decrease affects two key parameters:

1. Wind Pressure: Reduced to 85% of standard levels, diminishing the force exerted by jet fans to propel air.
2. Shaft Power: Proportional to the product of air volume (Q) and wind pressure (P), it similarly drops to 85%. However, the system's design ensures compliance with critical specifications:
    - Blowing wind speed: ≥ 35 m/s
    - Airflow volume: ≥ 43 m³/s
    - Shaft power: ≤ 50 kW (well within limits despite altitude-induced reductions).

Figure 3: Installation of Jet Fan at Nagdhunga Tunnel Construction Project
(Source: - NTCP Project, HAC-Kandenko-subcon)

The tunnel employs longitudinal ventilation, leveraging jet fans to counteract natural and traffic-induced forces (e.g., vehicle piston effects, and pressure differentials between portals). While lower air density reduces the jet fan's thrust, it also decreases the mass of air being moved. This dual effect creates a balance: lighter air requires less force to propel, maintaining the system's capacity to sustain target airflow rates. Thus, ventilation performance remains uncompromised despite the altitude.

The Nagdhunga Tunnel exemplifies adaptive engineering, demonstrating that jet fan systems can effectively meet ventilation demands even at elevated altitudes. By accounting for reduced air density in both thrust and load calculations, the design ensures reliable operation within specified parameters, setting a precedent for future high-altitude tunnel projects in Nepal and beyond.

Figure 4: Layout of Nagdhunga Tunnel Construction Project on Google Map

5. Limitations

While this research provides critical insights into Nepal's pioneering tunnel project, the following constraints must be acknowledged to contextualize its applicability and scope:

1. Narrow Geographic Focus

The analysis is confined to the Nagdhunga Tunnel, Nepal's first road tunnel under construction. Findings may not generalize to other tunnels in the country due to variations in:

- Terrain and climate: Altitude, geology, and weather patterns differ across regions.
- Traffic dynamics: Vehicle types, density, and operational patterns vary by location.
- Design parameters: Future tunnels may adopt distinct structural or ventilation configurations.

2. Operational Data Gaps

The study relies on pre-construction or theoretical ventilation data, which poses limitations:

- Long-term performance: Actual airflow efficiency, pollutant dispersion, and system durability under continuous use remain untested.
- Extreme scenarios: Impacts of severe weather (e.g., monsoon-driven humidity) or exceptional traffic congestion on air quality are not fully modelled.

3. Modelling Assumptions and Real-World Validity

If computational simulations were employed, results hinge on theoretical inputs such as:

- Traffic projections: Assumed vehicle volumes/speeds may diverge from real traffic behaviour post-construction.
- Environmental variables: Predictions about wind patterns, temperature fluctuations, or emergency events (e.g., fires) require empirical validation.

Implications for Future Research:

These limitations underscore the need for adaptive, site-specific studies as Nepal's tunnel infrastructure expands. Post-construction monitoring, real-world stress testing, and comparative analyses across diverse projects will strengthen the reliability of ventilation design standards for the country's unique challenges.

6. Conclusion

Tunnel ventilation systems are categorized by their airflow dynamics: longitudinal and transverse. In longitudinal ventilation, air flows parallel to the tunnel's axis, either aiding or opposing traffic movement. This design minimizes cross-sectional space, reducing construction costs and complexity. Transverse ventilation, by contrast, directs airflow perpendicular to traffic, enabling continuous air replacement through dedicated ducts. This system excels in fire scenarios by extracting smoke near its source, shortening smoke-filled zones and enhancing evacuation safety.

In Nepal, tunnel projects face unique constraints:

- Space limitations due to mountainous terrain, demanding compact designs.
- Frequent surface road connections, complicate airflow management.
- Strict emission regulations at portals in ecologically sensitive zones.

These factors necessitate tailored ventilation strategies. For instance, longitudinal systems may suit tunnels with minimal environmental impact zones, while transverse systems could be prioritized in fire-prone or high-traffic urban tunnels. Hybrid approaches are also emerging, blending both methods to address site-specific demands.

The choice between longitudinal and transverse ventilation hinges on a balance of safety, cost, terrain, and environmental compliance. As Nepal expands its tunnel infrastructure, adaptive solutions; grounded in global advancements yet responsive to local challenges will be key to ensuring safe, sustainable road tunnel transportation networks.

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Review of the Developments in Visualisation Tools in Project Management in Construction Industry: Bridging the Gap between the Technology and its Implementation

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Abstract

The increasing adoption of the visualisation tools in construction project management is transforming the industry by enhancing efficiency, improving decision-making, and optimising project execution methods/approaches. Information Technologies such as Building Information Modelling (BIM), Digital Twins, Extended Reality (XR) and AI-powered Dashboards have enabled real-time data visualisation, risk assessment, and streamlined collaboration, and support in addressing the key challenges in the complex construction environments. Despite these advancements, some challenges such as interoperability issues, data integration, and user adoption hinder the full-scale implementation of these tools in construction management. This paper provides a comprehensive review of the evolutions, benefits, and challenges of the visualisation tools applicable to construction project management. It summaries the past case studies demonstrating the impact of 4D visualisation on project efficiency and AI-powered dashboards on a real-time project tracking. Additionally, it discusses the key barriers to widespread adoption that include technological constraints, data security concerns, and industry fragmentation. The paper highlights the future research directions that focus on the standardised data exchange protocols, AI-driven automation, and the integration of quantum computing for advanced project analytics. These insights contribute to ways of bridging the gap between technological advancements and practical implementation, providing future research and development areas that should be addressed for the wider adoption of the visualisation tools in efficient decision making in construction project management.

Key Words: Construction Project Management, Visualisation Tools, BIM, AI-driven Dashboards, Data Integration, Industry 5.0.

1. Introduction

Project management in the construction industry has evolved from traditional methodologies to technology-driven approaches, enabling more efficient project execution and real-time decision making (Adeniran et al. 2024). Visualisation tools have emerged as essential assets to enhance communication, coordination, and monitoring throughout the lifecycle of a project. Despite advancements in project management practices, only 50% of engineering and construction projects are completed on time, underscoring the need for improved visualisation techniques to mitigate risks and optimise decision making (Armstrong et al. 2023).

As one of the largest global industries, construction faces persistent challenges, including delays, cost overruns, safety risks, environmental concerns, regulatory compliance, and fragmented communication (Waqar et al. 2023). Traditional project management approaches often create technical barriers between stakeholders, limiting real-time collaboration and data-driven decision making (Tversky and Suwa 2009; Weimann et al. 2013). Technological advancements in digital visualisation, including Building Information Modelling (BIM) including 4D (3D CAD+ Schedule) simulations, Geographic Information Systems (GIS) and Augmented/Virtual Reality (AR/VR), have greatly enhanced the clarity, coordination, and precision of projects (Shaukat 2024). These tools reduce errors, enhance stakeholder collaboration and streamline workflows, ultimately increasing the project success rates.

This paper provides a comprehensive review of visualisation tools in construction project management, tracing their historical evolution and comparing traditional and modern visualisation techniques. The key technologies examined (Table 1) included BIM mainly 4D simulations, GIS, AR/VR, and AI-powered dashboards, highlighting their role in decision-making, collaboration, efficiency, and cost management. The review also explored implementation challenges, such as high costs, resistance to change, data integration issues, and cybersecurity risks. Finally, this paper discusses future directions, focusing on how AI, blockchain, and standardisation can drive wider adoption and improve the effectiveness of visualisation tools in construction project management.

Table 1: Key Visualisation Tools in Construction Project Management

Tool/Technology	**Key Features**	**Applications**	**References**
BIM	3D modelling, time and cost integration, collaboration platform	Project planning, design, and monitoring	Marasini *et al.* 2007; Chang et al. 2018; Cairoli and Tagliabue 2023; *Habin 2019* *Guo and Liao 2023*
4D BIM	Time dimension added to 3D model, construction sequence visualisation	Scheduling, progress tracking, identifying scheduling conflicts	Marasini *et al.* 2007; *Merve and Oztas 2013* Hasan and Rasheed 2019; Neves et al. 2019
AR/VR	Real-world overlay, immersive experience	Site monitoring, quality assurance, training, and design review	*Ratajczak et al. 2019;*
BIM-GIS Integration	Geographical context visualisation	Large-scale project planning and monitoring	*Gao and Wan 2023;*
Gantt Charts/CPM	Task scheduling, dependency visualisation, progress tracking	Simple project scheduling and monitoring	
Slip Chart Diagrams	Side-by-side comparison of	Identification of underperforming activities	Araújo & Lucko, 2016

Tool/Technology	Key Features	Applications	References
	planned vs. actual progress		
Mosaic Charts	Data-driven visualisation, flexible scheduling	Comparable effectiveness to Gantt charts	Luz and Masoodian 2011
Dashboards	Real-time KPI monitoring, automated alerts	Cost visualisation, automated financial updates, predictive modelling	Shi et al. (2015)

2. *Roles of Visualisation tools in Construction Project Management*

Project management in the construction industry has evolved significantly, shifting from traditional control-based approaches to technology-driven adaptive methodologies. Historically, large-scale projects such as the Pyramids of Giza and Roman aqueducts showcased early forms of project management, despite the absence of formalised frameworks (Seymour and Hussein 2014). The contemporary field of project management was shaped by early innovators like Henri Fayol, who established essential management functions such as planning, organising, commanding, coordinating, and controlling, and Henry Gantt, who created the Gantt Chart, a groundbreaking tool for scheduling (Fells 2000; Chiu 2010). These innovations laid the groundwork for structured project planning; However, it was not until the mid-20th century that project management became a formal discipline. A bibliometric study by Kim and Kang (2017) analysing 2,015 articles from 1983 to 2016 highlighted key research trends in project management, noting a shift from single-country research efforts to multinational collaborations, particularly in areas such as project governance, procurement management, and human resource management.

Since the introduction of the Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) in 1958, systematic approaches have been practiced for planning schedules, estimating costs, and evaluating risks. The project management methodologies evolved further by the creation of professional bodies such as the International Project Management Association (IPMA- 1965) and the Project Management Institute (PMI-1969)(Max and Hart 2025). The release of the Project Management Body of Knowledge (PMBOK) Guide by the PMI in 1987 further solidified best practices, offering standardised guidelines for project managers globally (Kwak 2003).

From the 1980s to the early 2000s, project management entered a phase of digital transformation driven by the rise of advanced computing capabilities and software tools. The introduction of project management software, such as Microsoft Project, Primavera and Astra Power Project has significantly enhanced scheduling, tracking, and reporting capabilities (Kwak 2003). The Theory of Constraints (TOC) by Goldratt (1986) and the emergence of the Scrum framework (1986) laid the foundation for agile methodologies, which later revolutionised project execution by emphasising flexibility, iteration, and collaboration (Seymour and Hussein 2014).

Since 1995, advancements in technology have significantly shaped the project management sector, particularly through the integration of cloud computing, tools for real-time collaboration, and AI-powered systems for tracking projects. Agile Manifesto in 2001 introduced a flexible and iterative approach that quickly gained popularity beyond software development (Seymour and Hussein 2014). By the late 2000s, the Software as a Service (SaaS) solution had become widespread, allowing project managers to access data remotely and manage projects more efficiently (Fox and Patterson 2016). The Fourth Industrial Revolution (4IR) has further accelerated the evolution of project management by integrating AI, robotics, machine learning, and automation to enhance decision-making, risk assessment, and workflow optimisation (Tiwari et al. 2018). Emerging technologies, such as digital twins, IoT-based smart sensors, and blockchain for contract management, have reshaped project execution by providing real-time data analytics and predictive insights (Aliu et al. 2023).

As project management continues to evolve, scholars predict the emergence of PM 5.0, a new phase that integrates human-AI collaboration, sustainability practices, and advanced data-driven decision-making (Russell et al. 2024). This phase focuses on enhancing efficiency through AI-powered automation, blockchain-enabled transparency, and digital tools such as augmented reality (AR) and virtual reality (VR) to improve stakeholder engagement (Vahdatikhaki and Hammad 2015).

Effective visual communication is fundamental for construction project management and enhancing efficiency, collaboration, and safety irrespective of project management methodologies traditional waterfall model, or new methods such as agile. Given the complexity of construction projects, which often involve multiple teams such as architects, engineers, contractors, and clients, ensuring accurate and real-time communication is critical for timely and effective decision making leading to project success (Zakaria et al. 2021). Beyond project management efficiency, visualisation techniques improve stakeholder engagement by fostering greater transparency and collaboration. As the field of project management continues to evolve, embracing cutting-edge visualisation solutions will be crucial for organisations seeking to maintain competitiveness, innovation, and sustainability in an increasingly data-driven environment (Aliyev 2025).

Visualisation tools bridge the gap of communication media between technical complexity and practical implementation, enabling teams to interpret project details more effectively, monitor progress, risk analysis and management. Visual analytics enables the analysis of multidimensional project data, providing actionable insights for project performance and decision-making (Russell et al. 2009). This paper discusses two groups of visualisation techniques- Construction Product and Process Visualisation (CPPV), and Real Time Information Dashboards (RTID).

2.1 Construction Product and Process Visualisation

The development and adoption of the construction product and process visualisation techniques such Building Information Modelling (BIM), Virtual Reality (VR)/ XR/AR in the last two decades have been proven to improve collaborative decision-making and to test what-if scenarios before the construction starts thereby detecting the design errors and evaluate the suitable construction methods. These modern visualisation tools enhance design clarity, coordination, and stakeholder engagement. Kang et al. (2007) demonstrate that the web-based 4D (3D CAD +Schedule) BIM model has been proven to minimise logical errors faster and with fewer mistakes than traditional 2D drawings and bar charts. Studies have demonstrated that 4D dynamic models are far more effective in safety planning and training than traditional 2D static drawings because they offer an immersive, real-world simulation of construction environments (Azhar 2017).

By combining BIM with web-based technologies such as three.js and ReactJS, project teams can achieve real-time visualisation of building designs and worker positions, facilitating hazard identification and safety measure implementation (Kumara et al. 2024). Moreover, the use of BIM with Extended Reality (XR), particularly Mixed Reality, has shown great potential in improving project execution by aligning digital plans with actual site conditions. Devices such as the Trimble XR10 with HoloLens 2 allow construction professionals to visualise and interact with BIM models directly on-site, leading to better compliance with design specifications and a reduction in discrepancies (Pevec and Pučko 2024).

A study conducted by Marasini et al. (2007) examined the impact of 4D visualisation tools on two construction projects: a precast concrete production facility and a high-density residential development. In precast facility projects, traditional project management techniques resulted in a cost overrun of 3.8% and a three-month delay owing to errors in 2D drawings and a lack of real-time tracking. By adopting 4D visualisation (3D + time simulations), the project achieved early detection of dimensional clashes, optimised resource scheduling, and improved stakeholder collaboration, resulting in an estimated significant cost savings. Similarly, the residential project, which encountered errors in architectural drawings and service coordination issues, leveraged 4D BIM technology to streamline construction sequences, improve site access logistics, and reduce project delays. Ojeda et al. 2024 found that Unmanned Aerial Vehicles (UAVs)-integrated BIM significantly improved project monitoring accuracy, allowing for real-time tracking and faster identification of construction delays compared to traditional site inspections.

2.2 Data Visualisation using Business Intelligence (BI) Dashboards

Dashboards serve as visual interfaces that aggregate and display key performance indicators (KPIs), enabling project managers to track costs, scheduling, and resource allocation more efficiently (Ruoff et al. 2023). As the industry moves toward Industry 5.0, Business Intelligence (BI) dashboards adopting AI-driven dashboards and predictive analytics will be critical for providing centralised, real-time access to critical project data, which will helping project managers to analyse project performance, forecasting delays, and identifying inefficiencies. However, challenges remain in integrating real-time data from multiple sources into a unified visualisation platform (Ghosh et al. 2024).

These technologies reduce misinterpretations, improve workflow alignment, and minimise rework by offering interactive, real-time models that stakeholders can manipulate and analyse. For instance, (Zakaria et al. 2021) developed a real-time dashboard for road construction projects, enabling stakeholders to monitor schedules, expenses, and quality metrics instantaneously. The dashboard’s automated alerts for project risks facilitated timely intervention, preventing schedule overruns and budget discrepancies. Da and Maximino (2020) demonstrated the effectiveness of an enterprise dashboard for monitoring waterproofing systems in wood construction, where real-time tracking of moisture levels, temperature, and humidity allowed for the early detection of potential defects and immediate corrective action. Similarly, Guerriero et al. (2012) developed a location-based dashboard for construction project management that provides visual site representation with real-time data on task progress, resource distribution, and potential risks. This tool is particularly beneficial for large-scale construction projects with dispersed teams, ensuring that stakeholders can access up-to-date project details remotely.

Beyond construction, visualisation tools are increasingly being applied in education and crisis management to support decision-making. Paredes et al. (2020) highlight how Educational Data Mining (EDM) and Learning Analytics (LA) leverage visualisation techniques to analyse student performance, identify learning patterns, and support academic decision-making. These findings demonstrate that interactive dashboards and graphical representations of complex datasets can enhance predictive capabilities, allowing proactive interventions and improved learning experiences. Similarly, Ruoff et al. (2023) explored the role of visualisation tools in crisis response dashboards, particularly in navigating data-heavy environments during the COVID-19 pandemic. The study found that interactive and conversational dashboards facilitated real-time data interpretation and improved decision-making efficiency and crisis-response strategies.

Gajera (2023) found that integrating Power BI dashboards with project control systems in construction significantly improved cost visibility, enhanced decision-making, and strengthened stakeholder engagement as compared to traditional financial reporting systems that rely on monthly budget reviews and static spreadsheets. They revealed that real-time financial tracking reduced reporting time by 25%, while 85% of industry professionals reported improved budgets and resource management. Additionally, 80% of the clients experienced better communication and project transparency, leading to higher stakeholder satisfaction. However, challenges such as data compatibility issues were identified, with 30% of the reports highlighting difficulties in aligning data from various sources. This study underscores the importance of ongoing training and structured implementation strategies to maximise the benefits of BI dashboards in project management. A study Shi et al. (2015) by examining the benefits of KPI visualisation dashboards for tracking performance in collaborative engineering projects compared to traditional KPI tracking through spreadsheets and periodic reports.

Beyond traditional dashboards, the integration of blockchain technology with visualisation tools has further strengthened financial transparency, automation, and security in project management. Elghaish et al. (2020) explored the integration of blockchain into Integrated Project Delivery (IPD) and found that smart contracts enhanced financial automation, streamlined reimbursement processes, and reduced human errors in cost management. They demonstrated that blockchain-based visualisation frameworks provide secure, real-time access to project financials, reducing the risks associated with manual transaction tracking and financial discrepancies. This method could potentially overcome financial obstacles in managing construction projects, facilitating secure and automated financial processes within the Architecture, Engineering, and Construction (AEC) sector.

3. Benefits of the Visualisation Tools

3.1 Improving Collaboration and Stakeholder Engagement

Visualisation tools also play a vital role in improving stakeholder collaboration, particularly in large-scale multi-party projects. Nobre et al. (2022) found that the IT Lingo-Cloud system, an AI-powered visualisation platform, significantly enhanced collaboration among stakeholders by enabling seamless information synchronisation and teamwork optimisation. The study reported that interactive dashboards facilitated real-time data generation, ensuring that all project-related information was accessible to key stakeholders. In addition, users found that visual decision-making support systems helped translate complex project data into actionable insights, leading to improved project coordination and execution.

3.2 Risk Mitigation and Predictive Analytics

Another critical benefit of visualisation tools in project management is the ability to monitor, predict, and mitigate risks. Chiu and Russell (2011) highlighted how interactive visualisation tools improve real-time risk assessment, schedule tracking, and deviation analysis. Their research found that by integrating multiple project views (e.g., product, process, and as-built visualisations), organisations were able to conduct holistic project analyses, leading to higher efficiency in risk management. In addition, features such as data filtering, adjusting granularity, and coordinating multiple views allow project managers to explore project complexities more effectively, ultimately improving cost control, scheduling accuracy, and quality assurance.

3.3 Project-based learning

Simic et al. (2023) demonstrated how data-driven visualisation tools enhance project-based learning methodologies. By integrating digital project management tools such as Jira and Confluence, this study highlighted how Business Intelligence (BI) dashboards provided real-time insights into project workflows and student engagement metrics. This study suggests that visualisation techniques can be applied beyond traditional project management, serving as effective tools for monitoring and optimising learning environments, training programs, and knowledge-sharing platforms.

4. Challenges in Implementing the Visualisation Tools

Despite the significant benefits of project visualisation tools, several challenges arise from interoperability limitations, data integration complexities, user adoption barriers, and computational constraints, which hinder the seamless implementation and effectiveness of visualisation technologies in construction and other industries.

Lopes and Boscarioli (2020) conducted a systematic literature review analysing 1,407 academic articles on Business Intelligence and Analytics (BIA) tools in construction. Their findings revealed that while over 64% of software solutions were custom-developed, budget preparation, cost management, and occupational safety emerged as the top three application areas for BIA tools. However, their research highlighted a significant gap in BIA adoption between construction and other industries, underscoring the need for cultural and organisational shifts to facilitate widespread adoption. Key challenges are analysed in the following sections.

4.1 Interoperability and Standardisation Challenges

One of the primary obstacles in implementing visualisation tools is interoperability, which refers to the ability of digital systems, platforms, and software to communicate and exchange data effectively. In particular, the construction industry relies on multiple software solutions, such as BIM, GIS, and AR/ VR applications, which often operate in isolation owing to incompatible data formats and lack of standardised protocols (Al-Siah and Fioravanti 2023; Johansson and Roupé 2024). Integrating BIM with extended reality (XR) technologies, for example, remains a challenge because of the absence of a universal model for seamless data transfer (Han and Leite 2022). The lack of interoperability hinders collaboration, delays project execution, and increases costs, ultimately limiting the effectiveness of visualisation tools.

4.2 Data Integration and Compatibility Issues

Data integration, which is the process of consolidating real-time data from multiple sources into a unified visualisation system, remains a key challenge. The quality, structure, and consistency of data inputs influence the effectiveness of visualisation tools, which often vary across different project management platforms. A study by Teizer et al. (2020) revealed that 30% of organisations using visualisation tools in construction reported significant data compatibility issues, often requiring manual data cleansing and realignment, delaying the intended benefits of real-time visualisation. Blockchain-based visualisation, which has the potential to enhance transparency and automate transactions, also faces adoption barriers owing to complex data integration requirements and security concerns (Elghaish et al. 2020). These compatibility constraints limit data-driven decision-making efficiency and increase reliance on traditional methods that lack dynamic visualisation capabilities.

Many organisations resort to ad hoc integration methods that limit scalability, reusability, and long-term reliability (Ali and Mohamed 2018). Additionally, integrating BIM with GIS, a necessary step for comprehensive project management, remains problematic because of the differences in data structures and encoding formats (Wan Abdul Basir et al. 2023). These technical challenges restrict project managers' ability to conduct seamless cross-platform data analysis, leading to fragmented insights and suboptimal decision-making.

4.3 User Adoption and Learning Curve Challenges

Despite their potential, visualisation tools face adoption resistance owing to their complexity, steep learning curves, and industry fragmentation. Many visualisation systems require specialised training, making it difficult for non-technical users to fully utilise advanced (Gueye and Boton 2023). In the construction sector, where project teams are often temporary, training all stakeholders in new visualisation software can be costly and time-consuming. In addition, the complexity of AI-enhanced dashboards and interactive 3D visualisations may overwhelm users, leading to low adoption rates and limited engagement (Boton et al. 2010).

Chiu and Russell (2011) highlighted several challenges in user adoption of visualisation tools. These include the complexity of multiview and interactive interfaces, which necessitate significant user training. Additionally, reliance on data quality is crucial, as incomplete or inaccurate datasets can result in misleading insights. Users may also experience information overload when they find it difficult to extract pertinent insights from large volumes of visualised data. Furthermore, there is a tendency for decision-makers to overly depend on visual analytics, often prioritising graphical representations over essential non-visual project data.

Ruoff et al. (2023) explored visualisation challenges in crisis management dashboards and found that while interactive dashboards improve data accessibility, some users prefer traditional interfaces because of familiarity. This highlights the importance of balancing intuitive design with functionality, ensuring that visualisation tools remain user-friendly and customisable to meet diverse needs.

4.4 Computational and Technological Constraints

The implementation of visualisation tools often requires high computational power, which poses challenges for organisations with limited IT infrastructure. Advanced 3D modelling-driven predictive analytics and real-time data visualisation demand significant processing capabilities, making these tools resource-intensive. Hadjimichael et al. (2024) identified computational constraints as a key barrier in visualisation for decision-making under deep uncertainty, emphasising the need for efficient algorithms and scalable infrastructure to handle complex, high-dimensional data.

Similarly, a study by Aliyev (2025) on Quantum AI (QAI) in project management found that while quantum computing has the potential to significantly enhance visualisation accuracy, its adoption remains limited due to infrastructure costs, qubit instability, and the need for specialised expertise. The hybrid quantum-classical systems proposed in the study by Aliyev (2025) offer a promising solution to overcome current technological limitations, but their widespread implementation requires further research and technological advancements.

4.5 Enterprise Data Integration: Challenges in overcoming data silos

In large enterprises, data silos hinder integration efforts, requiring schema mapping and deduplication techniques for accurate visualisation. A case study of Tamr (n.d.), a data integration company, demonstrated technical difficulties in building deployable and usable data visualisation software, highlighting compatibility challenges with legacy systems and inconsistent data formats (Stonebraker and Ilyas 2018). Similarly, in construction, the lack of standardised interoperability protocols between 4D BIM, project dashboards, and IoT sensor data leads to fragmented visualisation, making real-time project tracking less efficient.

4.6 Cost and Skill Shortages

High costs associated with data collation, conversion, and personnel training create barriers to the successful implementation of visualisation tools. Case studies across multiple industries have shown that financial constraints and the lack of skilled professionals are key factors limiting the adoption of integrated visualisation solutions (Schmidt et al. 2010). In Australia, multi-sourced spatial data integration remains expensive and time-consuming due to institutional fragmentation and inconsistent data coordination approaches (Mohammadi et al. 2007). Similarly, in construction, the integration of BIM, AI-driven dashboards, and real-time visualisation frameworks often require custom development, leading to higher costs and longer implementation timelines.

4.7 Software Incompatibility: Challenges in Integrating Visualisation with Legacy Systems

Technological integration is particularly challenging in sectors with existing legacy systems, where ensuring user experience and adoption is crucial. In the healthcare sector, the introduction of new visualisation tools often leads to software incompatibility issues, preventing smooth integration with existing hospital management systems (Nivodhini et al. 2024). A similar challenge exists in construction, where older project management software may not support modern AI-driven visualisation tools, resulting in manual data transfers, inefficient workflows, and an increased risk of errors.

5. Future Directions and Recommendations from the Previous Studies

The rapid advancement of visualisation tools in project management presents new opportunities for decision-making, optimising workflows, and improving collaboration.

5.1 Increased Adoption of AI and Blockchain for Enhanced Project Transparency

The integration of Artificial Intelligence (AI) and blockchain technology into visualisation tools has the potential to revolutionise data-driven project management. AI-driven predictive analytics can enhance real-time decision-making, automate anomaly detection, and optimise resource allocation, whereas blockchain technology can ensure secure data sharing and transparency in project documentation (Gajera 2023). Future research should explore the modelling prediction of AI-powered visualisation in different construction management scenarios, focusing on automated risk assessment, cost forecasting, and AI-enhanced project scheduling. Similarly, blockchain-based visualisation frameworks should be developed to secure digital transactions, automate contract execution, and establish immutable project records (Elghaish et al. 2020).

5.2. Standardization of Data Formats and Interoperability across Visualisation Platforms

One of the major barriers to the widespread adoption of visualisation tools is the lack of interoperability between different platforms and software systems. Standardising data formats, file structures, and communication protocols across BIM, GIS, and augmented reality (AR)/virtual reality (VR) applications will significantly improve integration, usability, and collaborative workflow (Al-Siah and Fioravanti 2023; Johansson and Roupé 2024). Future studies should focus on developing universal data exchange frameworks to ensure seamless collaboration between stakeholders using different visualisation technologies. Additionally, research should explore automated data transformation models that enable real-time synchronisation of project information across diverse software environments (Han and Leite 2022).

5.3. Training and Skill Development for Digital Competency in Project Management

The widespread use of visualisation tools is frequently impeded by insufficient technical knowledge and user adaptability. To promote their adoption across the industry, it is crucial to integrate digital skills training into the professional development programs for construction managers, engineers, and project teams (Gueye and Boton 2023). Future efforts should concentrate on the following: creating AI-driven training modules that offer interactive onboarding and visualisation techniques (Zhao et al. 2025); incorporating visualisation training into the academic curricula of architecture, construction management, and engineering programs; and encouraging hands-on workshops and ongoing learning programs to acquaint professionals with new visualisation technologies, such as 4D BIM, AI-enhanced dashboards, and reality capture tools. By addressing the skills gap, these initiatives facilitate digital adoption and boost productivity throughout the construction sector.

5.4 Government and Industry Support for Digital Construction Management Tools

The adoption of visualisation tools in construction requires strong regulatory frameworks and industry standards to drive digital transformation. Governments and industry bodies should mandate the use of BIM and visualisation technologies in major infrastructure projects while providing financial incentives and grants to encourage adoption. Additionally, creating open-access data visualisation platforms will enable collaboration and knowledge exchange across the industry. Policymakers must also work closely with researchers and industry experts to establish legal frameworks addressing data security, privacy, and ethical concerns in AI-powered visualisation tools (Chiu and Russell 2011). These initiatives will ensure a structured, secure, and efficient integration of visualisation technologies, fostering innovation and improved project outcomes in the construction sector.

5.5. Future Research on Power BI and Real-Time Visualisation for Dynamic Construction Environments

With the increasing integration of visualisation tools like Power BI dashboards into project management processes, future research needs to investigate their use across various control systems and construction industries (Gajera 2023). Moreover, advancements in AI and machine learning have the potential to significantly improve real-time analytics, providing more profound insights into project performance and aiding in predictive decision-making. Given the increasing complexity of dynamic construction environments, future research should focus on key areas such as enhancing security measures for integrating and visualising sensitive project data, developing real-time visualisation frameworks that adapt to evolving site conditions and project parameters, and advancing automated anomaly detection and early warning systems within construction dashboards. These efforts will ensure greater data protection, improved responsiveness, and proactive risk management in construction project management.

5.6. Advancing Visualisation Techniques for Deep Uncertainty Decision-Making

A study conducted by (Hadjimichael et al. 2024) emphasised the importance of creating standardised guidelines for visualising deep uncertainty in decision-making contexts. Future investigations should consider the following areas: Interactive and adaptive visualisation methods that boost user involvement and support decision-making. Multimodal visualisation approaches combine data from various sources, including sensor networks, AI-driven predictive models, and human-driven decision inputs. The significance of interdisciplinary collaboration among data scientists, decision analysts, and policymakers in enhancing visualisation techniques for complex and uncertain settings. Developing user-friendly and customisable visualisation interfaces is crucial for enabling real-time decision-making in high-stakes construction and infrastructure projects.

5.7. Exploring Emerging Technologies: AI, Automation, IoT, and Quantum Computing

As technology advances, exploring new areas like artificial intelligence, automation, machine learning, and the Internet of Things (IoT) opens up fresh opportunities for decision-making, predictive analysis, and project optimisation. Future research should explore AI-driven visual analytics for construction risk management and forecasting, the integration of IoT sensors with real-time visualisation tools for tracking progress and ensuring safety compliance, and the role of automation in enhancing visualisation workflows for project planning and execution (Aliu et al. 2023). Additionally, quantum computing presents new possibilities for processing large-scale project data, optimising scheduling, resource allocation, and uncertainty modelling (Aliyev 2025). By combining AI-powered automation, IoT-based real-time monitoring, and advanced visualisation tools, the construction industry can improve efficiency, mitigate risks, and enhance project predictability. The integration of AI, blockchain, and real-time analytics is pivotal in ensuring that visualisation technologies continue to evolve as reliable, scalable, and transformative tools in construction project management.

6. Conclusions

As the construction sector moves toward Industry 5.0, visualisation tools play an integral role in optimising project performance and ensuring sustainable development. The application of visualisation tools in construction project management has transformed the industry by enhancing decision-making, improving stakeholder collaboration, optimising resource allocation, and minimising project risks.

From Building Information Modelling (BIM) and 4D simulations to AI-driven dashboards and blockchain-based transparency frameworks, visualisation tools provide real-time insights and predictive analytics, enabling construction professionals to monitor progress, anticipate challenges, and streamline execution. Studies have demonstrated that technologies such as 4D visualisation reduce project delays and rework, whereas interactive dashboards improve cost estimation accuracy and scheduling efficiency. Despite these advantages, challenges such as interoperability issues, data integration complexities, steep learning curves, and computational constraints continue to hinder their widespread adoption.

To maximise the potential of visualisation tools, the standardisation of data formats, enhanced AI integration, and interdisciplinary collaboration are crucial. Future research should focus on developing adaptive and interactive visualisation techniques, refining security protocols for real-time data visualisation, and expanding the role of AI, automation, and the IoT in predictive project management. By embracing emerging technologies, investing in digital upskilling, and fostering a data-driven approach, construction organisations can enhance their efficiency, mitigate risks, and revolutionise project delivery.

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Synergistic Effects of Mechanochemical Activation and Limestone on Hydration Mechanisms in LC3: A review

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Abstract

Limestone Calcined Clay Cement (LC3) has emerged as a sustainable alternative to traditional Portland cement, capable of reducing CO_2 emissions by up to 40% through the partial replacement of clinker with calcined clay and limestone. While calcination is the conventional method for activating kaolinitic clays, recent developments highlight mechanochemical activation (MCA) as a viable, energy-efficient alternative. This review critically explored the role of MCA in enhancing LC3 performance, focusing on hydration mechanisms, mechanical strength, and environmental impact. A narrative approach was adopted to examine LC3 hydration and the mechanochemical activation of clays. Relevant literature was sourced from Google Scholar, Scopus, and Web of Science using keywords such as *"LC3"*, *"mechanochemical activation"*, and *"hydration kinetics"*. Emphasis was placed on recent studies (2018–2024), alongside key foundational works on SCM hydration. Over 30 peer-reviewed sources were reviewed, including experimental studies on hydration chemistry, activation techniques, and sustainability.

Key findings include that MCA helps to enhance the performance of LC3 by increasing pozzolanic reactivity up to 80%, reducing the induction period by 2–5 hours, and accelerating crystallization by 5–7 hours. MCA-LC3 achieves early strength gains and reaches similar strength at 28 days, outperforming calcined clay systems. It enables the use of low-grade clays like muscovite and reduces CO_2 emissions by an additional 21.2% beyond LC3's baseline 40% savings. MCA offers a low-energy, scalable solution for sustainable cement production. Nevertheless, standardisation of MCA activation protocols is needed to ensure consistency across diverse raw material sources. Further research should assess MCA-LC3's long-term durability under various environmental conditions. Strengthening industry collaboration and policy frameworks will facilitate large-scale implementation. Variability in clay composition presents challenges in optimising MCA parameters across different sources. Limited real-world performance data necessitates extended durability studies. The scalability of MCA-LC3 needs further validation for industrial adoption.

Key words: LC3, MCA, Carbo-Aluminates, Sustainability, Mechanical strengths

1. Introduction

The cement industry is indeed a significant contributor to global CO_2 emissions, with estimates ranging from 5% to 8% of total anthropogenic CO_2 emissions (Worrell *et al.*, 2001; Proaño *et al.*, 2020; Ostovari *et al.*, 2021). The demand for supplementary cementitious materials (SCMs) to lower CO_2 emissions from cement and concrete production is increasing (Juenger et al., 2019). However, according to Habert et al. (2020) traditional SCMs like fly ash derived from coal combustion and blast furnace slag, a by-product of pig iron manufacturing, are becoming limited in supply, highlighting an urgent need to identify alternative SCM sources. Among emerging alternatives, limestone calcined clay cement (LC3) has shown strong potential due to its reduced carbon footprint and use of widely available materials, such as clay and limestone, particularly beneficial for regions with limited access to traditional SCMs (Han et al., 2023). However, the effectiveness of LC3 is strongly influenced by the reactivity of the clay component. Kaolinitic clays are often crystalline and chemically inert, necessitating thermal activation to produce metakaolin, a reactive amorphous phase rich in silica and alumina (Mañosa, Alvarez-Coscojuela et al., 2024a; Inocente et al., 2021; Alujas Diaz et al., 2022). The calcination process, typically performed at temperatures ranging from 700 to 850 °C, induces dehydroxylation of the clay minerals, resulting in the breakdown of their crystalline structure and leading to improved pozzolanic reactivity.

While calcination remains the conventional method to activate clays for use in LC3 systems, its environmental and economic drawbacks have driven interest in alternative, lower-impact approaches. Mechanochemical activation (MCA) offers a promising solution, with potential energy savings of up to 90 percent and reduced emissions and costs (Fitos et al., 2015; Ke, Baki and Skevi, 2022). MCA is conducted at room temperature using planetary mills that apply mechanical forces like shearing, compression and impact to enhance reactivity (Baki et al., 2022). Adding chemical agents can further promote the formation of amorphous, reactive phases (Kumar, Panda and Singh, 2013). MCA has shown pozzolanic activity comparable to or exceeding that of calcined clays. Further in-depth understanding is required to gain a comprehensive understanding of the hydration mechanisms, mechanical properties and environmental impact of MCA LC3 systems, a gap also identified by Pinheiro et al. (2023). Hence, this review paper attempted to critically explore the role of MCA in enhancing LC3 performance, focusing on hydration mechanisms, mechanical strength, and environmental impact.

To achieve above mentioned aim, this review was conducted using journal articles, conference papers, and reputable websites published since 2018 in well-regarded sources. The total number of references selected, covering the period from 2018 to 2024, is relevant to the topic. Search terms such as “LC3”, “mechanochemical activation”, and “hydration kinetics” “Environmental Impact” were used to identify relevant publications. Data, findings, and research gaps from over 30 peer-reviewed papers were collected, analysed, and presented to address the objectives of this paper.

2. Comparative Evaluation of Hydration and Mechanical Properties

This section provides a comparative evaluation of conventional LC3 and MCA-LC3 systems, focusing specifically on hydration mechanisms and mechanical performance. By analysing findings from recent literature, this section highlights how the method of clay activation influences the rate and products of hydration, as well as the development of mechanical strength.

2.1 Hydration Mechanism and Pozzolanic Reactivity

The hydration behaviour and mechanical performance of LC3 are significantly influenced by the method of clay activation. A summary comparison of hydration-related aspects between traditional LC3 and MCA-LC3 is presented in Table 1.

Table 1: Comparison of traditional LC3 and MCA-LC3 in terms of hydration kinetics

Aspect	LC3	MCA-LC3
Hydration rate	Slower natural reactivity.	Reduced induction period by 2–5 hours and accelerated crystallisation by 5–7 hours (Kitamura et al., 2001; Ibragimov et al., 2016).
Heat of hydration	Lower heat release.	Up to 300 times greater heat release (Kitamura et al., 2001).
Microstructure	Less dense pore structure.	Denser and more refined pore structure (Ahmed et al., 2023).
Strength development	Comparable or slightly lower strength.	Higher compressive strength (Vargas et al., 2025).

Conventional LC3 systems rely on thermally activated kaolinitic clays (metakaolin) and limestone, which together create a synergistic effect that improves early-age performance. Upon the addition of water, clinker phases such as alite and belite hydrate to form calcium silicate hydrate (C–S–H) gel and portlandite mentioned by Tole et al. (2018), with reactivity further influenced by clay properties (Krishnan and Bishnoi, 2020). The metakaolin component quickly consumes portlandite through pozzolanic reactions, producing additional C–A–S–H gel enriched with alumina (Nguyen, Castel and Afroz, 2020). Simultaneously, carbonate ions from limestone react with aluminates from both cement and metakaolin to form AFm carboaluminate phases, particularly mono- and hemi-carboaluminates (Nguyen, Castel and Afroz, 2020). Antoni et al. (2012) were among the first to demonstrate that this synergy reduces porosity and enhances early strength. The resulting hydrated phase assemblage includes C–S–H, ettringite, carboaluminates, and aluminates (e.g., hydrogarnet), differing from the monosulphate-rich hydration profile in OPC (Mishra, Bishnoi and Emmanuel, 2019). However, due to the high reactivity of metakaolin, the induction period may be shortened, subtly altering early hydration kinetics (Nguyen, Afroz and Castel, 2020).

MCA-LC3 builds upon this chemistry by introducing a more energy-efficient and reactivity-enhancing approach. High-energy milling disrupts the crystalline structure of clays, significantly increasing surface area and amorphous content (Mañosa, Huete-Hernández, et al., 2024a). X-ray diffraction analyses show that mechanically treated kaolin exhibits lower crystallinity and higher pozzolanic potential than thermally activated counterparts. This structural transformation enhances the clay's interaction with the alkaline cement pore solution, boosting early portlandite consumption and pozzolanic activity. R3 calorimetry and Chapelle tests confirm higher lime reactivity for MCA clays (Mañosa, Huete-Hernández, et al., 2024a).

Furthermore, MCA also significantly accelerates hydration kinetics. Kitamura et al. (2001) reported that MCA-treated alumina-rich materials released up to 300 times more heat than non-activated forms, indicating rapid early hydration. Ibragimov et al. (2016) observed a reduction in the induction period by 2–5 hours and accelerated crystallisation by an additional 5–7 hours. Such enhancements could have been attributed to the improved availability of reactive aluminates. Msinjili et al. (2019) further demonstrated that the effectiveness of MCA is not limited to kaolinitic clays; illitic clays with low Fe_2O_3 content also show promising reactivity under optimal activation and replacement conditions.

2.2 Mechanical Strength Development

Compressive strength is a key performance indicator for any cement system. MCA-LC3 has demonstrated strong potential to improve both early and long-term compressive strength, offering a viable substitute for conventional thermally activated LC3. By accelerating hydration reactions and improving the reactivity of clay minerals, MCA can facilitate faster and more efficient formation of binding phases within the cementitious matrix. In the study conducted by Mañosa, Huete-Hernández et al. (2024), LC3 mixtures incorporating 100 percent mechanically activated kaolin demonstrated higher compressive strength at 7 days and comparable strength at 3 days relative to those produced with 100 percent calcined clay. As illustrated in Figure 1b, LC3 100MC exhibits improved performance at 7 and 28 days, with similar strength at 3 days within the error margin. This early strength enhancement could be attributed to accelerated hydration kinetics and more rapid matrix densification induced by the mechanochemical treatment. By 28 days, the MCA LC3 achieved a compressive strength of 42 MPa, compared to 40 MPa for the calcined clay sample, confirming that mechanochemical activation does not compromise longer-term strength development. Further evidence is presented in Figure 1a, which compares a broader range of LC3 mixtures with varying proportions of mechanically activated and calcined clay at 7 and 28 days. The results show that increasing the proportion of MCA clay (LC3 75CC 25MC, LC3 50CC 50MC, LC3 25CC 75MC, and LC3 100MC) leads to compressive strengths that are comparable to or greater than those of the fully calcined reference mix (LC3 100CC), particularly at 28 days. Mañosa, Huete-Hernández et al. (2024) also reported that 28-day SEM and porosimetry analyses showed MCA LC3 achieved pore structure and microstructural refinement comparable to calcined LC3, with the finer particle sizes observed in some cases likely contributing to improved particle packing and, consequently, higher compressive strength. These findings reinforce the potential to replace thermal calcination in developing binders suitable for structural applications.

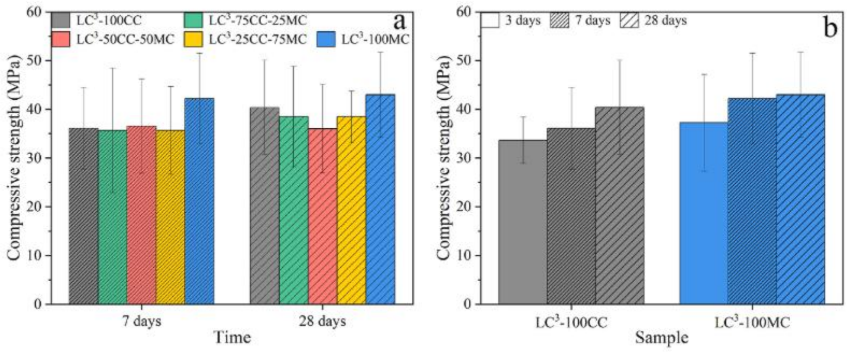

Figure 1: Compressive strength of (a) all LC3 samples at 7 and 28 days and (b) LC3-100CC and LC3-100 MC at 3, 7, and 28 days (Mañosa, Huete-Hernández, et al., 2024)

Further improvements in mechanical performance have also been observed when MCA is combined with supplementary materials. Őze, Badacsonyi and Makó (2024) reported that incorporating 50 percent waste glass powder during MCA improved compressive strength by approximately 8 percent after just 60 minutes of activation. The amorphous silica present in glass reacts synergistically with activated clay to produce additional calcium silicate hydrate. Similarly, Dvorkin et al. (2024) found that the inclusion of 20 to 40 percent fly ash and 0.5 to 1 percent sodium silicofluoride enhanced early hydration and doubled the compressive strength of cement paste cured at 80 degrees Celsius.

The advantages of MCA are also evident when applied to low-reactivity clays. Mañosa, Maldonado-Alameda and Chimenos (2024) demonstrated that a mix using 30 percent mechanically activated muscovite clay reached compressive strengths similar to a control mix containing high-grade metakaolin. By contrast, the same muscovite clay subjected to calcination resulted in considerably lower strength at all tested intervals. This confirms MCA is an effective method for improving the performance of abundant 2:1 clays that are typically unsuitable for high-strength cement applications. From a practical and engineering perspective, MCA-LC3 offers significant advantages. Faster early strength development supports shorter construction timelines, while higher reactivity may enable increased clinker substitution without sacrificing mechanical performance. Current data, including the consistent achievement of 28-day strength targets, for example, 42 MPa versus 40 MPa, highlight the reliability and potential of MCA-LC3 as a sustainable, high-performance binder.

3. Environmental Impact and Sustainability

3.1 Energy and Emission Reduction Potential

MCA offers substantial environmental benefits by eliminating or significantly reducing the need for thermal calcination. Unlike conventional processes that depend on fossil-fuelled kilns, MCA operates on electrical energy, which can be sourced from renewable power, thereby lowering emissions (Mañosa, Alvarez-Coscojuela et al., 2024). Even in regions reliant on fossil-based electricity, MCA's energy demand remains substantially lower than that of calcination. For example, Thorne et al. (2024) demonstrated a 21.1% reduction in CO_2 equivalent values in fly ash–cement blends compared to limestone-based systems. Similarly, alkali-activated concrete, often processed through milling, has shown a 44.7% smaller carbon footprint than conventional cement concrete (Moraes et al., 2023). Moreover, MCA enables highly reactive clays to be produced with shorter grinding durations, reducing overall energy consumption (Mañosa, Alvarez-Coscojuela et al., 2024).

3.2 Raw Material Flexibility and Local Resource Utilisation

MCA also supports the valorisation of clays that are typically unsuitable for calcination, such as muscovite, illite, and certain industrial by-products. Mañosa, Maldonado-Alameda and Chimenos (2024) demonstrated that muscovite-rich clay, which shows poor reactivity post-calcination, can be effectively transformed into a viable supplementary cementitious material through mechanical activation. This expands the spectrum of usable raw materials, particularly in regions lacking high-purity kaolinitic clays. Furthermore, the ability to utilise locally sourced or waste clays reduces the environmental impact associated with long-distance material transport (Thorne et al., 2024).

3.3 Process Efficiency and Industrial Viability

From a practical standpoint, MCA-LC3 is increasingly viable at scale. Modern milling technologies, including vertical roller mills and high-efficiency vibratory mills, offer enhanced energy performance over traditional ball mills (Mañosa, Alvarez-Coscojuela et al., 2024b). Ongoing research aims to identify the most energy-efficient grinding parameters, as excessive grinding beyond a certain threshold can result in diminishing returns in reactivity (Őze and Makó, 2023). Industrial interest continues to grow, with European pilot plants already adopting MCA-LC3 for SCM production (Kanagaraj et al., 2022; Mañosa, Alvarez-Coscojuela et al., 2024b).

3.4 Wider Environmental and Socioeconomic Impacts

In addition to carbon savings, MCA-LC3 avoids pollutant emissions such as NO_x and SO_2 that are typically released during calcination (Boesch, Hellweg and Koehler, 2009). By removing the need for high-temperature kilns, it also reduces capital and operational costs, making low-carbon cement production more accessible in regions with limited infrastructure. The environmental profile of MCA is expected to improve further as global electricity grids transition to renewable sources. The World Cement Association (2024) emphasises that mechanical activation has a strong potential to significantly lower energy use and emissions associated with SCM production.

4. Conclusion

The following conclusions can be drawn from the above review, highlighting the hydration behaviour, mechanical performance, and environmental benefits of MCA in enhancing LC3 cement systems:

a. MCA enhances early hydration by shortening the induction period and intensifying pozzolanic reactions, offering a more energy-efficient alternative to thermal activation. However, its long-term impact on phase stability and hydration progression required further investigation.
b. Mechanochemically activated LC3 demonstrates clear advantages in mechanical performance, delivering superior early strength and equivalent or improved 28-day strength compared to traditional calcined systems. Its effectiveness across varying clay proportions, incorporation of supplementary materials, and compatibility with low-grade clays such as muscovite highlights its strong potential as a structurally robust, low-clinker cement alternative.
c. MCA is a compelling addition to LC3 technology. It supports climate goals by lowering CO_2 emissions, enables the use of local low-grade clays, reduces energy consumption, and simplifies infrastructure needs. With maturing technology and growing industry adoption, MCA-LC3 represents a viable pathway toward greener cement production.

MCA has emerged as a promising technique to enhance the performance and sustainability of LC3 cement systems. It improves early hydration kinetics, strengthens mechanical properties, and reduces the environmental footprint by eliminating the need for thermal calcination. MCA enables the effective use of various clay types, including those unsuitable for conventional processing, while supporting lower energy consumption and emissions. Recent advancements, including pilot-scale implementations, highlight its growing feasibility and industrial relevance. Although further optimisation is needed for full-scale deployment, current evidence positions MCA as a key innovation in the transition towards robust, low-carbon cement solutions.
This study has examined key mechanical parameters of MCA-LC3, including compressive strength, hydration mechanisms, pozzolanic reactivity, and environmental impact. With additional time and resources, further investigation into other parameters, such as durability, long-term phase stability, hydration progression, and a broader range of mechanical properties, would be possible.

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Kathmandu Metro-Induced Ground Vibrations and Attenuation

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Abstract

The development of a mass rapid transit system, such as railways, is crucial for addressing the increasing traffic demands in Kathmandu Valley. However, rail-soil interaction can generate vibrations that impact nearby structures and disturb residents. Quantifying these effects is vital for urban planners to design resilient infrastructure. Given Nepal's limited railway infrastructure, physical data on these impacts is limited, necessitating the use of numerical modelling and finite element analysis. This study evaluates ground vibrations caused by a proposed Kathmandu Metro Train operating at a design speed of 60 km/h. Soil properties from Bhimsengola, Kathmandu, and train dynamics based on the Winkler foundation model were used to simulate conditions in Plaxis 3D software. The results reveal a peak vertical ground displacement of 5 mm at a distance of 25 m from the vibration source. Parametric analysis indicates that soil stiffness significantly influences vibration responses. Therefore, implementing soil improvement techniques is recommended to mitigate vibration impacts. Additionally, adopting a lighter passenger train with an axle load of 170 kN could further reduce vibrations. In the hypothetical scenario of high-speed trains operating at 216 km/h, advanced ground improvement measures or underground systems would be necessary to mitigate potential vibration impacts. The study highlights the importance of dynamic analysis in designing railway systems to safeguard sensitive structures and maintain urban liveability in Kathmandu Valley.

Key Words: Kathmandu Metro, Ground Vibrations, Finite Element Method (FEM), Rail-Soi Interaction, Vibration Mitigation.

1. Introduction

Kathmandu Valley is undergoing rapid urbanization, with an annual population increase of about 3.3%, leading to significant traffic congestion. Despite a rise in vehicle numbers, limited road space, inadequate transportation services, and inefficient traffic control measures are exacerbating the problem (Macrotrends, 2022; Nepal Central Bureau of Statistics, 2021). To address this, mass rapid transit (MRT) systems, particularly railways, have been proposed to alleviate traffic congestion while preserving the valley's historic charm. Railways are climate-smart, efficient, and cost-effective, offering a viable solution to the urban transport crisis (Bastola et al., 2020; Tiwari et al., 2019). Although mass transit via rail dates back to the 6th century, the only operational train service in Nepal is the Nepal Janakpur-Jaynagar Railway (Department of Railways, 2025). A project report for the Mechi-Mahakali Electrified Railway is in progress, and ongoing research explores the potential for railway development in Kathmandu Valley (Poudel et al., 2022). Proposals for an underground metro system have been discussed, with feasibility studies examining various configurations of underground and elevated railways (Poudel et al., 2022; Shrestha & Tiwari, 2018).

While underground railways offer advantages like enhanced safety and minimal disruption, embankment railways provide benefits such as lower construction costs, fewer technical challenges, and more routing flexibility (Connolly et al., 2014; Gupta & Sharma, 2018). One of the primary concerns associated with railway systems is vibration, which can cause ground settlement, destabilize nearby structures, and disrupt both humans and animals (Connolly et al., 2014; Huang et al., 2017; Sharma & Pandit, 2021). The extent of vibration impact depends on factors like train speed, soil properties, and railway design (Connolly et al., 2014; Gupta, 2016; Tiwari et al., 2019). While research on the planning and construction of metro systems in Kathmandu Valley has been extensive, there is limited data on the operational phase, particularly regarding vibration impacts in sensitive areas like hospitals and laboratories. Thus, numerical analysis is needed to evaluate the influence of various parameters on ground vibration response (Poudel et al., 2022; Sharma & Pandit, 2021). This study aims to investigate the effects of soil properties, train speed, axle load, embankment height, and ballast stiffness on railway-induced vibrations (Shrestha, 2021).

The research seeks to analyze the impact of different factors on ground vibrations, specifically examining how dynamic train actions affect the soil. The study will compare vibration responses across different soil types, train speeds, and embankment conditions, with the aim of recommending strategies for mitigating vibration impacts. Additionally, the study intends to develop time-history data for train-induced vibrations for structural analysis of nearby infrastructure. The scope of this research is limited to the Bhimsengola area near Sinamangal Station, a proposed MRT route in Kathmandu, using simplified soil models like the Linear Elastic and Mohr-Coulomb models. The study does not account for water table fluctuations or the broader geographical impact of vibrations beyond the study area (Poudel et al., 2022; Shrestha & Tiwari, 2018).

1.1 Sources of Railway-Induced Vibration

Railway-induced vibrations originate from the interaction between the train and various track components, such as rails, sleepers, embankments, ballast, and ground support. This interaction generates dynamic forces that propagate through the track and induce vibrations in the surrounding ground. Several factors influence the level and characteristics of these vibrations:

Stress Waves Induced by Track Structure Response: Vibrations are caused by the interaction between the train and the track structure, with factors like axle weight, wheel spacing, and train speed playing a significant role. The magnitude of these stress waves varies depending on the operational characteristics of the train and track (Poudel et al., 2022).

Vibration Sources at the Wheel-Rail Interface: Vibrations at the wheel-rail interface are caused by unsteady vehicle motion, such as bouncing, rolling, and pitching. Additionally, dynamic properties of the vehicle bogie, wheel defects (e.g., eccentricity or imbalance), misalignment of motors, and acceleration/deceleration contribute to the overall vibration intensity.

Track Discontinuities: Rail defects like unevenness, waviness, and misalignments in track joints, switches, and curves cause additional forces that amplify vibrations. Tilting tracks further exacerbate vibration levels (Connolly et al., 2014).

Variable Support Conditions: The geometry, stiffness, and spacing of track components like sleepers and ballast, as well as the mechanical properties of the ground beneath the track, significantly influence the propagation of vibrations. Variations in these factors can alter the extent to which vibrations are absorbed or transmitted through the ground (Sharma & Pandit, 2021).

Understanding these sources is critical for devising effective solutions to mitigate the impact of railway-induced vibrations. The complex interactions between the vehicle, track, and surrounding environment necessitate a strategic approach to vibration reduction.

1.2 Transmission of Railway-Induced Vibration

Railway-induced vibrations primarily travel through the ground but can also propagate through the air. The primary mechanism for ground-borne transmission involves seismic waves generated by the dynamic interaction between the train wheels and rail surfaces. These seismic waves travel through the soil and are classified into body waves (longitudinal and shear waves) and surface waves, such as Rayleigh waves. Rayleigh waves, which propagate along the ground surface, are notable for their long-range travel and greater impact on surrounding structures and residents compared to body waves.

The propagation of these seismic waves is modeled using equations such as Navier's equation, which describes the displacement and stress in the soil as the waves travel through it. Understanding how these waves propagate is essential for predicting the potential impact of railway-induced vibrations on nearby structures. Proper modeling allows for assessing how vibration levels decrease with distance from the source and aids in the development of effective mitigation strategies (Poudel et al., 2022).

1.3 Vehicle Dynamic Load and Vibration Modelling

The dynamic load on the track and the resulting vibrations generated by trains are often random and influenced by complex interactions between various forces. Early research on vibration prediction focused on subway systems, but more recent studies have expanded to include surface trains. Researchers have developed methods to model and predict railway-induced vibrations, using empirical relations and statistical techniques. For instance, some studies have predicted ground-borne noise levels in buildings near subway tunnels, using empirical formulas to estimate vibration amplitudes (Sharma & Pandit, 2021). Statistical methods have also been applied to predict vibration levels in buildings near subway systems (Connolly et al., 2014). Research on high-speed rail systems in Europe has highlighted the uncertainties involved in predicting vibration levels due to the multitude of factors at play (Poudel et al., 2022). In-situ vibration testing, such as studies conducted in metro depots, shows that vibration amplitudes decrease significantly with distance from the source. This strategy is more relevant to high-speed rail, whereas the Kathmandu Metro, with a design speed of 60 km/h, operates within standard urban transit limits. Advanced vibration modelling techniques allow for the estimation of vibration levels based on various parameters, including train speed, track condition, and proximity to the vibration source.

Correia et al. (2007) modelled high-speed train tracks consisting of rails, sleepers, and rail pads supported by ballast, sub-ballast, a capping layer, and underlying soil. The study focused on the Thalys HST and assumed that, at train speeds below the critical speed, the axle load at each point follows a bell-shaped distribution (Figure 1). The load distribution was established using the solution of Winkler beam in the elastic foundation approach according to Equation (1).

$$F(s) = \frac{F_e}{2L} e^{-\left|\frac{s}{L}\right|} \left(cos\left|\frac{s}{L}\right| + sin\left|\frac{s}{L}\right| \right), \quad (1)$$

where, F(s) represents the distribution of force, Fe is the wheel load, L is the characteristic length, and s is the distance in the moving reference frame.

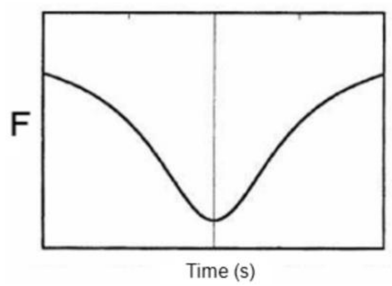

Figure 1: Distribution of load due to single axle (Correia et al. 2007)

The total impact of the train was determined by combining the load effects from all its axles. Each axle's load distribution was modelled based on the Thalys train. This superposition captures the overall vibration or force exerted by the moving train. The dynamic analysis was done using various 2D FEM software and the comparisons with measurement data were done. Figure 2 shows the simplified Vehicle model.

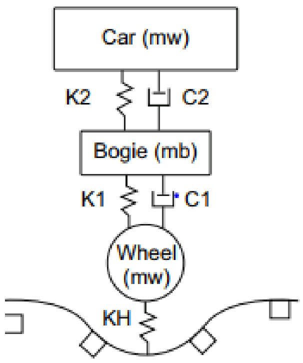

Figure 2: Simplified Vehicle model

A 3D numerical model was used to study the effect of embankment material on ground-borne vibration. The simplified vehicle model included detailed track geometries to realistically simulate force transmission from the vehicle to the track. Boundary damping, defined by stiffness parameters $k1$ and $k2$ and damping coefficients $c1$ and $c2$ were applied to absorb outgoing waves and mimic an infinite medium. Due to symmetry, only a quarter carriage was modelled to reduce computational effort.

The numerical analysis is based on a linear elastic Mohr-Coulomb (M-C) soil model, which does not account for damping or nonlinear soil behaviour. Additionally, the input soil profile is derived from a single borehole, which may not fully represent the spatial variability of soil conditions across the Kathmandu Valley. As such, the findings should be interpreted as site-specific and not directly generalized to the entire region. These limitations can be addressed through parametric studies; however, further research incorporating advanced soil models, damping characteristics, and multiple borehole data is recommended for more comprehensive vibration assessment.

2. Methodology

In this model, the ballast and embankment are represented as linear elastic materials, while the ground soil is modelled using the Mohr-Coulomb approach (Figure 3). The soil properties required for the Mohr-Coulomb model are determined based on the results of the Standard Penetration Test (SPT) conducted at BH-2 (Table 1) for the Kathmandu Valley Metro Project, using empirical methods. Table 2 shows the correlation equations and data employed for the material models.

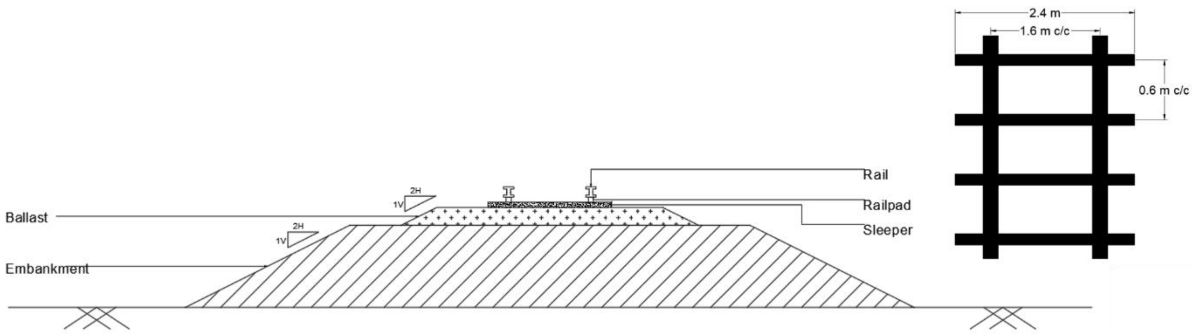

Figure 3: Cross section of the formation adopted in the study

Table 1: Borehole Log BH-2

Scale 1=50cm Each	Depth m	Thickness m	Sampling Depth m	Sampling Type	Soil Classification	Group Symbol	Soil Symbol	SPT (Field Record) 15 cm	30 cm	45 cm	Value N
	0.00 1.00	1.00			Fillings materials						
			1.50	SPT				6	7	11	**18**
		3.50	3.00	SPT	Gray to white medium dense gravely sand	SW		10	12	13	**25**
	4.50		4.50	SPT				4	5	7	**12**
	6.00	1.50	6.00	SPT	Gray medium dense silty sand, traces of gravels	SP		11	13	15	**28**

	5.00	7.50	SPT	Gray to white medium dense coarse to medium sand, traces of gravels	SW	10	13	15	**28**
		9.00	SPT			13	12	13	**25**
11.00		10.50	SPT			11	13	14	**27**
	5.00	12.00	SPT	Gray to white medium dense coarse to medium sand, traces of gravels	SW	10	12	12	**24**
		13.50	SPT			11	13	14	**27**
16.00		15.00	SPT			12	16	22	**38**
	5.00	16.50	SPT	Gray to white medium dense coarse to medium sand, traces of gravels	SW	13	17	21	**38**
		18.00	SPT			14	23	29	**52**
21.00		19.50	SPT			13	24	28	**52**
	5.00	21.50	SPT	Gray to white medium dense coarse to medium sand, traces of gravels	SW	14	23	27	**50**
		23.00	SPT			13	24	28	**52**
		24.50	SPT			14	26	28	**54**
26.00		26.00	SPT			14	25	27	**52**
	5.00	27.50	SPT	Gray to white medium dense coarse to medium sand, traces of gravels	SW	13	26	29	**55**
		29.00	SPT			14	26	28	**54**
31.00		30.50	SPT			16	27	29	**56**
33.00	2.00	32.00	SPT	Gray to white medium dense coarse to medium sand, traces of gravels	SW	15	26	28	**54**
	5.50	33.50	SPT	Dark gray medium sandy silt	ML	7	8	8	**16**
		35.00	SPT			8	6	7	**13**
		36.50	SPT			8	7	7	**14**
38.50		38.00	SPT			3	4	6	**10**
	11.50	39.50	SPT	Dark gray stiff clayey silt of low plasticity, traces of gravels	ML	4	5	5	**11**
		40.00	UDS						
		41.00	SPT			4	5	6	**11**
		42.50	SPT			7	6	6	**12**
		44.00	SPT			8	7	6	**13**
		45.50	SPT			6	6	8	**14**
		47.00	SPT			7	8	8	**16**
		48.50	SPT			7	8	6	**14**
50.00		50.00	SPT			8	7	6	**13**

Table 2: Correlation equations and data employed for the material models

1	Unsaturated Unit Weight	γ,unsat = 16 + 0.1N
2	Saturated Unit Weight	γ,sat = 18 + 0.01N
3	Angle of Friction	ϕ_p' = ($0.3N_{60}$) + 27
		ϕ_w' = 27.1 + $0.3N_{60}$ -0.00054$[N_{60}]^2$
4	Modulus of Elasticity	E = 300(N +6)
5	Poisson's Ratio	u=0.3
6	Damping Coefficient	ξ=3%

Where ϕp' is calculated from Peck et al. (1991), and ϕw' is calculated from Wolff (1989). The modulus, E is estimated according to Peck et al. (1974). Similarly, the material Properties used for the analysis are listed in Tables 3 to 7 below:

Table 3: Material parameters

Depth, m	N_{60}	E, kN/m^2	γ_{sat}	γ_{unsat}	ϕ_p'	ϕ_w'	$\phi_{adopted}$'	ν
0 - 4.5	22	8400	19.02	18.2	32.4	33.4	32	0.3
4.5 - 6	27	9900	19.07	18.7	35.4	34.8	35	0.3
6 - 33	23	8700	19.03	18.3	39.9	33.7	34	0.3
33 - 38.5	7	3900	18.87	16.7	30.9	29.1	29	0.3

Table 4: Properties of rail and sleepers

Paramter	**Unit**	**Rail**	**Sleeper**
Cross section area (A)	m^2	$7.7*10^{-3}$	$5.13*10^{-2}$
Unit weight (γ)	kN/m^3	78	25
Young's modulus (E)	kN/m^3	$200*10^6$	$36*10^4$
Moment of inertia around the second axis (I_3)	m^4	$3.055*10^{-5}$	0.0253
Moment of inertia around the third axis (I_2)	m^4	$5.13*10^{-6}$	$2.45*10^{-4}$

Embankments are thick wall of earth that is built to carry a railway over an area of low ground. The side slope of 2H:1V is adopted for embankment the height of embankment is varied from 1 m to 3 m to analyse the impact of height of embankment in vibration transmission.

Table 5: Properties of ballast and embankment (Aagah and Aryannejad, 2014)

Type	Ballast	Embankment
Material model	Linear Elastic	Linear Elastic
Drainage Type	Drained	Drained
Γ, sat	20 kN/m^3	19 kN/m^3
Γ, unsat	19 kN/m^3	18 kN/m^3
E'	200 - 300 MPa	200 MPa
ν'	0.3	0.3

The dynamic parameters for this analysis are primarily based on the design speed of the Kathmandu Valley Metro, which is 16.67 m/s (60 km/h). However, this speed reflects the maximum design limit and is not expected to be maintained throughout the route due to frequent stops at 1–3 km intervals typical in an urban setting. In practice, the operational speeds will be significantly lower, with average speeds likely ranging between 10 km/h and 60 km/h. Therefore, this study considers that range for parametric analysis, focusing on realistic urban metro conditions rather than high-speed rail scenarios. The previously considered 60 m/s (216 km/h) case is excluded, as it is not representative of Kathmandu's metro system.

Table 6: Properties of concrete base

Type	Soil and Interface
Material model	Linear Elastic
Drainage Type	Non Porous
Γ, unsat	$27\ kN/m^3$
Γ, sat	-
E'	$3.1 * 10^7 kPa$
ν'	0.15

Table 7: Properties of tunnel lining

Type	Plates
Material type	Elastic
d	0.35 m
Γ	$27\ kN/m^3$
E'	$3.1 * 10^7 kPa$
ν'	0.15

The length of each car is 22.100 meters, with an overhang of 2.250 meters. The wheelbase of each bogie is 2.500 meters, and the distance between Axle-2 and Axle-3 within a car is 12.600 meters. The train consists of 2 cars, totalling 8 pairs of wheels. The axle weights vary as 325 kN, 250 kN, and 170 kN, which correspond to individual wheel loads of 162.5 kN, 125 kN, and 85 kN, respectively. This axle configuration is based on the axle arrangement in the cars of the train as per Delhi Metro Rail Corporation Limited (2021).

The model domain is set with the boundary properties, except for z=0, being defined as viscous to minimize wave reflection from the boundaries. The model's length is 6 meters, incorporating 11 sleepers. A dynamic point load is applied at each intersection of the rail and the sleepers, and time history is generated for each point load. The time history superimposes the influence of wheel load based on the speed of the train, the location of the point load, and the wheel spacing of the train. This time history is then assigned to each point load using the Load Multiplier function, effectively simulating the train load (Figure 4). Figure 5 shows the Plaxis 3D model of subway train.

2.1 Dynamic loading

Figure 4 illustrates the dynamic load distribution from a single axle (left) and the time history of the load at an arbitrary sleeper, referenced at zero time, for a train speed of 30 m/s (right).

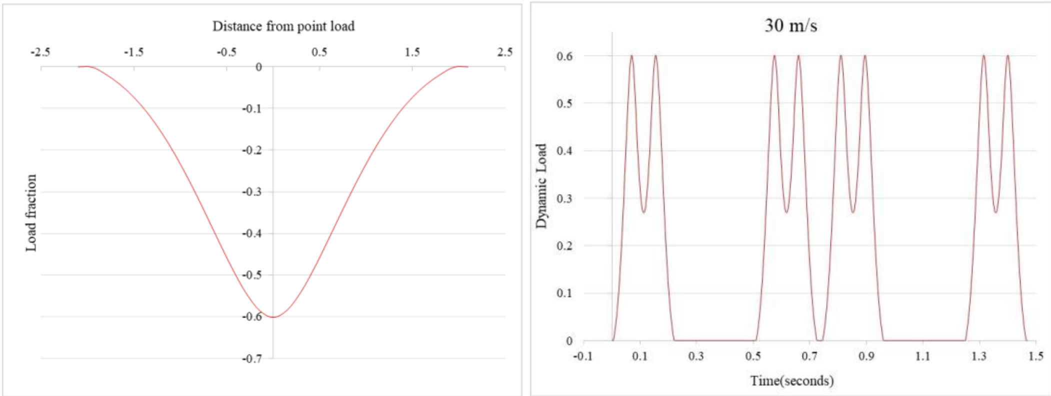

Figure 4: Dynamic analysis: Distribution of dynamic load due to single axle (Left); *Time history of load at an arbitrary sleeper at arbitrary zero time at train speed 30 m/s (Right)*

The design speed of 16.67 m/s (60 km/h) reflects the realistic operating speed for the Kathmandu Metro. Speeds higher than this, as shown in Table 8, are included solely for hypothetical analysis to understand the potential impact of increased speeds on ground vibrations. These cases are not intended to represent the actual operating conditions of the urban subway system.

Table 8: Dynamic Time Period and Signal Interval for each Speed of Train Considered

Speed	**Signal Interval**	**Dynamic Time Interval**
16.67 m/s	0.006 s	3 s
30 m/s	0.005 s	1.85 s
40 m/s	0.005 s	1.40 s
50 m/s	0.002 s	1.15 s
60 m/s	0.002 s	0.90 s

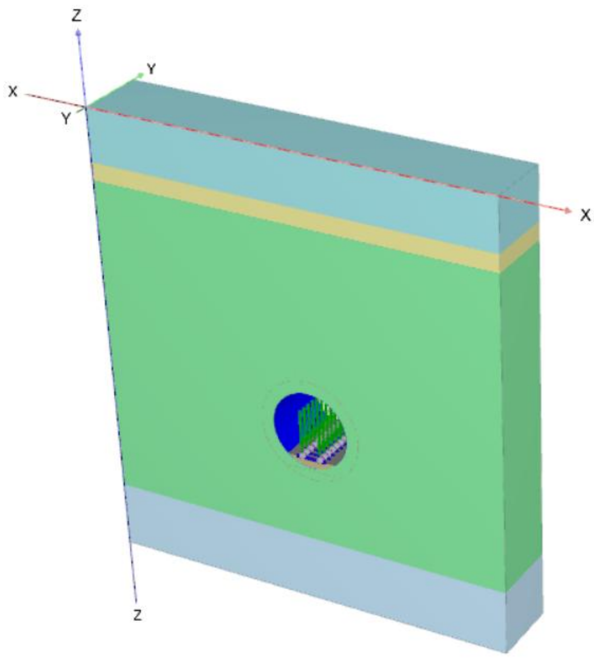

Figure 5: Plaxis 3D model of subway train

The full type model is considered for the analysis. For dynamic analysis, a larger area requires higher computational time and hence a section of 6 m is considered. The boundaries of the model are set as: Xmin=0, Xmax=35, Ymin=0, Ymax=6m. The radius of a single tunnel is adopted as 3.25 m. The lining of the tunnel is adopted as 0.35 m.

This paper focuses on analysing the ground response to train-induced vibrations by examining the effects of key parameters, including soil friction angle, soil stiffness, soil cohesion, and train axle load. The study evaluates vertical velocity and vertical acceleration at various distances from the vibration source to understand how these factors influence vibration propagation through the soil.

The study involves simulating soil vibrations induced by a metro train traveling at 60 km/h. Vertical displacement and vibration levels are evaluated at varying distances from the source to assess attenuation characteristics. The peak vertical displacement at 25 meters from the source is compared against allowable limits referenced from established metro guidelines. The study considers soil stiffness as a key factor influencing vibration response. While detailed ground improvement methods are beyond this study's scope, the analysis highlights the potential benefits of increasing soil stiffness—through techniques appropriate to local soil types such as clayey or sandy soils—as a strategy to mitigate vibrations.

A parametric study was conducted to evaluate the effect of ballast stiffness on ground vibrations by considering stiffness values of 200 MPa and 300 MPa. The simulation results focus on peak particle acceleration and velocity to assess vibration mitigation. A 10% reduction in peak particle acceleration was observed when increasing ballast stiffness from 200 MPa to 300 MPa, while changes in velocity were negligible. This suggests that 200 MPa ballast stiffness provides a cost-effective solution. Although the primary focus of this study is on underground (subway) metro systems, a limited parametric investigation was also conducted on embankment-supported surface train scenarios to compare vibration characteristics under different track configurations.

3. Results and Analysis

The dynamic load of the train is initially borne by the rails and then transmitted to the ballast through the sleepers, with the resulting vibrations propagating through the embankment and the surrounding soil. A numerical simulation was carried out using typical Kathmandu Valley soil conditions, considering a 1-meter-high embankment and a metro train traveling at its design speed of 60 km/h (16.7 m/s). The time history of vertical displacement was analysed at three monitoring points: directly beneath the rail, at the edge of the embankment, and at a location 25 meters vertically below the ground surface, directly above the tunnel alignment. These monitoring points are illustrated in Figure 4, which shows their spatial relationship to the track, embankment, and tunnel.

The vertical displacement response at these locations is presented in Figure 6, with the peak vertical displacement at the tunnel crown (i.e., the point 25 meters below ground level) reaching approximately 5 mm. However, the simulation results at greater depths or distances were affected by second-degree numerical integration error—a known limitation of the software—which can introduce minor inaccuracies in the calculated ground response over time (Figure 6).

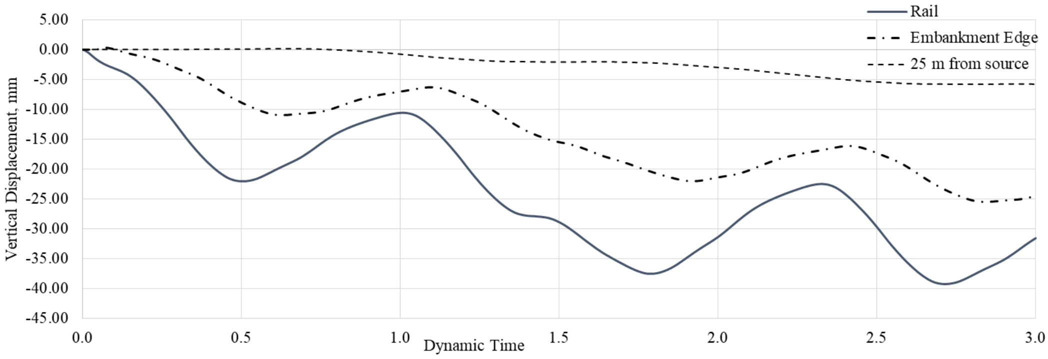

Figure 6: Time History of Vertical Displacement at speed 16.67 m/s

The angle of friction of the soil influences how effectively vibrations are transmitted through the ground. Higher friction angles typically reduce ground response by enhancing the soil's ability to resist shear forces, while lower friction angles result in greater vibration amplification (Figure 7).

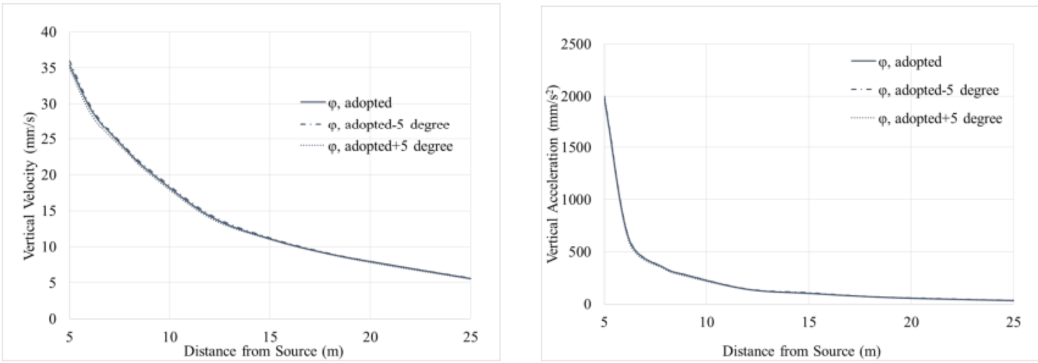

Figure 7: Variation of ground response with angle of friction of soil: Vertical velocity vs distance from source (Left Figure); vertical acceleration vs distance from source (Right Figure)

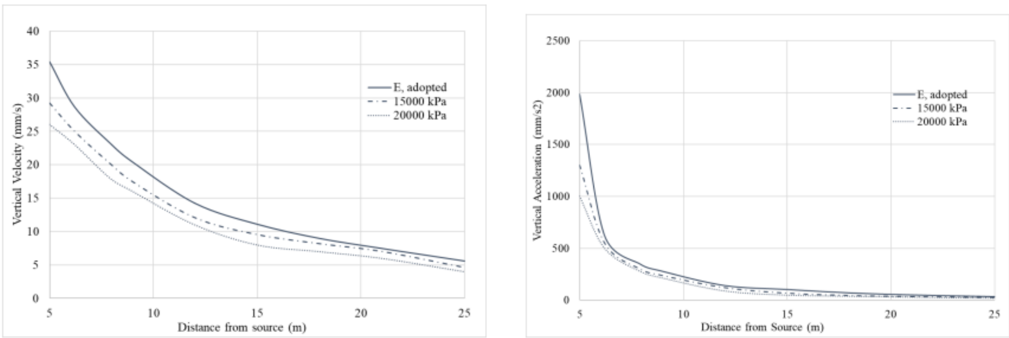

Figure 8: Variation of ground response with stiffness of soil: Vertical velocity vs distance from source (Left Figure); vertical acceleration vs distance from source (Right Figure)

The stiffness of the soil significantly affects the ground response, with stiffer soils resulting in lower vertical displacements and vibration amplitudes. Softer soils, on the other hand, tend to experience greater displacement and stronger vibrations, amplifying the impact of railway-induced vibrations (Figure 8). Similarly with cohesion results, Figure 9 is presented. The stiffness was selected based on average values representative of the dominant soil layers near the surface. A more detailed justification of the adopted stiffness values, considering site-specific geotechnical data and soil stratification, is provided to clarify the choice and its impact on the simulation results.

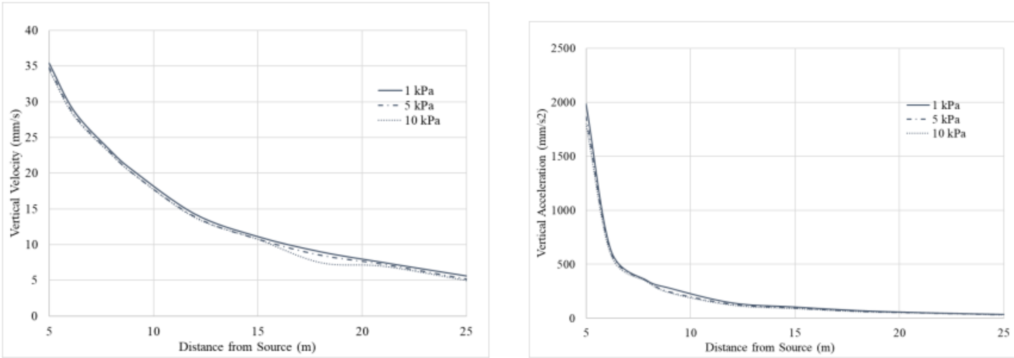

Figure 9: Effect of Cohesion of the soil on ground response: Vertical velocity vs distance from source (Left Figure); vertical acceleration vs distance from source (Right Figure)

The cohesion values used reflect conservative estimates based on local geotechnical data for Kathmandu Valley silty sands, capturing realistic soil variability despite generally low cohesion in such soils. The vertical velocity and acceleration of the soil particles increase in direct proportion to the increase in the train's axle load (Figure 10).

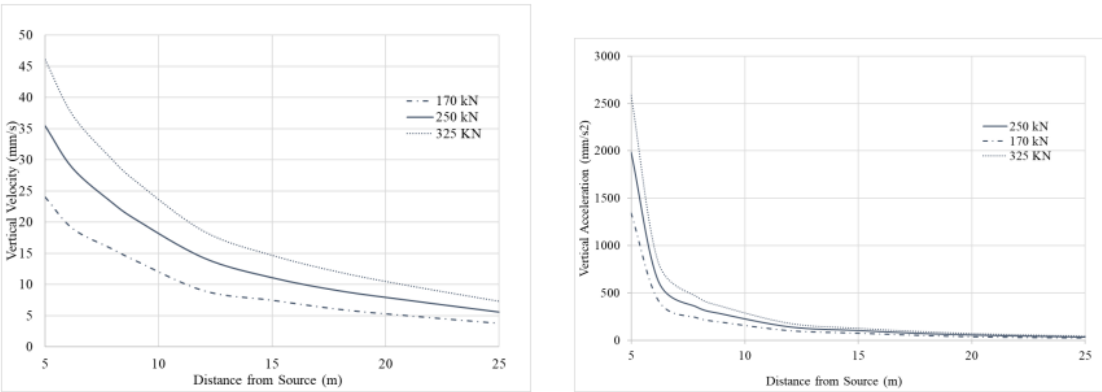

Figure 10: Effect of axle load of the train on vibration: vertical velocity vs distance from source (Left Figure); vertical acceleration vs distance from source (Right Figure)

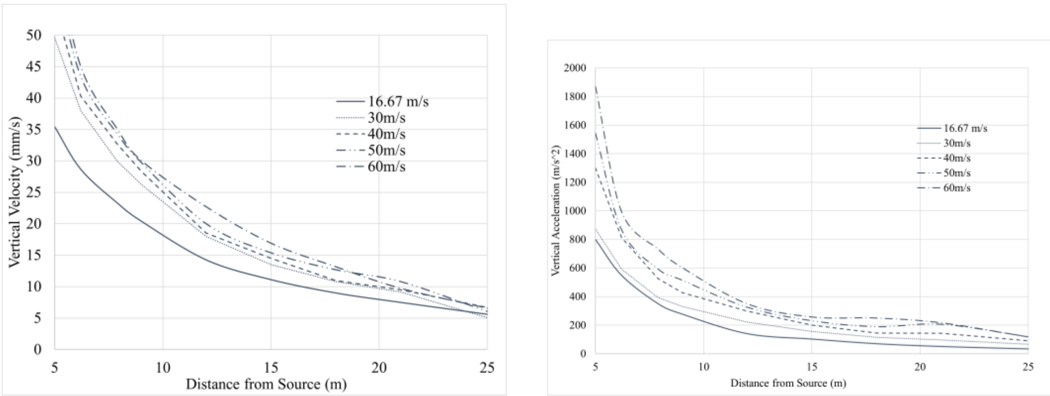

Figure 11: Effect of axle load of the train on vibration: Vertical velocity vs distance from source (Left Figure); vertical acceleration vs distance from source (Right Figure)

The adopted speed of 16.67 m/s (60 km/h) is representative of the Kathmandu metro design speed, while other speeds included are for comparative purposes only. The speeds outside this range are not directly relevant to the local context, and the figure aims to illustrate general trends rather than specific conditions. As the speed of the train increases, both the vertical velocity and acceleration of the soil particles also increase. This relationship highlights the significant impact of train speed on the magnitude of ground vibrations, with higher speeds leading to more pronounced soil movement (Figure 11).

4. Conclusion

Soil vibration decreases with distance from the source. For a train speed of 60 km/hr, the peak vertical displacement at 25 meters remains within the allowable limits as per Delhi Metro guidelines. The soil's stiffness is the key factor influencing vibration response, and ground improvement techniques focusing on increasing soil stiffness can effectively mitigate vibration impacts. The study shows that ground response is directly proportional to the train's axle load, suggesting that using trains with lower axle loads (170 kN) reduces vibration. A 10% reduction in peak particle acceleration was observed with an increase in ballast stiffness from 200 MPa to 300 MPa, though velocity changes were negligible, indicating that 200 MPa ballast is a cost-effective choice. Increasing embankment height from 1 to 3 meters reduced peak vertical velocity by 28% and peak vertical acceleration by 26%. These findings highlight the importance of optimizing train specifications, soil properties, and design to minimize railway-induced vibration impacts. Future studies should incorporate advanced soil models, damping effects, and multiple borehole data to improve the reliability and regional applicability of vibration assessments.

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Poster Presentation 1

From Blueprint to Build: How AI is Reshaping Construction

Srijana Khadka
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Executive Summary

Artificial intelligence (AI) is the application of computer systems able to perform tasks or produce output normally requiring human intelligence, especially by applying machine learning techniques to large collections of data. As we are all aware the rapid advancements are reshaping project management across various sectors revolutionising industries such as IT, manufacturing, retail, and telecommunications.

Considering the success of the application of AI in other industries, there is a potential to apply AI techniques and tools in the construction industry. However, in the current scenario, its application is limited and in addition to that according to the McKinsey digital globalization index, the construction industry is one of the least digitized industries globally, thus making it difficult to successfully apply advanced digital technologies to tackle the problems within the industry. The main aim of the study was to understand the current applications of AI in the construction industry emphasizing on what are the sub-fields of AI and how AI-driven tools are being used in the industry and their advantages. However, the challenges and limitations of applications of AI techniques in the construction industry have not been well considered in the study.

In order to understand the current state of AI in the construction industry, it was first important to understand the major components and the major subfields of AI and how can it be applied. The major components of AI are learning; knowledge representation; perception; planning; action, and communication and among many sub-fields of AI, for the purpose of this study 5 were considered (1) Machine learning (2) Computer vision (3) Natural language processing (4) Robotics (5) Optimisation. The different areas within the construction industry where it can be applied and its advantages have been summarized below:

Sub-domain of AI	Uses	Advantages
Machine learning	Health and safety monitoring, Cost estimation, Supply chain and logistics Process improvements, Risk prediction	Relevant predictive and prescriptive insights; Increased efficiency Cost savings; Improved safety; Efficient utilisation of resources; Reduced mistakes and omissions
Computer vision	Safety Management, Progress Monitoring, Productivity Tracking and Quality Control.	Faster inspection and monitoring; Better accuracy; Reliability and transparency; Cost effective; Increased productivity; Increased safety

Natural language processing	Document management; Safety management; Compliance; Risk management; Building Information Modelling (BIM)	Increased productivity; Cost effectiveness; Time efficiency; Improve communication among stakeholders
Robotics	Site monitoring; Performance evaluation; Offsite assembly; Management of construction materials, plant and equipment	Increased safety; Increased productivity; Improved quality; Better reliability and accuracy; Faster and more consistent than humans
Optimisation	Streamline construction schedules; Minimise delays, Improve project efficiency	Increased productivity (optimised processes); Increased efficiency; Cost and time savings

Poster Presentation 2

Examining the Socio-Economic Consequences of the Budhigandaki Hydropower: Insights from Khari and Chainpur Villages in Dhading District

Manoj Kapri
Project Planner
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Executive Summary

The Budhigandaki Hydropower Project—a proposed 1,200 MW storage-based scheme—represents a significant national initiative to address Nepal's longstanding energy challenges. The creation of a 45-kilometre-long reservoir is expected to inundate approximately 49.8 square kilometres of land and displace over 8,000 households. Among the most critically impacted are the villages of Khari and Chainpur in Dhading District, areas rich in cultural heritage and home to agrarian and indigenous groups, including the Kumal community.

This research employs a qualitative case study approach to explore the socio-cultural and economic implications of the project for these communities. Data were gathered through in-depth interviews, informal discussions, oral histories, focus group dialogues, and prolonged field observation. Relevant policy documents and planning materials were also reviewed to assess institutional frameworks and identify implementation gaps. By centering local perspectives and lived experiences, the study offers an interpretive understanding of displacement, adaptation, and resistance in the face of large-scale infrastructure development.

Key findings highlight a range of challenges. Compensation processes have been inconsistently applied, often based on outdated land records, and implemented with limited community consultation. Proposed resettlement sites are frequently unsuitable for agriculture or long-term habitation, contributing to further livelihood insecurity. The lack of transparency and participatory planning has led to mistrust in state institutions, exacerbating psychological distress and social fragmentation. Traditional occupations such as farming, pottery, and fishing face significant disruption, placing cultural continuity at risk.

While the Budhigandaki project is promoted as a driver of national progress, its success depends on an inclusive and ethically grounded implementation strategy. The study recommends ensuring timely, transparent, and context-sensitive compensation; identifying and developing safe, viable resettlement areas; and facilitating meaningful community participation at all stages of planning and execution. Cultural preservation and sustainable livelihood restoration must be prioritised to ensure long-term resilience and social justice.

Ultimately, the Budhigandaki Hydropower Project holds considerable potential to contribute to Nepal's energy future. However, its legitimacy and effectiveness will hinge on the extent to which it respects and uplifts the voices, rights, and well-being of those most affected. Equitable development is not only a policy imperative but also a prerequisite for achieving lasting and inclusive progress.

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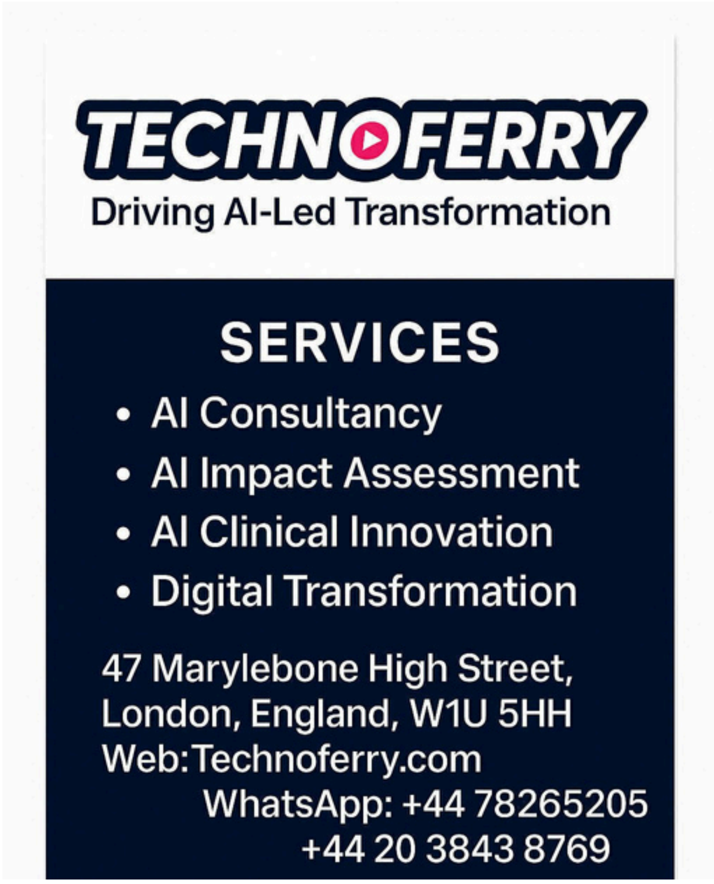

On the publication of the 10th Conference proceedings, it is an honour to support SONEUK's initiative towards an innovative and flourishing Nepal. As a founding member and past Chair Person, I would like to convey my best wishes for their future endeavours.

Ghanashyam Paudyal

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Warm congratulations on the SONEUK Conference 2025. Wishing the event resounding success in driving forward developments in science, engineering, and technology. The dedication of the SONEUK team in uniting thought leaders and fostering meaningful exchange is deeply valued.

Er Rudra Koirala
Immediate Past Chairperson
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Congratulations to SONEUK Conference 2025!

Wishing the event great success in advancing science, engineering, and technology.
The SONEUK team's efforts in bringing together experts and ideas are truly appreciated.

Er Shailendra Kajee Shrestha
Past Chairperson,
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Thank you for providing me an opportunity to support SONEUK as a sponsor for the success of the 10th Annual Conference.

Bigendra Bhari
Director
Sbhari LTD
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I would like to extend my warmest wishes for a successful and impactful 10th SONEUK Annual Conference.

Dr. Bidur Chapagain
MEng CEng MICE, SER Certifier

Huge Congratulations to newly elected SONE UK Team lead By Er. Subodh Timilsina. Best Wishes for successful 10th annual conference and publication of conference proceeding.
As a proud founder Member, I would like to extend my Warm wishes for success in the field of new Engineering innovation, research and professional excellence for Country and Global.

Rajendra Kharel
Executive Director
ESSR Consulting Group Ltd
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Best wishes to SONEUK on the publication of its 10th Conference Proceedings, a remarkable achievement in promoting research, knowledge sharing, and academic excellence.

Dr. Roshan Bhattarai
Manager, Transmission System Planning
ENOWA, NEOM, Saudi Arabia

We at PMPS Consulting extend our warmest wishes to SONEUK for the successful completion of its 10th Annual Conference, to be held in Cambridge, UK. This milestone event marks a decade of dedication to academic and professional excellence, and we commend SONEUK's continued efforts in fostering collaboration, knowledge sharing, and innovation across disciplines.

Subodh Timilsina
Director

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