11TH SONEUK CONFERENCE

Society of Nepalese Engineers in UK

Uniting Engineers for Change

SCIENCE, ENGINEERING AND TECHNOLOGY

4TH JULY 2026 | LONDON, UK

CONFERENCE PROCEEDINGS

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Editorial

Research and innovation in science, engineering, and technology play a vital role in addressing some of the world's most pressing challenges, including, but not limited to, climate change, food security, healthcare advancement, and the development of autonomous systems. Continued investment in research and development drives technological progress, improves quality of life, and contributes to a more sustainable future for our planet. In recognition of the importance of these efforts, the *Society of Nepalese Engineers in the UK* (SONEUK) is pleased to host its 11th Annual Conference on Science, Engineering, and Technology on 4th July 2026 in Heathrow, London, United Kingdom. The 11th SONEUK Conference arrives at a pivotal moment for engineering and disaster management professionals. As climate change accelerates and communities face mounting pressures, e.g., from erratic monsoons in Nepal to infrastructure demands across the UK, the papers collected in this volume chart a bold path forward.

The conference showcases nine peer-reviewed research papers, each presenting valuable insights into emerging developments and advancements across the fields of science, engineering, and technology. In addition, a dedicated poster presentation session has been arranged to promote knowledge exchange, foster professional dialogue, and provide networking opportunities for both early-career and experienced engineers. Together, these contributions highlight the transformative potential of research and innovation in addressing key challenges and creating new opportunities for Nepal and the wider global community. What unites these nine contributions is a shared recognition that the traditional approaches are no longer sufficient. Whether confronting flood risks in the Himalayan watershed or design errors in complex engineering projects, the authors demonstrate that resilience must be built proactively, not merely bolted onto failing systems.

Several papers explore the transformative potential of artificial intelligence and emerging digital technologies. One study reveals how deep learning models now consistently outperform conventional statistical approaches for flood prediction across Nepal's diverse river basins, offering the possibility of early warnings that reach vulnerable communities before waters rise. The same paper examines how generative AI tools could rapidly synthesise emergency information and generate multilingual alerts suited to Nepal's linguistically diverse population. Another contribution investigates AI-driven engineering innovation more broadly, examining technical characteristics such as data requirements, computational complexity, and integration with conventional workflows—while also addressing the practical realities of localising AI infrastructure in developing countries, including data centre availability, cooling requirements, energy profiles, and renewable energy potential. A third paper focuses specifically on project management, exploring how machine learning, predictive analytics, and real-time data integration can strengthen climate resilience throughout the project lifecycle, drawing valuable lessons from both UK engineering practices and Nepali infrastructure challenges.

Yet technology alone is not the answer. Practical obstacles remain, such as sparse monitoring networks, unreliable connectivity, skills gaps, and community scepticism toward automated warnings. The authors wisely advocate for strengthened data infrastructure, structured capacity building, and public-private partnerships. These enabling conditions are essential if AI and IoT systems are to deliver on their promise.

Alongside digital innovation, this volume offers rich insights from more traditional engineering and scientific inquiry. A longitudinal study of land-use change in the Kathmandu Valley, spanning four decades, reveals the relentless pressure of urbanisation on agricultural land and conservation areas. Archaeological analysis of Kapilvastu reimagines the monastic landscape through recent excavations, reminding us that understanding the past informs sustainable development. A BIM-based framework for residential construction in Nepal addresses the urgent need for sustainability assessment tools tailored to developing economies, while a review of LC3 cement highlights how indigenous clay resources could enable low-carbon construction pathways. The analysis of foreign direct investment determinants in Nepal's construction sector offers practical guidance for policymakers seeking to attract infrastructure capital, and a detailed FEM study of geosynthetically reinforced pavements provides engineers with evidence-based solutions for heavily loaded bends and uphill sections.

Together, these papers represent a commitment to rigorous inquiry and practical impact. They acknowledge uncertainty while refusing paralysis. They embrace innovation while respecting context. For conference delegates, this volume offers both inspiration and actionable knowledge, a foundation upon which safer, more resilient communities can be built.

As the Editorial Team, we are privileged to present these conference proceedings. We sincerely thank all the authors, reviewers, keynote speakers, and members of the SONEUK Executive Committee for their invaluable contributions and support. Their dedication and expertise have been instrumental in the success of this publication.

Compiling these proceedings has been a rewarding experience, and we trust that readers will find the papers both insightful and informative, reflecting the breadth and quality of research presented at the conference.

Welcome to the 11th SONEUK Conference.

Dr Deepak GC – Coordinator

Dr Rudra Paudel	Dr Bidur Ghimire	Dr Birendra Shrestha
Mr Hari Nepal	Dr Jaya Nepal	Dr Ramesh Marasini
Prof Hom Nath Dhakal	Dr Raj Kapur Shah	Dr Roshan Bhattarai
Mr Krishna Kishor Shrestha	Dr Rudra Paudel	Dr Ramhari Poudyal
Ms Sangita Pokheral	Prof Keshav Dahal	Dr Rishiram Parajul

Society of Nepalese Engineers UK

Message from the Chairperson

It is my great pleasure to welcome you to the 11th Annual Conference of the Society of Nepalese Engineers UK (SONEUK). It is an honour to gather with distinguished engineers, researchers, academics, industry professionals, and students as we continue our shared commitment to advancing engineering excellence, innovation, and collaboration.

This year's conference provides a valuable platform to exchange ideas, showcase research, and strengthen partnerships between academia, industry, and professional institutions. Under our chosen theme, we reaffirm SONEUK's commitment to promoting engineering knowledge, encouraging interdisciplinary collaboration, and inspiring practical solutions that address both local and global challenges.

A particular highlight of this year's conference is the keynote address by Professor Dr Hom Dhakal, who will deliver a lecture entitled "Sustainable Bio-composites for Advanced Applications: Opportunities for Circularity – State of the Art, Challenges and Emerging Trends." His internationally recognised research and leadership in sustainable composite materials will offer important insights into the opportunities and challenges of developing environmentally responsible engineering solutions within a circular economy.

We are deeply honoured to welcome Mr Bipin Duwadi, Charge d'Affaires a.i. (Acting Ambassador) of Nepal to the United Kingdom, as our Chief Guest. His gracious presence reflects the continued support of the Embassy of Nepal for the engineering profession and its commitment to strengthening professional, academic, and institutional collaboration between Nepal and the United Kingdom.

We are also grateful for the presence of Er Subash Chandra Baral, President of the Nepal Engineers Association, and Dr Aarti Thapa Hamal, President of the Nepal Doctors Association UK. Their participation highlights the importance of collaboration across professional bodies and further strengthens ties between Nepalese professionals in the UK and their counterparts in Nepal.

On behalf of SONEUK, I extend my sincere appreciation to all keynote speakers, session chairs, authors, reviewers, sponsors, exhibitors, volunteers, and delegates. Your dedication, expertise, and enthusiasm make this conference possible, and your contributions continue to strengthen our engineering community.

As SONEUK enters its second decade, we remain committed to fostering professional development, supporting research and innovation, and creating opportunities for meaningful collaboration among engineers across all disciplines. Together, we can continue to inspire the next generation of engineers and contribute to sustainable development in both Nepal and the wider global community.

I wish you all an engaging, productive, and enjoyable conference, and I hope the discussions and connections made today will lead to lasting collaborations and future innovations.

Thank you for your participation, and I look forward to welcoming you throughout the conference.

Subodh Timilsina
Chairperson
Society of Nepalese Engineers UK
(SONEUK)

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नेपाली राजदूतावास
EMBASSY OF NEPAL
LONDON,U.K.

Message

It is a privilege to extend my warmest greetings and best wishes to all members of the Society of Nepalese Engineers, the United Kingdom (SONEUK) on the occasion of 11th Annual Conference.

I also wish to express my deep appreciation to Chairperson Mr Subodh Timilsina for successfully steering the Society and the members of the Executive Committee for their unwavering commitment to the professional advancement, unity, and welfare of Nepali engineers in the UK.

The Embassy deeply values SONEUK's active engagement in promoting engineering excellence through academic conferences, seminars, continuing professional development, research initiatives, and knowledge-sharing forums. Your work spans critical areas of engineering methods, systems, and technologies, with a strong emphasis on practical application and knowledge transfer. These contributions are highly relevant to Nepal's national development priorities and are instrumental in fostering long-term capacity building.

I am particularly encouraged by the flagship initiatives introduced by SONEUK's Sixth Executive Committee, notably the CPD and Research Competition, which provide a valuable platform for young engineers and professionals to strengthen their research, innovation and analytical skills, competencies that are essential for professional excellence and for addressing the complex engineering challenges of the future. Such initiatives cultivate a culture of lifelong learning, innovation, and evidence-based practice within the engineering community. I believe that the initiatives taken by SONEUK will also be instrumental to the *Prativa Prapti Kendra,* an initiative by the Government of Nepal to connect talents from around the world to contribute to the nation.

Celebration of the 11th Conference is a testament to the resilience, unity, and growth of the Nepalese engineering community in the UK. Equally commendable is SONEUK's celebration of International Women in Engineering Day in collaboration with the Embassy of Nepal in June this year. In addition, I commend SONEUK for its commitment to social responsibility and for keeping the community spirit alive among the Nepali diaspora in the UK

Once again, I wish the 11th Conference of SONEUK a great success! Together, we can harness the expertise, innovation, and experience of Nepalese engineers in the UK for the development and prosperity of Nepal.

Wednesday, 01 July 2026

Bipin Duwadi
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ASNEngr
American Society of Nepalese Engineers

Founded in 2007
www.asnengr.org

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.

June 24, 2026

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 11th 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)
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NEPAL ENGINEERS' ASSOCIATION
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Message From the President

It gives me immense pleasure to extend, on behalf of Nepal Engineers' Association (NEA) and the entire engineering fraternity of Nepal, our warmest greetings and heartfelt congratulations to the Society of Nepalese Engineers in the United Kingdom (SONEUK) on the publication of these conference proceedings and the commencement of your 11th Annual International Conference in London.

The theme chosen for this year's publication and event, **"Science, Engineering, and Technology,"** is both timely and vital. As the global community evolves, engineers face the critical responsibility of driving sustainable innovation, navigating digital transformation, and prioritizing safety and net-zero milestones. Seeing our diaspora engineering community addressing these pivotal challenges through active research brings immense pride to us back home in Nepal.

NEA deeply values the knowledge, expertise, and global perspective that SONEUK members bring to the table. Written proceedings and platforms like this serve as vital repositories of contemporary technological advancements and research insights that can support Nepal's own developmental aspirations. We are confident that the 14+ research projects featured in this publication will inspire actionable ideas and foster deeper collaborations between our two organizations.

I would like to commend the SONEUK Executive Committee, the editorial team, and the organizers for their dedication to bringing this volume and conference to fruition. I wish the 11th SONEUK Annual International Conference a highly successful, productive, and impactful outcome.

Er. Subash Chandra Baral
President
34th Central Executive Committee

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Next-Generation Flood Resilience: Leveraging AI and Emerging Technologies for Smarter Disaster Management

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Abstract
Communities across Nepal face increasing flood risk as climate change drives more erratic monsoon patterns and accelerates glacial melt across the Himalayan watershed. Nepal's steep terrain causes water to move rapidly through narrow river channels, often producing downstream floods within hours. Current disaster management systems, while improving, still struggle with fragmented data collection, limited forecasting accuracy and poor coordination between authorities at different levels. This paper reviews how artificial intelligence (AI) and emerging digital technologies can help address these gaps and support a shift toward proactive flood management in Nepal. Deep learning methods have shown promising results in flood prediction tasks across several Nepali river basins, with models consistently outperforming conventional statistical approaches for the irregular rainfall patterns found across Nepal's diverse terrain. Recent advances in generative AI tools present opportunities for rapid information synthesis during emergencies and for multilingual alert generation suited to Nepal's linguistically diverse communities. The paper further examines how IoT sensor networks, satellite and drone imagery, blockchain systems and digital twin simulations could strengthen different stages of flood response, drawing on both global evidence and Nepal-specific deployments. Practical obstacles to technology adoption are also discussed, including sparse monitoring networks, unreliable connectivity, tight institutional budgets, shortages of technical expertise and community scepticism toward automated warning systems. Based on an analysis of technological advancements, the paper recommends strengthening national data infrastructure, delivering structured capacity-building programs, establishing public-private partnerships, and integrating new tools into existing national disaster risk reduction strategies. Together, these steps offer a pathway for Nepal to move beyond reactive emergency response toward systems that can anticipate flood threats, warn communities effectively and coordinate protection efforts before damage occurs.

Keywords: Flood resilience, Disaster Risk Reduction, Artificial Intelligence, Machine Learning, Early Warning Systems, Remote Sensing, Climate Change Adaptation.

1. Introduction
Nepal sits in one of the world's most flood-prone regions. The southern Himalayan slopes receive intense monsoon rainfall each year, glacial lakes threaten to burst without warning, and snowmelt rushes down steep valleys with little time for downstream communities to react. Between 2016 and April 2025, around 50,000 disaster incidents, including floods, landslides and fires, killed over 5000 people and injured more than 15000, with economic losses exceeding

NPR 33 billion (Nepal in Data, 2025). The September 2024 floods brought this reality into sharp focus. Kathmandu Valley experienced record-breaking 24-hour rainfall, with nearly 240 mm recorded at Tribhuvan International Airport, triggering floods and landslides that killed 249 people and caused an estimated NPR 46.68 billion in economic losses (National Disaster Risk Reduction and Management Authority, 2024). The country has made genuine progress on flood management since establishing the National Disaster Risk Reduction and Management Authority (NDRRMA) in 2019. But gaps remain wide. Early warning systems in river basins such as Karnali still provide communities with only about 2-3 hours of lead time, often enough to save lives but not livelihoods (Smith et al., 2017). Sparse hydro-meteorological station networks and equipment constraints continue to limit the reliability and reach of early flood warning in watersheds like the Ratu in the Koshi Basin (Bajracharya et al., 2021). Federal, provincial and local governments struggle to work together smoothly, and local response teams often depend on short-term project funding rather than permanent institutional support (Narayan et al., 2022).

Elsewhere in the world, artificial intelligence (AI) and digital tools are changing how countries deal with floods. Machine learning models consistently outperform traditional statistical methods for flood prediction, even with limited historical data (Mosavi et al., 2018). IoT sensors can monitor rivers in locations too remote for manual observation, while satellites processed through cloud platforms map flood extents within hours. Digital twins take this further, letting planners simulate scenarios and test interventions before disasters strike. Yet Nepal has been slow to adopt these tools. A 2025 review of machine learning work in Nepal's water sector confirms that while researchers are increasingly interested, the field lags well behind global standards (Chaulagain et al., 2025). We examine the realistic potential of AI and digital technologies for Nepal's disaster management authorities, review evidence of their effectiveness, identify adoption barriers, and propose actionable steps. In doing so, this paper contributes a structured, Nepal-focused synthesis of emerging technologies that disaster management practitioners, policymakers and researchers can draw on when making decisions about technology investment and institutional reform. The aim is to support Nepal's transition from a system that responds to floods after they occur to one that anticipates, communicates and acts before communities are put at risk.

2. Methodology

This paper presents a narrative synthesis of literature on AI and emerging digital technologies for flood resilience, focusing on Nepal. Literature was identified primarily through Google Scholar and resources accessed via the University of Hull library, supplemented by grey literature from institutional sources including ICIMOD, the World Bank, NDRRMA and Nepal in Data. Additional relevant studies were identified through citation chaining from key references. No strict date limits were applied, though preference was given to recent publications to capture current technological developments. Studies addressing flood predictions, early warning systems, damage assessment or disaster coordination using digital technologies were considered for inclusion. Priority was given to research conducted in Nepal or in comparable mountainous, data-scarce settings. Global studies were included where they provided foundational evidence or methodological insights applicable to the Nepalese context. The selected literature was organized thematically by technology type and synthesized to identify evidence of effectiveness, practical barriers and opportunities for adoption.

3. Flood Risk in Nepal

3.1 Where Flood Hit Hardest

Sharma et al. (2019) identify three types of terrain that bear the brunt of Nepal's floods. The terai plains along the southern border, where more than half the population lives, flood regularly when monsoon-swollen rivers overflow. The Koshi, Gandaki and Karnali basins funnel water from Himalayan catchments through valleys that have grown increasingly crowded over the decades. Kathmandu Valley, meanwhile, faces mounting risk as drainage infrastructure struggles to keep up with construction. Climate change is making things worse. The World Weather Attribution team analysed the September 2024 disaster and found that climate change made extreme 3-day rainfall events 70% more likely and 10% heavier (Zachariah et al., 2024). Up in the mountains, glaciers are vanishing at an alarming pace. ICIMOD reports that Hindu Kush Himalayan glaciers melted 65% faster between 2011 and 2020 than in the previous decade. On current emission pathways, they could lose up to 80% of their volume by 2100 (Wester et al., 2023). The consequences are already visible. In August 2024, a glacial lake burst in Solukhumbu District, sweeping away 14 properties, including a school, health post and several homes (ICIMOD, 2024).

3.2 What Early Warning Systems Can and Cannot Do

Nepal began experimenting with community-based flood warnings in 2002, starting in the East Rapti-Narayani river basin. Over the following decade, these systems expanded to cover eight river basins. The Department of Hydrology and Meteorology (DHM) has 286 meteorological stations and 170 hydrological stations nationwide, though most remain manually operated. When floods threaten, warnings are disseminated via mobile phones, SMS and local FM radio (Smith et al., 2017). However, Smith et al. (2017) note that these systems often do not provide warnings to the people with sufficient time. In the Karnali basin, communities get only 2-3 hours' notice, though newer forecasting methods could extend this to 7-8 hours. Real-time rainfall data remain scarce because Nepal's hydrometeorological station networks are sparse, and ground-based gauges have limited spatial coverage (Bajracharya et al., 2021). And even when warnings go out, many people struggle to understand what they mean or what they should do (Budimir et al., 2020). The legal framework compounds the problem. Despite having disaster legislation, Nepal's laws remain largely general rather than disaster-specific, while flood and landslide rules are fragmented and often weakly enforced. This dominance of general laws over specific, enforceable policies is identified as a critical reason for the country's continued vulnerability (Nepal in Data, 2025).

4. Technologies that could Make a Difference

4.1 Machine Learning and Deep Learning

Machine learning refers to computational methods that learn patterns from data to make predictions, while deep learning is a more advanced subset that uses layered neural networks capable of identifying complex relationships across large datasets (LeCun et al., 2015). Researchers have begun testing machine learning approaches on Nepal's rivers, and the results look promising. Duwal et al. (2023) applied Support Vector Machine (SVM), Random Forest and neural network models to flood susceptibility mapping in the Karnali River Basin. The SVM model outperformed the others, achieving AUROC scores of 92.8% on training data and 98.7% on test data. NDVI emerged as the most influential predictor, followed by elevation and distance to the river. Deep learning has taken this further in the Morang district, where a study combining Convolutional Neural Networks for spatial analysis and Recurrent Neural Networks for temporal patterns produced a comprehensive flood risk map classifying the region into five risk levels. The study found that roughly a quarter of residents live in high-risk zones, findings that could directly shape settlement policies (Thapa et al., 2025). Deep learning shows particular promise for predicting how rainfall turns into river flow, a tricky problem in Nepal's steep terrain. One study compared Long Short-Term Memory (LSTM) neural networks against HEC-HMS, a widely used hydrological model, in the Modi basin. The LSTM achieved a Nash-Sutcliffe Efficiency of 0.87, a measure of how well the predictions match reality, exceeding HEC-HMS at 0.73 (Marasini and Pokhrel, 2024). In the Seti Gandaki basin, a neural network with dropout and batch normalisation achieved 94.6% accuracy and an AUC of 98.9%, indicating near-perfect discrimination between flood and non-flood areas (Biswash et al., 2025). These Nepal-specific findings align with global research. A widely cited review found that combining multiple models, decomposing data into components, and optimising algorithms all increase prediction accuracy (Mosavi et al., 2018). More recent work shows LSTM networks outperforming other recurrent architectures, achieving a Nash-Sutcliffe score above 0.98 (Liu et al., 2023). These results are promising, but most studies remain confined to individual river basins with relatively good data availability. Scaling such models across Nepal's thousands of catchments would require hydrological records that simply do not exist for most watersheds, particularly above 3,000 meters where only two streamflow stations currently operate (Panthi et al., 2021). Translating these research prototypes into operational forecasting tools that work reliably across Nepal's diverse terrain remains an open challenge.

4.2 Large Language Models

Large language models are large-scale, transformer-based neural language models trained on massive amounts of text data, enabling them to understand, generate and translate human language across a wide range of tasks (Minaee et al., 2024). These models, which power tools like ChatGPT, offer a different kind of help. Rather than predicting floods, these systems could help communicate about them. One pilot project found that AI-generated emergency alerts achieved 98% accuracy when translated into Spanish while staying within character limits and using approved warning vocabulary (Seivold and Lyttle, 2024). In Nepal, where people speak more than 120 languages, this matters enormously. A survey of large language models in disaster management identified applications across vulnerability assessment, disaster prediction, early warning generation and information coordination, though the authors caution that most studies rely on generic models and highlight the need for domain-specific training and robust evaluation frameworks (Lei et al., 2025). In practice, these tools could help disaster response teams in Nepal rapidly compile situation reports, draft warnings in Nepali and local languages, or conduct hypothetical flood scenarios during preparedness planning. However, these applications remain largely theoretical in Nepal. Most large language models are trained predominantly on English text and their performance in Nepal's wide range of languages, particularly those with limited digital presence, is untested. Cloud-based AI tools also depend on reliable internet connectivity, yet Nepal's communication infrastructure remains vulnerable during the very disasters when these tools would be needed most (Bhandari, 2025).

4.3 Sensors and the Internet of Things

The Internet of Things (IoT) refers to a network of interconnected physical objects embedded with sensors and communication capabilities, enabling them to connect and exchange data with one another across a wide range of application domains, including environmental monitoring (Salih et al., 2022). ICIMOD established a Community-Based Flood Early Warning System on the Ratu River in 2015, installing wireless sensors at three upstream sites at a cost of around USD 3,500 per installation to detect rising water levels and alert downstream communities. Upgraded in 2017 with sensors extended across the border with India, the system now provides between one and three hours of warning and serves around 64,000 people along the Ratu River across Nepal and India (Pyakurel, 2023). Globally, IoT flood monitoring has grown more sophisticated. Researchers have tested long-range, low-power wireless networks (LoRaWAN) that operate on solar panels, achieving reliable data transmission across 600 meters in field trials, while the gateway is designed to cover up to 10 kilometers (Zakaria et al., 2023). More advanced IoT designs have been proposed that integrate water level, rainfall, soil moisture and ground movement sensors, using on-device AI to evaluate flood risk directly at the sensor node (Skoubris and Hloupis, 2023). Despite these global advances, Nepal’s IoT landscape remains largely dependent on cellular networks, with specialised low-power wide-area technologies yet to see widespread adoption (Dinesh, 2024), indicating that significant infrastructure development will be needed before such advanced systems can be widely deployed in Nepal.

4.4 Satellites and Drones

Satellites and unmanned aerial vehicles (UAVs), commonly referred to as drones, serve as complementary remote sensing platforms in disaster management, with satellites capturing temporal and spatial data across large areas and drones enabling rapid, high-resolution data collection at close range (Al Shafian and Hu, 2024). Satellite radar can penetrate cloud cover, which is crucial during Nepal’s monsoon season, enabling near-real-time flood mapping. A study traced floods across three Terai districts from 2019 to 2024 using Sentinel-1 radar data processed through Google Earth Engine, finding that approximately 6% of the study area flooded three or four times over the period, with 130 mm of three-day cumulative rainfall identified as a preliminary threshold for major flood events (Khatiwada et al., 2025). Through its SERVIR-HKH program, ICIMOD has developed two operational flood forecasting tools for Nepal. The first provides 10-day streamflow predictions for major rivers using ensemble modelling. In contrast, the second generates 48-54-hour flash-flood predictions for smaller, rapidly responding catchments using the HIWAT high-resolution weather model. Both tools are cloud-hosted and delivered via open-source web applications, thereby making sophisticated forecasting accessible without requiring expensive local infrastructure. Since 2019, Nepal’s DHM has formally incorporated these forecasts into its operational flood outlook (Tsering et al., 2021). However, Tsering et al. (2021) acknowledge that forecasting river discharge alone does not indicate which specific areas will be inundated and translating discharge predictions into meaningful community-level impact information remains a critical challenge in operational flood management. ICIMOD addressed this gap by developing a rapid flood-mapping method using Sentinel-1 SAR imagery, which can penetrate monsoon cloud cover to produce near-real-time inundation maps. Initially developed during the 2017 Bangladesh floods, the method was subsequently refined and extended to Nepal’s Terai and the Koshi River Basin to support flood management and relief operations (Uddin et al., 2021). Beyond satellite-based monitoring, drone technology has also emerged as a valuable tool for disaster response and damage assessment at a more localised scale. Nepal was among the first countries to deploy drones at scale following the 2015 earthquake for damage assessment and emergency response (World Bank, 2025). Following the June 2021 Melamchi flood disaster, a drone survey conducted by the World Bank was deployed over the affected watershed to document the extent of inundation and compile an inventory of damaged structures (Takamatsu et al., 2022). Building on such deployments, the National Disaster Risk Reduction and Management Authority (NDRRMA) has since signed a Memorandum of Understanding with the drone association to institutionalise the use of drones in disaster response (World Bank, 2025). Translating this commitment into operational capability will require investment in trained operators, equipment maintenance and the capacity to analyse and act on the imagery collected.

4.5 Blockchain and Digital Twins

Blockchain is a decentralized, tamper-resistant digital ledger technology that enables multiple parties to record and share data transparently without relying on a central authority, making it particularly suited to coordinating resources and information across organisations in humanitarian and disaster response contexts (Negi, 2025). Digital twins are virtual replicas of physical systems fed by real-time data that allow planners and emergency managers to simulate conditions and test disaster scenarios under a range of circumstances (Yang et al., 2024). Blockchain technology offers a way to coordinate and track relief assistance transparently across multiple organisations. The World Food Programme's Building Block platform, described as the world's largest blockchain-based humanitarian platform, enables multiple agencies to coordinate assistance while protecting personal data. Since 2022, it has prevented more than USD 287 million in overlapping assistance across Ukraine, Syria and Palestine, with its use now expanded across 159 organisations (World Food Programme, 2026). Blockchain applications in humanitarian supply chains offer benefits including secure records, streamlined payments and reduced fraud, with initial pilots already conducted in Nepal to deliver digital assets to rural communities in post-disaster scenarios (Negi, 2025).

Digital twins represent a more ambitious approach, creating virtual simulations of entire river basins fed by real-time sensor data that allow planners to test scenarios such as dam failures or levee breaches. China is building digital twins of major river basins, including the Yangtze and Yellow Rivers, whereas the EU has a comparable initiative through its Destination Earth program (Yang et al., 2024). More importantly, Yang et al. (2024) argue that such systems could significantly improve early warning, emergency rehearsal and scenario planning for flood events, addressing critical gaps exposed by recent disasters such as the 2021 Germany/Belgium floods. However, both technologies face significant adoption barriers. Blockchain adoption in humanitarian supply chains is constrained by regulatory uncertainty, lack of knowledge and employee training and high sustainability costs (Sahebi et al., 2020). Digital twins require high upfront investment, reliable connectivity and sophisticated IT infrastructure that remain challenging even in developed countries (Attaran and Celik, 2023).

5. From Individual Tools to Integrated Resilience

The technologies reviewed in this paper map onto different phases of the disaster cycle and their collective value is greater than the sum of their parts. Before any flood event, machine learning and deep learning-based flood risk maps can provide planners with the spatial evidence needed to identify high-risk zones and guide safer settlement and infrastructure decisions. Machine learning models can also support streamflow forecasting even in catchments where data is scarce, and when combined with IoT sensor networks, these forecasts can translate into ground-level warnings that give communities meaningful lead time. Digital twins can take this preparedness further by allowing planners to test their responses to extreme flood scenarios in a virtual environment before committing to real decisions. During an active flood, radar satellites can see through cloud cover to map inundation, while drones can assess damage in locations that ground teams cannot reach. Together, these tools can close the information gap that has historically slowed emergency response in Nepal. Large Language models can help translate warnings into local languages, making alerts more accessible to communities across Nepal's linguistically diverse regions. In the aftermath, blockchain platforms can support more transparent and accountable relief distribution across responding organisations. Together, these technologies can support a more systematic and connected approach to flood resilience than Nepal currently has in place.

6. Challenges and Barriers to Adoption in Nepal

Despite the promise these technologies hold, significant barriers stand between their potential and their practical deployment in Nepal. These challenges span data availability, physical infrastructure, governance, finance, human capacity and community readiness. Data scarcity sits at the root of most problems. Nepal's hydrological monitoring network is sparse and unevenly distributed, with most streamflow stations concentrated in the lowland areas and only two stations above 3,000 meters (Panthi et al., 2021). This is particularly problematic given that flood risk is highest in remote mountain catchments where data coverage is thinnest. Panthi et al. (2021) further note that machine learning and data-driven models require extended training datasets to accurately capture complex hydrological processes, records that are simply not available across many of Nepal's river basins. Connectivity limitations pose another significant barrier to reliable early warning delivery. Although Nepal has expanded access to mobile and telephone networks, the infrastructure remains vulnerable to the very hazards it is meant to address, including heavy rainfall, landslides and windstorms, with even brief disruptions critically delaying warning messages and communities reporting SMS alerts arriving up to six hours late in some cases (Bhandari, 2025). Without consistent network reliability, the timely delivery of warnings to at-risk communities cannot be guaranteed. Institutional and governance challenges compound technical constraints.

Nepal's DRRM framework reflects what Narayan et al. (2022) described as a centralised-decentralised dichotomy, where the capacity of governance to meet well-intentioned policies remains low and budgetary allocations continue to prioritise response over preparedness, despite the cost savings associated with the latter. Financial constraints and skill gaps also present significant obstacles. Local governments often lack adequate budgets, technical human resources and technological access to operationalise disaster management systems effectively (Narayan et al., 2022). These capacity gaps extend to disaster management institutions more broadly, where agencies report limited in-house expertise for communication and impact-based early warning analysis, while many community members remain sceptical of official warnings after past forecasts proved inaccurate (Bhandari, 2025). Ethical considerations, including data privacy, community consent and the risk of algorithmic bias in automated warning systems, will require attention as these technologies mature.

7. Recommendations and Future Directions

Realising the potential of AI and emerging technologies for flood resilience in Nepal requires coordinated action across six interconnected areas. The immediate priority is strengthening national data infrastructure through expansion of IoT-enabled hydrometeorological stations capable of real-time data transmission, supported by sustained government investment and international development partnerships. Alongside this, systematic capacity building in AI, geospatial analytics and digital early warning tools must be delivered through structured programs targeting staff at DHM, NDRRMA and local governmental levels. Public-private partnerships should be established with mobile network operators and technology firms to extend sensor networks and connectivity into remote areas where government resources are insufficient. Furthermore, investment in Nepal-specific AI models should be prioritised, building on existing basin-level research to develop operationally deployable forecasting tools tailored to Nepal's unique hydrological and topographic conditions. All emerging technologies must be integrated into Nepal's existing national disaster risk reduction frameworks and international commitments to ensure institutional ownership and long-term sustainability. Anticipatory action programs must be extended beyond the Terai to incorporate urbanising areas, ensuring that urban flood risk receives equal attention within Nepal's broader disaster resilience agenda. Collectively, these steps represent a broader long-term vision for Nepal's transition toward a climate-resilient digital disaster management ecosystem that is anticipatory, adaptive and sustained by strong institutional foundations.

8. Conclusion

Nepal's exposure to increasingly severe flood events, driven by climate change, glacial retreat and rapid urbanisation, underscores the growing importance of adopting advanced technologies in flood disaster management. This paper has shown that Artificial Intelligence, IoT, remote sensing and complementary digital tools offer well-evidenced pathways for improving flood prediction, early warning communication, damage assessment and disaster coordination in the Nepalese context. Technology alone, however, is not sufficient. Realising these benefits in practice requires sustained institutional commitment, coordinated national investment and genuine engagement with the communities facing the greatest flood risk. The central argument of this paper is that Nepal must move away from a predominantly reactive approach to disaster management toward one that is anticipatory and grounded in real-time data. Achieving this requires not only the adoption of AI-driven tools but also the governance structures, trained personnel and financial resources to sustain them. Future research should examine how these technologies perform under real operational conditions in Nepal, assess community acceptance of automated warning systems and develop cost-effective deployment models suited to resource-constrained settings. With those foundations in place, Nepal has a real opportunity to get ahead of flood risk rather than simply recover from it.

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AI-Driven Engineering Innovation: Technical Capabilities, Cost Implications, and Infrastructure Localisation in Nepal

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Abstract
Recent advances in machine learning, blockchain systems, and Large Language Models (LLMs) have moved AI from a supportive tool to an active participant in engineering workflows. This paper presents a comprehensive technical and economic analysis of AI-driven engineering innovation, with a specific focus on Nepal. The study evaluates the core technical capabilities of machine learning, blockchain, and LLMs, including their computational requirements, scalability, data dependencies, and integration with engineering systems. A detailed cost analysis compares cloud-based and on-premises deployment models across these technologies. The findings show that while AI systems often require high initial investment, they can deliver long-term cost efficiency, improved system performance, and environmental benefits. Furthermore, this paper introduces a sovereign AI infrastructure model tailored to Nepal, leveraging the country's renewable energy resources and addressing constraints such as limited connectivity and a geographically dispersed landscape. The proposed multi-tier architecture combines centralised high-performance computing with edge-based deployments for real-time applications. Through representative engineering use cases, including hydropower optimisation, construction management, and engineering education, the paper demonstrates the practical relevance of AI in addressing Nepal's development challenges. The study concludes with strategic recommendations for policy, infrastructure, and phased implementation, offering a roadmap for sustainable, localised AI adoption in developing countries.

Keywords: Artificial Intelligence, Machine Learning, Blockchain, Large Language Models, Engineering Innovation, Cost Analysis, Infrastructure Localisation, Nepal, Sustainable AI.

1. Introduction
Artificial Intelligence (AI) is increasingly transforming engineering practice by enabling systems capable of data-driven analysis, predictive modelling, and intelligent decision-making. Traditionally, engineering disciplines relied on deterministic models and empirical methods; however, recent advances in machine learning and deep learning have introduced new paradigms that enhance system optimisation, automation, and performance across complex engineering domains (Patil and Gudivada, 2024; Cabrera *et al.*, 2025).
Machine learning (ML) has demonstrated strong applicability in areas such as structural health monitoring, predictive maintenance, and seismic risk assessment. ML techniques have shown strong potential in structural engineering applications, including seismic risk assessment and damage prediction (Kiani, Camp and Pezeshk, 2019). ML techniques have been used to

estimate seismic fragility curves and predict structural damage under uncertainty, thereby reducing the need for computationally expensive numerical simulations (Cabrera *et al.*, 2025). These techniques are utilised via IoT to improve patient outcomes in healthcare, enhance the quality of care, and monitor resources to optimise healthcare infrastructure (Senisetty, B., and P, 2026). They are also used for diagnosing diseases, precision medicine, clinical learning, medical imaging analysis, personalised treatment, and organised medical records (Senisetty, B., and P, 2026). ML-based approaches have been adopted in predictive maintenance, where models analyse sensor data to detect anomalies and forecast failures in healthcare infrastructure, including biomedical devices, in real time (Moufid *et al.*, 2025). Similarly, ML-based optimisation is increasingly used in energy systems, smart grids, and industrial processes to improve efficiency and reliability. ML techniques such as time-series forecasting and reinforcement learning are increasingly used to optimise smart grid operations, improve load forecasting, and enhance renewable energy integration (Senisetty, B. and P, 2026). These approaches enable more adaptive and resilient engineering systems compared to traditional rule-based methods.

Alongside ML, blockchain technology has emerged as a complementary tool for engineering applications by providing secure, transparent, and decentralised data management systems, particularly in supply chain and infrastructure management (Dutta *et al.*, 2020). Top companies have implemented blockchain in various domains, including agriculture, manufacturing, energy, healthcare, civil engineering and aviation in a wide range of applications, including logistics management and traceability, smart contracts in international markets, and trading (Patil and Gudivada, 2024). In supply chain and construction engineering, blockchain enables secure tracking of materials, verification of certifications, and automated execution of contractual agreements through smart contracts (Patil and Gudivada, 2024). Studies have demonstrated its potential to improve accountability and reduce fraud in infrastructure projects. Additionally, blockchain has been explored in energy systems for peer-to-peer energy trading and decentralised grid management, contributing to more flexible and distributed energy networks (Patil and Gudivada, 2024).

More recently, Large Language Models (LLMs) have introduced new capabilities in engineering workflows, including natural language understanding, knowledge extraction, and technical reasoning, making them suitable for tasks such as documentation generation, standards interpretation, and engineering decision support (Kiani, Camp and Pezeshk, 2019). In construction engineering, LLMs have been applied to extract structured information from contracts and generate blockchain-compatible smart contracts, improving efficiency and reducing manual effort (Dutta *et al.*, 2020). Furthermore, LLMs are increasingly being integrated with domain-specific datasets and retrieval systems to enhance their reliability and applicability in engineering workflows.

Despite these global advancements, the adoption of AI in engineering remains limited in developing countries due to challenges such as insufficient infrastructure, a lack of high-quality datasets, and financial constraints. Nepal represents a compelling case where these challenges coexist with significant opportunities. The country faces critical engineering demands in areas such as hydropower development, seismic resilience, and infrastructure modernisation. At the same time, Nepal possesses substantial renewable energy resources, particularly hydropower, which can support the deployment of sustainable AI infrastructure.

A key issue in the adoption of AI systems is the trade-off between cloud-based and localised infrastructure. While cloud platforms offer scalability and low initial costs, they raise concerns about data sovereignty, long-term operational expenses, and dependence on foreign providers.

In contrast, localised or on-premises AI infrastructure can provide greater control, enhanced security, and improved long-term cost efficiency, particularly for large-scale or sensitive engineering applications (Cabrera *et al.*, 2025). In addition to individual technologies, recent research has explored the integration of AI systems within broader engineering workflows. Data-oriented architectures (DOA) have been proposed as an alternative to traditional service-oriented architectures (SOA) for managing large-scale data pipelines in ML systems. DOA emphasises data flow and transformation, enabling more scalable and efficient handling of heterogeneous engineering data (Li *et al.*, 2025). Furthermore, the energy consumption and environmental impact of AI systems have become critical considerations, with recent studies highlighting the carbon and water footprint associated with large-scale AI and blockchain operations (Siddik, Amaya and Marston, 2023; Li *et al.*, 2025).

Although existing research has extensively explored AI applications in engineering, there is limited work addressing the combined challenges of cost, infrastructure, and localisation in developing-country contexts. This gap is particularly relevant for Nepal, where engineering innovation must be aligned with economic feasibility, energy sustainability, and national priorities.

This paper addresses these gaps by providing a comprehensive analysis of AI-driven engineering innovation with a focus on Nepal. The main contributions of this study are as follows:

1. Technical Analysis: A detailed evaluation of machine learning, blockchain, and LLM technologies in engineering applications.
2. Cost Framework: A comparative analysis of cloud-based and on-premises deployment models, including economic and environmental considerations.
3. Infrastructure Localisation: A proposed conceptual sovereign AI infrastructure model tailored to Nepal's geographic and energy context.
4. Practical Use Cases: Demonstration of AI applications in key engineering sectors such as hydropower, construction, and education.

2. Technical Capabilities of Machine Learning, Blockchain, and Large Language Models for Engineering Systems

AI technologies are increasingly integrated into modern engineering systems, enabling advanced optimisation, intelligent automation, and data-driven decision-making. The technical capabilities of AI are primarily driven by three key paradigms: ML, blockchain systems, and LLMs. Each of these technologies offers distinct functionalities and computational requirements, making them suitable for different engineering applications.

In developing-country contexts such as Nepal, the adoption of these technologies must account for constraints in data availability, computational infrastructure, and energy resources. This section presents a technical analysis of these AI paradigms, focusing on their capabilities, architectural requirements, and applicability to engineering systems.

2.1 Machine Learning for Engineering Optimisation

ML has become a fundamental tool for solving complex optimisation and prediction problems in engineering. By leveraging historical and real-time data, ML models can identify nonlinear relationships, improve system efficiency, and support predictive decision-making (Kiani, Camp and Pezeshk, 2019; Cabrera *et al.*, 2025).

In engineering domains relevant to Nepal, ML has demonstrated strong applicability in several areas:

- Seismic Risk Assessment: ML models such as support vector machines, random forests, and neural networks are used to predict structural vulnerability and generate seismic

fragility curves. These approaches reduce reliance on computationally expensive simulations and improve prediction accuracy under uncertainty (Kiani, Camp and Pezeshk, 2019).
- Hydropower Optimisation: Time-series models, particularly Long Short-Term Memory (LSTM) networks, enable accurate forecasting of river flow, reservoir levels, and energy generation, improving grid stability and operational efficiency (Senisetty, B and P, 2026).
- Agricultural Monitoring: ML combined with remote sensing supports crop yield prediction, soil moisture estimation, and pest detection, contributing to resource optimisation and food security.

Despite these advantages, ML deployment in Nepal faces challenges such as limited labelled datasets, fragmented data systems, and inconsistent data quality. To address these constraints, several techniques are critical:
- Transfer Learning: Adapting pre-trained models to local contexts reduces data requirements.
- Domain Adaptation: Enables generalisation across geographic and environmental variations.
- Edge-Based Inference: Supports real-time decision-making in low-connectivity environments.

From a systems perspective, ML architectures are evolving from traditional Service-Oriented Architectures (SOA) to Data-Oriented Architectures (DOA), where data pipelines and transformation processes are central to system design. DOA improves scalability, reduces latency, and enhances interoperability in data-intensive engineering systems (Cabrera *et al.*, 2025). Some applications of ML across engineering domains that has been adopted by renowned companies are shown in Table 1.

Table 1: Applications by renowned companies in engineering domains

Engineering Domain	Applications	Example Companies
Agriculture	Yield prediction, irrigation optimisation, pest detection	John Deere, The Climate Corporation
Manufacturing	Predictive maintenance, process optimisation, quality control	Siemens, Bosch
Energy	Load forecasting, grid optimisation, and fault detection	Shell, EDF, National Grid
Healthcare	Medical image analysis, treatment optimisation, and resource planning	NHS, Philips
Civil Engineering	Structural monitoring, traffic optimisation, and construction planning	AECOM, Bentley System
Aviation	Flight optimisation, predictive maintenance, aerodynamic design	Airbus; Boeing; Rolls-Royce

2.2 Blockchain for Engineering Systems

Blockchain technology provides a decentralised and tamper-resistant framework for managing engineering data. Its core properties: immutability, transparency, and distributed consensus, make it particularly suitable for applications requiring trust and traceability (Patil and Gudivada, 2024).

In engineering contexts, blockchain enables:
- Material Traceability: Ensuring compliance with quality standards in construction projects
- Infrastructure Asset Management: Secure lifecycle tracking of engineering assets
- Disaster Response Coordination: Real-time, decentralised data sharing across agencies

However, traditional blockchain systems based on Proof-of-Work are computationally intensive and energy inefficient. For practical engineering applications, especially in resource-constrained environments, alternative approaches are required:

- Energy-Efficient Consensus Mechanisms: Proof-of-Stake (PoS) and PBFT reduce computational overhead
- Hybrid Architectures: Combining on-chain verification with off-chain storage improves scalability
- Permissioned Blockchains: Provide controlled access and higher throughput for engineering systems

From an engineering perspective, blockchain functions as an integration layer that enhances data integrity across distributed systems rather than a standalone solution. Some applications of Blockchain across engineering domains are listed in Table 2.

Table 2: Applications of Blockchain across engineering domains (Patil and Gudivada, 2024)

Engineering Domain	Applications	Example Companies
Agriculture	Food traceability, logistics, and crop insurance	Walmart, Alibaba, AgriDigital
Manufacturing	IoT security, supply chain finance	IBM, Ford, Hyundai
Energy	Smart grids, energy trading	LO3 Energy, KEPCO
Healthcare	Medical records, device tracking	NHS, MedVault
Civil Engineering	Smart contracts, digital twins	IBM, Siemens
Aviation	Ticketing, reward systems	Singapore Airlines

2.3 Large Language Models for Engineering Practice

LLMs represent a significant advancement in AI, enabling natural language understanding, technical reasoning, and knowledge synthesis. These models act as intelligent assistants that augment engineering workflows (Hochreiter and Schmidhuber, 1997). Key applications in engineering include:

- Multilingual Documentation: Translation and generation of technical documents
- Engineering Education: Interactive learning and problem-solving support
- Standards Compliance: Assisting in interpreting codes and generating reports

Agentic AI extends LLM capabilities by enabling autonomous task planning, access to tools, and iterative decision-making, enabling systems to execute complex engineering workflows with minimal human intervention.

In developing-country contexts, full-scale LLM training is often infeasible due to computational constraints. Therefore, efficient deployment strategies are essential:

- Domain-Specific Fine-Tuning: Improves relevance using local datasets
- Parameter-Efficient Methods: Techniques such as Low-Rank Adaptation (LoRA) reduce computational requirements
- Model Compression: Enables deployment on edge or local systems

LLMs can be integrated into engineering workflows through techniques such as retrieval-augmented generation and knowledge-enhanced training, allowing them to incorporate domain-specific standards and datasets (Patil and Gudivada, 2024). Some applications of LLM across engineering domains are listed in Table 3.

Table 3: Applications of LLMs across engineering domains

Engineering Domain	LLM Applications	Example Companies
Agriculture	Crop advisory, decision support	Bayer, Phytoform Labs
Manufacturing	Design assistance, quality control	ScaleAI, Siemens
Energy	Smart grid support, data interpretation	Google DeepMind, Microsoft
Healthcare	Clinical documentation, decision support	PathAI, Sully.ai
Civil Engineering	Documentation, compliance, BIM support	Autodesk, Aleph Alpha
Aviation	Maintenance logs, training support	IBM, Boeing, Airbus

2.4 Integration into Engineering Workflows and Limitations

Modern engineering workflows increasingly integrate AI systems with simulation tools, sensor networks, and data platforms. LLMs and ML models can be combined with structured databases and real-time data streams to enhance decision-making and automation. However, several challenges remain:

- Model Reliability: Risk of inaccurate or biased outputs
- Data Dependency: Performance depends on data quality and availability
- Security Risks: Potential misuse or adversarial attacks
- Computational Constraints: Limited infrastructure in developing regions

These limitations highlight the need for hybrid architectures, human-in-the-loop systems, and robust validation frameworks to ensure safe and effective deployment.

2.5 Deployment Cost, Infrastructure, and Energy Analysis

The deployment of AI systems in engineering applications involves multiple interrelated factors, including computational cost, infrastructure requirements, scalability, and long-term operational sustainability. These considerations are particularly critical in developing-country contexts such as Nepal, where limitations in financial resources, connectivity, and technical infrastructure influence technology adoption.

Table 4: Deployment in ML vs Blockchain vs LLM

Cost Factor	ML	Blockchain	LLM
Cost Structure	Compute-based (training + inference), storage, cloud subscription-based, or hardware (on-premises)	Public: transaction fees (gas, priority) Private: Infrastructure and network setup	Token-based pricing (API) or high infrastructure cost (GPU cluster, either cloud or on-premise)
Nature of Cost	Low (cloud) to moderate (on-premise)	Low (public)/ High (private setup)	Low (cloud access)/ very high (on-premise)
Scalability	High (cloud-based); hardware-limited (local)	Public: limited throughput; private: scalable within a controlled network	High (API, cloud); limited by hardware in on-premise setup
Infrastructure requirement	Moderate (GPUs/CPUs depending on model complexity)	Public: minimal; private: servers, nodes, networking	API: minimal; On-premises: very high (GPU clusters, high memory, storage)

Energy Consumption	0.001–0.01 kWh per inference	~0.025 kWh per transaction (Digiconomist, 2025)	~0.004 kWh per request in GPT-3 (Brown *et al.*, 2020)
Water Footprint	5–50 ml per inference	~387.5 ml per transaction (Siddik, Amaya and Marston, 2023)	~16.67 ml per request in GPT-3 (Li *et al.*, 2025)
Carbon Footprint	0.0002–0.002 kg CO_2e	~0.00575 kg CO_2e (DESNZ, 2024)	~0.00092 kg CO_2e (DESNZ, 2024)

Table 4 highlights the characteristics of ML deployment for blockchain and LLMs. From a practical perspective, ML systems emerge as the most feasible option for immediate implementation in resource-constrained environments such as Nepal. Blockchain deployment is justified in scenarios requiring high levels of transparency, trust, and data integrity, particularly through private networks despite their higher initial costs. LLM adoption, while offering advanced capabilities, requires careful consideration of long-term operational costs and infrastructure readiness. Overall, the selection of an appropriate technology must align with application-specific requirements, available resources, and strategic priorities, balancing short-term deployment feasibility with long-term scalability and sustainability.

Energy consumption is a critical factor in evaluating the sustainability of AI systems. While individual ML inference tasks consume relatively small amounts of energy, large-scale deployments can result in significant cumulative demand (Li *et al.*, 2025). Blockchain systems, particularly those using energy-intensive consensus mechanisms, exhibit higher per-transaction energy consumption, while LLMs require substantial resources during training and inference (Siddik, Amaya and Marston, 2023; Li *et al.*, 2025).

The environmental impact of AI systems depends heavily on the energy source. In regions relying on fossil fuels, AI deployment contributes significantly to carbon emissions. However, Nepal's hydropower-based energy system provides a low-carbon alternative, enabling sustainable AI infrastructure development. Localised AI deployment powered by renewable energy can significantly reduce environmental impact while ensuring long-term operational efficiency. Nepal's moderate climate supports energy-efficient cooling strategies, further enhancing sustainability. Additionally, carbon trading makes low-carbon data centres in cold, mountainous regions economically attractive, as seen in European countries, where operators benefit from reduced emissions and carbon-credit incentives. Combined with renewable energy and natural cooling, this approach lowers operational costs while aligning AI infrastructure with climate goals.

2.6 Implications for Nepal

The analysis indicates that a hybrid deployment model that combines cloud-based scalability with localised infrastructure is the most practical approach. Key insights include:

- Local infrastructure is preferable for sensitive and large-scale applications
- Cloud platforms are suitable for rapid prototyping and low-volume use
- Renewable energy enables sustainable AI deployment
- Hybrid architectures provide cost optimisation and flexibility

These findings highlight the importance of aligning AI deployment strategies with national infrastructure capabilities and sustainability goals.

3. Infrastructure Localisation Model

The effective deployment of Artificial Intelligence in engineering systems requires not only algorithmic advancements but also a robust, scalable, and geographically adaptive computing infrastructure. In developing countries such as Nepal, where terrain complexity, energy distribution patterns, and connectivity constraints significantly influence system design, infrastructure localisation is a critical enabler of sustainable AI adoption. This section proposes a conceptual sovereign AI infrastructure model designed to support national-scale engineering intelligence while ensuring data sovereignty, energy efficiency, and operational resilience.

The proposed architecture is motivated by the need to reduce dependence on external cloud ecosystems, mitigate latency constraints in remote engineering applications, and leverage Nepal's renewable energy potential, particularly hydropower, for sustainable computation. This aligns with recent national policy directions, including Nepal's National Artificial Intelligence Policy (2025), which emphasises the development of domestic AI infrastructure, data sovereignty, and sectoral AI applications in energy and infrastructure systems (Government of Nepal, 2025). The design follows a hierarchical distributed computing paradigm that integrates centralised high-performance computing with regional and edge intelligence layers. Furthermore, recent government initiatives under the current administration highlight the strategic importance of sovereign AI capabilities and localised compute infrastructure to reduce dependency on foreign cloud providers and enhance national technological resilience (Government of Nepal, 2026).

3.1 System Architecture Overview

The proposed sovereign AI infrastructure (Fig. 1) adopts a three-tier hierarchical architecture consisting of a National AI Compute Centre, Regional Edge Nodes, and Field-Level Deployment Systems. This multi-layered design enables a balance between computational intensity, real-time responsiveness, and geographical distribution.

At the system level, the architecture follows a hybrid cloud-edge continuum in which model training, inference, and decision execution are distributed based on computational demand, latency constraints, and data sensitivity. This structure is particularly suitable for engineering applications such as hydropower forecasting, seismic monitoring, construction automation, and infrastructure asset management, where both high-performance computation and real-time decision-making are required. This hybrid approach is consistent with Nepal's broader digital transformation agenda under the Digital Nepal Framework (2019), which identifies energy, infrastructure, and smart systems as priority sectors for technology-driven development (Government of Nepal, 2019a).

3.1.1 Tier 1: National AI Compute Centre

The National AI Compute Centre forms the foundational layer of the sovereign AI ecosystem. It is responsible for large-scale computational tasks, including training machine learning models, simulating engineering systems, and performing national-scale data analytics. This facility operates as a centralised high-performance computing (HPC) hub supporting both scientific and engineering AI workloads.

A key design consideration for this layer is energy-aware compute localisation. Given Nepal's significant hydropower resources, the strategic placement of compute infrastructure near energy generation sites can reduce operational costs and improve energy reliability. This alignment between energy production and computational demand represents a critical advantage for sustainable AI infrastructure development. Such an approach directly supports national priorities outlined in the National AI Policy (2025), which emphasises leveraging renewable energy sources for sustainable AI infrastructure and promoting environmentally responsible computing practices (Government of Nepal, 2025).

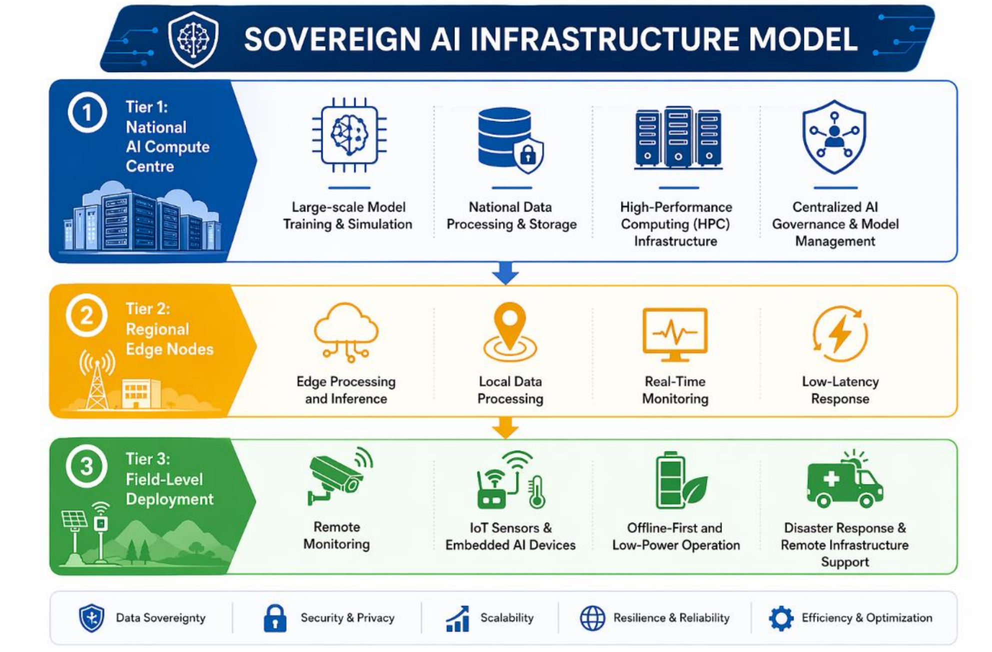

Figure 1. Sovereign AI Infrastructure Model

The proposed compute capacity in the range of 100–500 PetaFLOPS supports computationally intensive tasks such as seismic risk simulation, hydrological modelling, infrastructure digital twins, and training of domain-specific large language models. These capabilities are essential for enabling national-scale engineering intelligence systems.

From an infrastructure engineering perspective, thermal management is addressed through a hybrid cooling strategy combining free-air cooling, leveraging Nepal's moderate climatic conditions, with advanced liquid cooling systems for high-density GPU clusters. This significantly reduces the power usage effectiveness (PUE) of the system while maintaining operational stability under continuous workloads.

3.1.2 Tier 2: Regional Edge Intelligence Nodes

The Regional Edge Layer extends computational capabilities beyond the centralised facility by distributing processing power across major urban and industrial centres, including Kathmandu, Pokhara, Biratnagar, and Nepalgunj. This layer serves as a critical intermediary between centralised computation and field-level deployments.

The primary function of this layer is to enable low-latency inference for time-sensitive engineering applications such as flood prediction alerts, structural health monitoring, and real-time grid balancing. In addition, regional nodes perform data preprocessing, feature extraction, and compression, thereby reducing bandwidth consumption and improving overall system efficiency. The decentralisation of compute resources also aligns with government efforts to improve digital infrastructure accessibility beyond urban centres, as outlined in national ICT and digital inclusion strategies (Government of Nepal, 2019a).

This distributed design significantly enhances system resilience by reducing dependence on the central compute facility. In the event of network disruptions or natural disasters, regional nodes can continue to operate autonomously, ensuring continuity of critical engineering services.

High-speed fibre-optic connectivity is required to synchronise regional nodes with the national compute centre, enabling periodic model updates, coordination of federated learning, and centralised monitoring. This architecture aligns with modern edge-cloud hybrid paradigms widely adopted in large-scale cyber-physical systems.

3.1.3 Tier 3: Field-Level AI Deployment Systems

The Field Deployment Layer represents the closest point of interaction between AI systems and physical engineering environments. This layer consists of embedded systems, mobile AI units, and IoT-enabled sensors deployed in geographically distributed and often infrastructure-limited regions.

These systems enable real-time monitoring and decision support in applications such as disaster response, infrastructure inspection, hydropower plant monitoring, and agricultural engineering systems. Mobile AI units deployed for emergency response scenarios can perform on-site inference without requiring continuous cloud connectivity, thereby ensuring operational continuity in crisis conditions. This approach is particularly relevant in the context of Nepal's national priorities for disaster risk reduction and resilient infrastructure, where real-time, localised intelligence is critical for effective response and recovery operations (Government of Nepal, 2019b).

Given Nepal's challenging topography and limited connectivity in remote regions, this layer prioritises offline-first AI operation and energy-efficient computing. Devices in this tier are designed to operate under intermittent connectivity conditions and are often powered by renewable micro-sources such as solar panels or micro-hydropower systems. This ensures sustainable operation even in geographically isolated regions.

The integration of IoT sensors, unmanned aerial systems, and embedded edge processors enables continuous data acquisition from physical infrastructure, creating a real-time digital representation of engineering systems nationwide.

3.2 System-Level Design Considerations

The effectiveness of the proposed infrastructure model depends on several cross-cutting system engineering principles that govern scalability, interoperability, resilience, and security.

Scalability is achieved through modular expansion across all three tiers, allowing incremental growth of compute, storage, and networking capacity without system redesign. Interoperability is ensured through standardised APIs and integration protocols that allow seamless interaction with existing engineering systems, including SCADA platforms, GIS systems, and national data repositories.

Data sovereignty and security represent core design principles of the architecture. By ensuring that sensitive engineering and infrastructure data remains within national boundaries, the system reduces dependency on external cloud providers and enhances compliance with national regulatory frameworks. This is consistent with Nepal's emerging regulatory approach to AI governance, which emphasises national control over data, ethical AI use, and secure digital infrastructure as outlined in recent policy initiatives and legislative discussions (Government of Nepal, 2025). Blockchain-based audit mechanisms may further enhance data integrity and traceability within this ecosystem.

Resilience is addressed through distributed system design, ensuring that failure in one tier does not cascade across the entire system. This is particularly important in Nepal, where seismic activity and natural disasters can disrupt centralised infrastructure. Energy-aware design principles are also integrated to optimise computational workloads based on the availability of renewable energy, particularly hydropower generation cycles.

3.3 Phased Implementation Strategy

The deployment of sovereign AI infrastructure is envisioned as a phased strategy to minimise financial risk and ensure the progressive development of capabilities. Such phased development aligns with the government's broader AI vision, which emphasises gradual capacity building, pilot deployments, and scaling of AI systems across priority sectors, including energy, infrastructure, and public services (Government of Nepal, 2025). In the initial phase, a pilot National AI Compute Centre is established to validate system architecture and support early-stage engineering applications. This is followed by the gradual deployment of regional edge nodes in major urban centres, enabling distributed inference capabilities and improving system responsiveness.

In the final phase, field-level integration is achieved by deploying embedded systems and IoT networks across critical infrastructure domains. This progressive rollout ensures that each stage builds upon validated infrastructure capabilities while allowing continuous refinement of system performance.

3.4 Strategic Implementation Framework for Nepal

The deployment of a sovereign AI-driven engineering ecosystem in Nepal requires a structured, phased implementation strategy that aligns infrastructure development, policy formation, and human capital readiness. Recent national initiatives highlight the importance of integrating AI policy, infrastructure investment, and workforce development to achieve long-term technological self-reliance and innovation capacity (Government of Nepal, 2026). Given the strong interdependence between compute infrastructure, data governance, and sectoral integration, a staged roadmap is essential to ensure scalable and sustainable AI adoption in engineering systems.

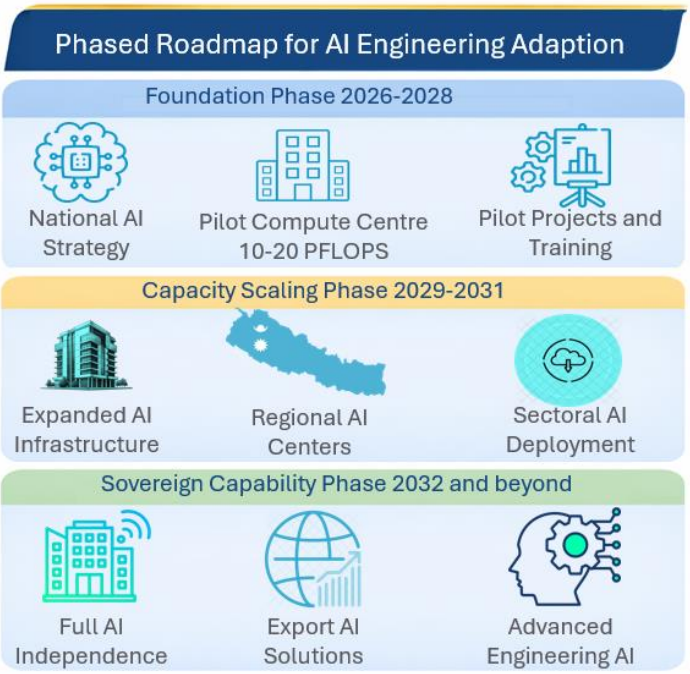

Figure 2. Phased Roadmap for AI Engineering Adaptation

3.4.1 Phased Roadmap for AI Engineering Adoption

The proposed roadmap consists of three progressive phases representing increasing levels of technological maturity and sovereignty (Fig. 2).

In the foundation phase (2026–2028), Nepal establishes a National AI Strategy focused on engineering applications and develops a pilot AI compute infrastructure with a capacity of 10–20 PetaFLOPS. This phase prioritises experimentation in key domains such as hydropower forecasting, infrastructure monitoring, and disaster risk analysis. Parallel efforts focus on developing engineering-specific AI training programs and establishing a regulatory sandbox to support controlled innovation.

The capacity scaling phase (2029–2031) expands compute infrastructure beyond 100 PetaFLOPS and extends AI deployment across critical engineering sectors, including energy, transportation, construction, and disaster management. During this phase, Nepal-specific AI models and datasets are developed, while regional AI competence centres are established to decentralise expertise and improve system resilience.

In the sovereign capability phase (2032 and beyond), Nepal achieves full-cycle AI development capacity, enabling independent design, deployment, and maintenance of engineering AI systems. This phase emphasises export-oriented AI solutions tailored to mountain engineering, hydropower optimisation, and climate-resilient infrastructure, positioning Nepal as a regional hub for specialised engineering AI systems.

3.4.2 Policy and Institutional Framework

In the short term (0–12 months), a National AI Engineering Task Force is established to coordinate strategy, define standards, and prioritise sectoral applications. Data-sharing frameworks for engineering datasets are introduced, alongside incentives to accelerate AI adoption in engineering industries.

In the medium term (1–3 years), a Nepal Engineering AI Cloud initiative is being developed to provide shared computational resources for engineering applications. Standardisation frameworks and certification mechanisms are introduced to ensure quality assurance in AI-enabled engineering systems. Public–private partnerships and AI-integrated engineering curricula further strengthen ecosystem development.

In the long term (3–5 years), Nepal aims to achieve AI self-sufficiency in critical engineering domains, develop exportable AI solutions, and integrate AI across national development priorities, establishing itself as a regional hub for engineering AI innovation.

3.4.3 Risk Assessment and Mitigation Strategy

Technical risks related to scalability, model reliability, and infrastructure integration are addressed through hybrid cloud–edge architectures, phased deployment, and continuous benchmarking against international standards.

Economic risks, including high initial investment and uncertain returns, are mitigated through phased funding strategies and early deployment of AI-as-a-Service models to generate revenue streams. Diversified financing mechanisms further reduce dependency on single funding sources.

Operational risks such as system downtime, cybersecurity threats, and skill shortages are managed through redundant system design, disaster recovery planning, and structured workforce development programs. Continuous monitoring of system performance ensures long-term operational stability.

4. Representative Engineering Use Cases

This section presents representative engineering use cases demonstrating the integration of Machine Learning (ML), Large Language Models (LLMs), and blockchain technologies in Nepal's critical infrastructure domains. Unlike conventional application-centric studies, the discussion is framed from a systems engineering perspective, in which AI technologies are embedded within cyber-physical infrastructures to enable perception, reasoning, trust verification, and automated decision-making. The objective is to illustrate how AI transitions from isolated models that perform discrete tasks to integrated infrastructure-intelligence systems that support real-time engineering operations.

4.1 AI-Enabled Smart Grid and Hydropower Optimisation System

Nepal possesses significant renewable energy potential, with approximately 83,000 MW of hydropower (42,000MW economically viable), receives sunlight of an average of 6.8 hours per day with potential capacity of about 47628 MW of solar energy, and 1,686 MW of wind energy capacity (Neupane *et al.*, 2022; Lohani *et al.*, 2023). Despite this abundance, the national energy system continues to face operational constraints due to intermittency in renewable generation, limited forecasting accuracy, and weak coordination between generation and demand centres. These challenges often result in grid instability, including voltage fluctuations and frequency deviations, particularly during seasonal hydrological variations.

To address these challenges, an integrated AI-driven smart grid framework is required, in which multiple data modalities and computational layers operate in coordination. The system is driven by heterogeneous data streams from SCADA systems, smart meters, and distributed IoT sensors, providing real-time operational visibility into the grid. These structured datasets are complemented by unstructured inputs such as meteorological reports, operator logs, and maintenance records, which contain contextual information critical for operational decision-making.

Within this framework, machine learning models, particularly Long Short-Term Memory (LSTM) networks, are utilised for time-series forecasting of hydrological patterns, energy generation, and demand behaviour (Hochreiter and Schmidhuber, 1997). These models can capture long-term temporal dependencies in energy systems, thereby improving prediction accuracy for renewable energy variability. In parallel, Large Language Models are integrated as contextual reasoning modules that interpret unstructured operational data, generate structured summaries of grid conditions, and assist operators in decision-making processes. This enables the transformation of traditional forecasting systems into context-aware energy intelligence platforms.

The integration of Retrieval-Augmented Generation mechanisms further enhances system reliability by grounding LLM outputs in verified historical datasets, engineering constraints, and operational guidelines. This reduces the risk of hallucinations and ensures alignment with domain-specific knowledge. In addition, the system incorporates an optimisation layer for demand-response scheduling and grid balancing, which can leverage reinforcement learning or heuristic optimisation techniques.

To ensure practical deployment in distributed environments, particularly in remote regions of Nepal, computational efficiency is addressed through model compression techniques such as quantisation, pruning, knowledge distillation, and caching. These techniques enable deployment on edge devices with limited computational capacity while maintaining acceptable inference performance.

Recent research has demonstrated the effectiveness of integrating blockchain with machine learning-based forecasting systems. In particular, hybrid architectures combining blockchain and LSTM models have been shown to improve energy utilisation stability by approximately 70 per cent compared to conventional baseline methods, highlighting the value of combining predictive intelligence with decentralised trust mechanisms in energy systems (Senisetty, B and P, 2026).

4.2 Blockchain and LLM-Enabled Construction Intelligence System

Recurring challenges, including contract inefficiencies, fragmented documentation, limited transparency, and weak coordination among stakeholders characterise construction engineering in Nepal (Koirala and Bhusal, 2026). These issues frequently lead to delays, cost overruns, and reduced quality in infrastructure delivery. Addressing these challenges requires a shift from traditional document-centric workflows toward intelligent, automated, and verifiable construction management systems.

Blockchain technology provides a foundational layer for such systems by enabling decentralised, tamper-resistant recording of contractual agreements, project milestones, and material-tracking information. Through smart contract mechanisms, predefined conditions can be encoded as executable digital logic that automatically enforces compliance and triggers actions, such as payments or approvals, upon verification of project milestones. This eliminates the need for centralised trust and enhances accountability across stakeholders.

However, the effectiveness of blockchain systems is significantly enhanced when combined with Large Language Models. LLMs serve as contract intelligence modules that generate structured smart contract templates based on historical construction agreements and regulatory frameworks. They also facilitate the extraction of contractual clauses from unstructured legal documents and their conversion into structured representations suitable for blockchain deployment. Furthermore, LLMs help identify inconsistencies, missing obligations, or ambiguous terms in contracts, thereby improving legal and technical robustness.

The resulting system can be conceptualised as a cyber-physical construction-intelligence pipeline in which LLMs perform contract generation and interpretation, blockchain systems execute and validate contractual logic, and IoT-based sensing systems verify physical progress on construction sites. Data collected from sensors, drones, and field inspection systems provides real-world validation of project execution, ensuring that digital contracts remain synchronised with the development of physical infrastructure.

This integration enables a continuous feedback loop between digital agreements and physical execution, thereby transforming construction management into a transparent, automated, and verifiable process. Recent studies have shown that LLM-based extraction techniques significantly improve the structuring of contractual data for blockchain-based smart contract systems in civil engineering applications, demonstrating the feasibility of AI-assisted contract automation frameworks (Moayyed and Anumba, 2025).

4.3 AI-Driven Engineering Education and Standards Compliance System

Nepal’s engineering ecosystem faces persistent challenges, including fragmented technical knowledge, inconsistent enforcement of engineering standards, and limited access to up-to-date regulatory documentation. These challenges span multiple sectors, including civil engineering, hydropower development, electrical installation, industrial manufacturing, and information technology systems. In practice, national standards such as the Nepal Building Code and electrical safety guidelines are applied inconsistently, particularly outside major urban centres.

In contrast, industrial quality assurance practices often lack standardisation and formal documentation.

To address these systemic issues, an AI-driven engineering knowledge and compliance system can be developed based on a Retrieval-Augmented Generation architecture. In this framework, a structured knowledge base is constructed from digitised engineering standards, technical manuals, and historical project documentation. This knowledge base serves as the authoritative reference layer for all system outputs.

On top of this foundation, Large Language Models function as reasoning engines that retrieve relevant information and generate context-aware responses grounded in verified engineering knowledge. This ensures that outputs remain aligned with official standards while enabling natural language interaction. The system supports multilingual communication, enabling engineers to interact in both English and Nepali, thereby improving accessibility in diverse operational environments.

At the application level, the system provides engineering decision support, automated compliance checks, and structured report generation. Engineers can use the system to interpret regulatory requirements, validate design compliance, and generate standardised documentation for field and office use. In addition, the system can function as an educational assistant, supporting engineering training through interactive problem-solving and concept explanation.

Deployment of such systems follows a hybrid architecture in which cloud-based infrastructure is used for periodic updates of standards and model improvements. In contrast, edge-based deployments enable offline or low-connectivity operation in remote regions. Continuous feedback from field engineers further enhances system performance through iterative learning mechanisms.

This transformation effectively converts static engineering documentation into a dynamic, intelligent knowledge system, enabling continuous access to updated technical expertise and improving compliance across infrastructure projects.

4.4 Cross-Domain System-Level Integration

Across all three use cases, a unified architectural paradigm emerges in which AI systems are no longer deployed as isolated tools but as integrated cyber-physical infrastructures. These systems consist of multiple interacting layers, including data acquisition mechanisms, AI reasoning engines, trust verification systems, and edge-based deployment nodes.

The data layer aggregates structured and unstructured inputs from sensors, operational systems, and engineering documentation. The AI layer combines predictive machine learning models with the reasoning capabilities of Large Language Models. The trust layer is implemented using blockchain-based mechanisms to ensure data integrity and transactional transparency. The edge layer enables localised computation for low-latency inference, while the application layer delivers domain-specific services in energy, construction, and education sectors.

This layered architecture demonstrates that effective AI deployment in Nepal requires hybrid systems that integrate prediction, reasoning, and trust within a unified framework. Such systems are particularly suitable for developing regions where infrastructure constraints necessitate distributed, energy-efficient, and resilient computing architectures.

5. Discussion

The findings of this study demonstrate that successful AI adoption in engineering depends on the integration of technologies within a coherent infrastructure and governance framework.

While AI technologies are computationally and economically intensive, their integration into engineering systems yields substantial long-term benefits in efficiency, reliability, transparency, and decision intelligence. It aligns with emerging national AI priorities focused on infrastructure, energy, and digital governance.

From a technical perspective, machine learning remains the most mature and widely applicable paradigm for engineering optimisation tasks and is also strongly supported by prior studies (Kiani, Camp and Pezeshk, 2019; Cabrera *et al.*, 2025; Senisetty, B and P, 2026). However, the analysis also highlights a critical dependency on data quality and availability, which remains a major limitation in Nepal's engineering ecosystem. The adoption of transfer learning, domain adaptation, and edge inference strategies is therefore not optional but essential for ensuring practical deployment in resource-constrained environments.

Private and permissioned blockchain architectures are significantly more suitable than public blockchain networks for national infrastructure applications due to their improved scalability, predictable cost structure, and governance alignment. However, the computational overhead associated with traditional consensus mechanisms remains a limitation, necessitating the adoption of energy-efficient protocols such as Proof-of-Stake and Byzantine Fault Tolerant models (Dutta *et al.*, 2020). When integrated with machine learning and IoT systems, blockchain acts not merely as a data storage mechanism but as a verification and integrity layer within engineering cyber-physical systems.

LLMs extend the capabilities of engineering systems beyond numerical prediction to include semantic reasoning, documentation automation, and knowledge synthesis, which are further amplified in agentic AI settings through coordinated multi-LLM planning and execution. Nevertheless, concerns regarding hallucination, bias, and domain unreliability persist, particularly in safety-critical engineering applications (Hochreiter and Schmidhuber, 1997; Patil and Gudivada, 2024). The use of retrieval-augmented generation and domain-specific fine-tuning partially mitigates these risks by grounding model outputs in verified engineering datasets and regulatory frameworks.

The cost and infrastructure analysis further reinforces the importance of deployment strategy in determining the feasibility of AI adoption. While cloud-based systems offer accessibility and rapid deployment, their long-term operational costs and external dependencies pose strategic limitations. Conversely, on-premises and localised infrastructure require a higher initial investment but offer greater sovereignty, security, and long-term economic efficiency. The proposed conceptual sovereign AI infrastructure model directly addresses this trade-off by introducing a multi-tier architecture that distributes computation across national, regional, and field-level systems, thereby optimising both performance and cost efficiency consistent with policy directions emphasising sovereign AI capabilities.

Environmental considerations also play a critical role in evaluating AI feasibility. Although individual inference costs for ML and LLM systems remain relatively low, large-scale deployments introduce significant cumulative energy demand. Blockchain systems based on high-energy consensus mechanisms further exacerbate this issue. However, Nepal's hydropower-based energy infrastructure presents a unique opportunity for low-carbon AI deployment, enabling sustainable computation if properly aligned with national energy planning, as recognised in national AI and energy policy discussions. This positions Nepal as a potentially favourable environment for developing green AI infrastructure.

The representative engineering use cases further validate the system-level applicability of the proposed framework. In hydropower systems, integrating LSTM-based forecasting models with LLM-driven contextual reasoning and blockchain-based verification yields measurable improvements in grid stability and operational efficiency. In construction engineering, the combination of LLM-based contract generation and blockchain-enabled smart contracts enables transparent, automated, and verifiable project execution workflows. In engineering education and standards compliance, retrieval-augmented LLM systems provide scalable access to regulatory knowledge, improving consistency and reducing dependency on centralised expertise.

Across all applications, a consistent architectural pattern emerges in which AI systems operate as multi-layered cyber-physical infrastructures composed of data acquisition layers, predictive intelligence modules, reasoning engines, trust verification mechanisms, and edge deployment nodes. This layered structure ensures robustness, scalability, and adaptability in environments characterised by limited connectivity and heterogeneous infrastructure.

Overall, the successful adoption of AI in engineering systems is not primarily a question of model capability but of system design, infrastructure alignment, and governance integration. In this context, collaboration with Nepali AI professionals and researchers in the global diaspora represents an important opportunity, as many are actively engaged in advanced AI development and are increasingly willing to contribute to national initiatives through knowledge transfer, joint research, and remote collaboration. For developing countries such as Nepal, where resource constraints coexist with high engineering demands, hybrid and localised AI ecosystems represent the most viable pathway for sustainable technological transformation.

6. Conclusion

This paper examined the technical capabilities, deployment considerations, infrastructure requirements, and energy implications of these technologies for engineering applications in Nepal. It proposed a sovereign AI infrastructure model that combined centralized high-performance computing resources, regional edge nodes and field-level deployments to address the challenges associated with connectivity, scalability and data sovereignty supported by representative engineering use cases across critical sectors.

The findings demonstrate that AI can significantly improve engineering decision-making, operational efficiency, and service delivery when supported by appropriate infrastructure and governance mechanisms. Nepal’s renewable energy resources further create favourable conditions for sustainable AI deployment. The study also highlights that while cloud-based services remain valuable for rapid development and experimentation, hybrid and localised infrastructures provide greater long-term resilience, governance, data sovereignty, and cost efficiency for national-scale engineering applications. However, challenges related to data quality, model reliability, computational costs, cybersecurity, and regulatory governance remain significant. Future research should focus on empirical validation of the proposed architecture, energy-aware AI optimisation strategies, Nepal-specific engineering datasets, and decentralised AI governance frameworks. Overall, this work provides a practical foundation for sustainable AI-enabled engineering transformation in Nepal and other developing regions.

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Responsible AI Adoption in Developing Economies: A Governance Framework for Nepal's Digital Infrastructure Sector

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Abstract
Nepal is undergoing a rapid digital transformation, with artificial intelligence (AI) increasingly embedded in public sector ICT systems, e-governance platforms, and national digital infrastructure projects. However, this adoption is proceeding without a coherent, enforceable governance framework, creating significant risks related to algorithmic bias, data sovereignty, accountability deficits, and vendor dependency. While the recent introduction of the *National AI Policy 2082 (2025)* outlines critical national goals including training 5,000 AI professionals and elevating Nepal's position on the global AI Readiness Index the lack of explicit statutory baseline mechanisms and strict enforcement measures leaves the state exposed to severe infrastructural vulnerabilities. Drawing on a comparative analysis of international AI governance frameworks including the EU AI Act, the UK's pro-innovation approach, Singapore's Model AI Governance Framework, and UNESCO's global recommendations, this paper proposes the Responsible AI Adoption (RAI) Framework, a three-pillar governance model tailored for developing economies. The RAI Framework addresses regulatory foundations, institutional capacity, and stakeholder accountability, and is operationalised through a four-phase implementation roadmap designed to transition Nepal's aspirational policies into practical technical controls.

Keywords: Artificial Intelligence Governance, Digital Infrastructure, ICT Policy, Responsible AI, Technology Regulation.

1. Introduction

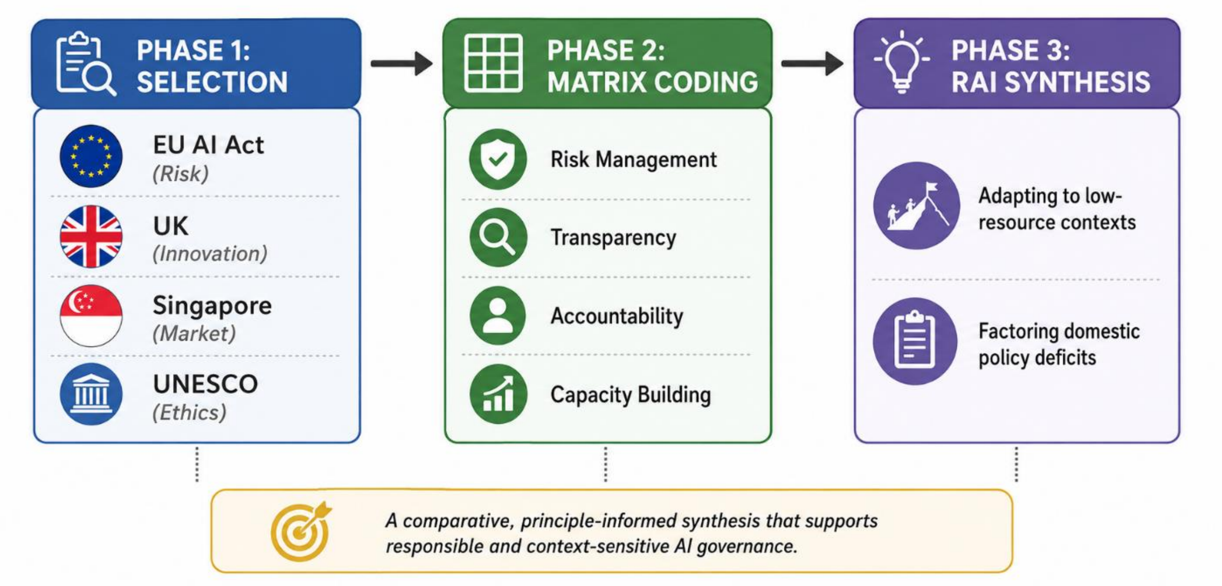
Since the launch of the *Digital Nepal Framework* in 2019, Nepal has invested substantially in digital infrastructure modernisation. Broadband connectivity has scaled aggressively; according to the Nepal Telecommunications Authority (NTA), mobile broadband penetration has reached over 87%, with 4G networks successfully deployed across 750 out of 753 local administrative levels. This rapid expansion is underpinned by the deployment of complex e-governance platforms like the *Nagarik App*, designed to centralize and automate citizen document verification.

While the government approved its milestone *National AI Policy 2082* in August 2025 and subsequently founded a *National AI Centre* under the Ministry of Communication and Information Technology (MoCIT) in late 2025, a deep operational disconnect remains. The current framework defines ambitious milestones, yet it provides no statutory enforcement tools or clear allocations of legal liability. International comparisons emphasize that the primary challenge for emerging economies is an intense capacity deficit; on the Oxford Insights Government AI Readiness Index, Nepal ranks 150th out of 193 nations, heavily restricted by infrastructural limits and a severe shortage of localized data verification capabilities.

The core issue is that individual infrastructure deployments default to fragmented contractual conditions set by external tech vendors. This introduces deep data sovereignty vulnerabilities, structural lock-ins, and algorithmic biases that disproportionately affect historically marginalized populations. This paper addresses this gap by presenting the *Responsible AI Adoption (RAI) Framework*, providing a sequenced roadmap to turn Nepal's high-level AI policy into concrete engineering guardrails.

2. Methodology

To establish a rigorous foundation for the proposed governance architecture, this study adopts a qualitative, deductive-inductive comparative policy analysis approach. The methodology is structured around three distinct phases: framework selection, comparative dimension coding, and contextual synthesis.



2.1 Framework Selection Criteria

Four primary international frameworks were selected to benchmark governance approaches, chosen based on their regulatory mechanisms and relevance to Nepal:

- **The European Union AI Act (2024):** Selected as the premier global benchmark for legally binding, hard-law, risk-based classification models.
- **The United Kingdom Pro-Innovation Framework:** Selected to evaluate a flexible, sector-led approach that balances technological agility with foundational safety standards.
- **Singapore's Model AI Governance Framework:** Selected as a mature model for proportionate, market-driven guidance tailored to small island or hub economies navigating global trade.
- **UNESCO's Recommendation on the Ethics of AI (2021):** Selected because Nepal is an active state signatory, providing an existing normative, multilateral commitment.

2.2 Comparative Dimension Coding

The four frameworks were analysed using deductive qualitative coding across five structural dimensions: (1) *Risk management methodologies*, (2) *Accountability mechanisms*, (3) *Transparency requirements*, (4) *Institutional arrangements*, and (5) *Capacity development strategies*.

2.3 Synthesis and Framework Development

Through an inductive synthesis process, the common variables and operational limits identified in these international frameworks were mapped against the explicit socio-economic and structural constraints of Nepal's public sector ICT landscape. This analytical mapping directly informed the formulation of the three pillars of the Responsible AI Adoption (RAI) Framework, ensuring that the final model is not a direct replication of Western frameworks, but an architecture optimized for low-resource settings.

3. Literature Review

3.1 Global Developments in AI Governance

The international AI governance landscape has transitioned from voluntary ethical principles to enforceable, binding regulatory mechanisms. The enactment of the European Union's AI Act (2024) codified a precedent by treating AI systems as products subject to strict risk classification, imposing mandatory compliance and ex-ante conformity assessments for high-risk applications, which explicitly include systems embedded in critical infrastructure management. Alternatively, the United Kingdom has pursued a decentralised, sector-led architecture, utilizing existing regulators supported by a centralized AI Safety Institute to track frontier model capabilities. Singapore's Model AI Governance Framework offers a practical, organization-centric approach emphasizing voluntary adoption, technical flexibility, and commercial viability.

A consensus within recent governance literature emphasizes that *proactive governance* introduced during a system's design phase is significantly more cost-effective and structurally robust than *reactive regulation* implemented retrospectively after algorithmic pipelines have integrated into public services.

3.2 AI Governance in Low-Resource and Developing Settings

Scholarly focus on AI adoption within developing and emerging economies reveals distinct systemic disparities compared to advanced digital states. Research highlights that the primary barrier in low-resource settings is not a lack of ethical awareness, but a severe asymmetry in technical and regulatory capacity between AI-exporting multinational corporations and AI-adopting sovereign states (Khan, 2026). This disparity creates a condition of systemic regulatory dependence, where developing states frequently accept vendor-defined software architectures and automated policies by default (Singh & Pathak, 2023).

Furthermore, data governance deficits introduce deep algorithmic risks. Large language models (LLMs) and predictive scoring systems deployed in South Asia are predominantly pre-trained on Western or non-representative global datasets; when applied locally without extensive fine-tuning, they generate systemic errors and discriminatory outputs that disadvantage marginalized groups (Sahoo & Jena, 2022).

3.3 Digital Sovereignty and Public Sector AI Accountability

Digital sovereignty has evolved from data privacy protections to representing a state's core capacity to maintain strategic autonomy over its digital landscape. In developing economies that lack local hyper-scale computing infrastructure, public sector agencies are structurally dependent on international cloud providers (Fratini et al., 2024). This reliance risks

institutionalizing data exfiltration, where sensitive national metadata is stored, managed, and algorithmically processed across foreign borders beyond domestic judicial reach.
Concurrently, global production indexes demonstrate that while the Global South represents an expanding user base for AI technologies, the ownership of foundational infrastructure remains hyper-concentrated within a small number of states (ICRIER, 2026). This concentration deepens dependency, leaving developing public sectors vulnerable to sudden changes in vendor licensing, algorithmic adjustments, and technological lock-in. To counter this, recent literature emphasizes the integration of strict algorithmic impact assessments, mandatory human-in-the-loop oversight, and local open-architecture procurement policies within public administration (Almeida & Santos Júnior, 2025).

4. Nepal’s Digital Infrastructure and Policy Environment: A Case-Based Analysis

4.1 Empirical Case Studies of AI Diffusion

To accurately evaluate the governance gap, the discussion must be grounded in the structural realities of Nepal's current public-sector technological rollouts. AI is currently entering Nepal’s digital core through three distinct operational vectors:

1. **The Nagarik App and Integrated Digital ID:** The *Nagarik App* serves as Nepal's unified e-governance interface, consolidating citizen identity records including citizenship certificates, passports, PAN data, and land registries. Planned integrations of machine-learning modules for automated document classification and predictive routing must navigate a fundamental structural exposure: Nepal lacks comprehensive, localized data-cleaning and localized model-validation protocols. This absence introduces immediate risks of automated identification failures and the potential processing of national demographic metadata in external public clouds.
2. **NTA Broadband Infrastructure and Network Management:** The expansion of 4G capabilities to 750 local levels has vastly enlarged Nepal's digital footprint. However, the core backbone switches, intelligent traffic routing, and diagnostic automation layers are completely manufactured and managed by foreign vendor systems. Operating effectively as un-auditable "black boxes," domestic telecom engineers lack the source code access or algorithmic verification rights needed to confirm where routing data flows, making the infrastructure highly vulnerable to external lock-in.
3. **Revenue and Tax Compliance Automation:** Machine-learning analytical tools are actively being piloted within land revenue and internal tax administrations to isolate anomalies and flag tax evasion. Trained heavily on legacy data with significant historical regional variations, these models risk codifying historical geographic biases, generating systemic automated penalties for citizens in underserved provinces without providing a clear, statutory process for human appeal or redress.

4.2 The Legislative Vacuum

Nepal’s primary legislative tool for technology remains the antiquated *Electronic Transactions Act (ETA) 2063 (2006)*. Written decades prior to the emergence of machine learning pipelines, the ETA completely lacks provisions regarding algorithmic liability, automated decision-making transparency, or data provenance. While the *National AI Policy 2082 (2025)* outlines important strategic pillars (such as establishing a National AI Centre), it functions purely as an aspirational policy document and lacks the statutory authority to enforce penalties or compel vendor compliance.

Table 1 summarizes how Nepal contrasts against mature international frameworks.

Table 1: Comparative AI Governance Frameworks and Nepal's Position

Country / Region	Key Framework	Legal Bindingness	Enforcement Body	Applicability to Nepal
European Union	EU AI Act (2024)	Legally binding regulation	National Competent Authorities	High – Risk-based classification model is highly adaptable to critical infrastructure.
United Kingdom	AI Safety Institute / Pro-innovation framework	Voluntary / Sector-led	DSIT / Sectoral Regulators	Medium – Technical safety benchmarks offer a valuable blueprint for diaspora collaboration.
Singapore	Model AI Governance Framework	Voluntary guidance	IMDA	High – Practical corporate and procurement templates match developing-economy limits.
UNESCO	Recommendation on Ethics of AI (2021)	Non-binding global guidance	Member States	High – Nepal is a formal signatory, providing an established diplomatic entry point.
Nepal	National AI Policy 2082 (2025)	Aspirational policy only	MoCIT / National AI Centre	**Baseline Gap** – No binding statutory AI legislation, no audit rules, and no enforceable vendor liability.

5. AI Risk Matrix and Institutional Readiness Assessment

5.1 Risk Scoring Methodology

To structure governance priorities, a qualitative risk assessment was executed using a two-dimensional scoring matrix adapted from the EU AI Act's risk classification methodology.

$$\textit{Risk Level} = \textit{Likelihood} \times \textit{Impact}$$

- **Likelihood (1–5):** Scored based on the historical frequency of related technological incidents in South Asia, the structural vulnerability of current public sector infrastructure, and the presence or absence of active oversight mechanisms.
- **Impact (1–5):** Evaluated based on the potential severity of consequences regarding systemic discrimination against citizens, compromises to data privacy, loss of infrastructure availability, or erosion of institutional trust.

Table 2: AI Risk Matrix for Nepal's Digital Infrastructure Sector

Risk Category	Key Operational Threat	Likelihood	Impact	Combined Risk Score	Mitigation Priority
Data Sovereignty	National metadata processed by foreign hyper-scalers due to a lack of Tier-3/Tier-4 domestic data centers.	5	5	**25 (Critical)**	**Immediate** – Require localized processing pipelines for high-risk datasets.
Algorithmic Bias	Automated decisions trained on Western or non-representative datasets, reinforcing regional and social inequality.	4	5	**20 (Critical)**	**Immediate** – Mandatory localized validation and representative data auditing.
Vendor Lock-in	Deep structural reliance on proprietary closed software architectures, preventing long-term sovereign maintenance.	5	4	**20 (High)**	**Structural** – Open-source standard mandates and core engineering code access requirements.
Accountability Gaps	Government agencies discharging legal	4	4	**16 (High)**	**Contractual** – Define clear, non-exculpable

Risk Category	Key Operational Threat	Likelihood	Impact	Combined Risk Score	Mitigation Priority
	liability for automated mistakes to external technology suppliers by default.				state liability boundaries.
Capacity Deficit	Insufficient AI technical literacy among government procurement officers to evaluate vendor performance or safety claims.	5	3	**15 (High)**	**Educational** – Launch localized literacy cohorts and advisory networks.
Cybersecurity Vulnerability	Algorithmic injection or manipulation targeting critical public utilities and communications networks.	3	5	**15 (High)**	**Technical** – Implement algorithmic audit logs and zero-trust routing.

5.2 Scoring Rationale and Analysis

- **Data Sovereignty (Score: 25):** Evaluated at the maximum risk profile. Nepal's public sector lacks the centralized computing power required to execute large-scale machine learning workloads locally. Consequently, public agencies are often structurally forced to route data through external cloud instances. Absent clear legal boundaries, this introduces a permanent vulnerability to data harvesting and loss of strategic control over national data assets.
- **Algorithmic Bias (Score: 20):** Given the demographic, linguistic, and socio-economic diversity of Nepal, deploying off-the-shelf automated classifiers without rigorous local validation poses an immediate risk of systematic errors in resource distribution and public service delivery.

6. The Responsible AI Adoption (RAI) Framework

The proposed *Responsible AI Adoption (RAI) Framework* addresses these vulnerabilities through a three-pillar, integrated governance architecture designed specifically for resource-constrained contexts.

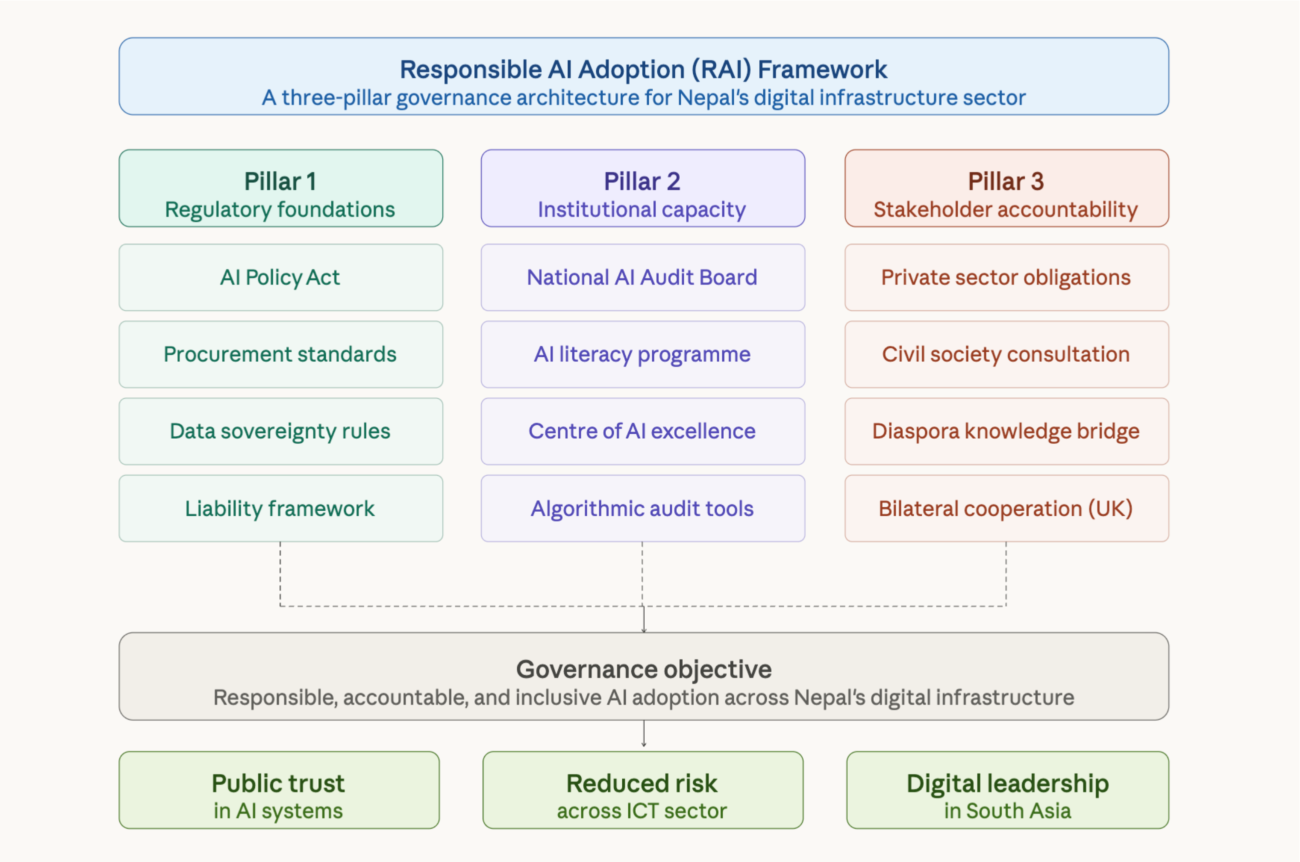


Figure 1: The Responsible AI Adoption (RAI) Framework – Three-Pillar Governance Architecture

6.1 Pillar 1: Regulatory Foundations

The first pillar establishes the legal and procedural bedrock of AI governance. It encompasses four components. An AI Policy Act would create a statutory basis for AI regulation in Nepal, defining AI, establishing risk classification criteria, and empowering the Ministry of Information Technology to issue binding sector-specific guidance. Mandatory AI procurement standards would require all government ministries and public entities to apply conformity criteria when acquiring AI-enabled systems, including requirements for algorithmic transparency, data localisation, and supplier accountability documentation. A data sovereignty framework would legislate minimum standards for the storage, processing, and cross-border transfer of data generated by AI systems in public infrastructure, reducing Nepal's exposure to foreign data exfiltration. Liability rules would establish clear accountability chains for AI-driven decisions affecting citizens, ensuring that government agencies cannot discharge liability to technology vendors by default.

6.2 Pillar 2: Institutional Capacity

The second pillar addresses Nepal's most acute governance vulnerability: the institutional capacity to evaluate, oversee, and audit AI systems in use across public infrastructure. It proposes the establishment of a National AI Audit Board, an independent technical body with authority to conduct algorithmic audits of AI systems deployed in high-risk public infrastructure contexts. This body would report to Parliament, ensuring democratic accountability.

Complementing this, a structured AI Literacy Programme for civil servants would equip procurement officers, ministry officials, and project managers with the technical understanding necessary to evaluate AI vendor claims, specify accountability requirements in contracts, and identify governance red flags. The pillar also includes a Centre of AI Excellence, to be co-developed with international partners, that would function as a national repository of AI governance knowledge, tools, and regulatory templates.

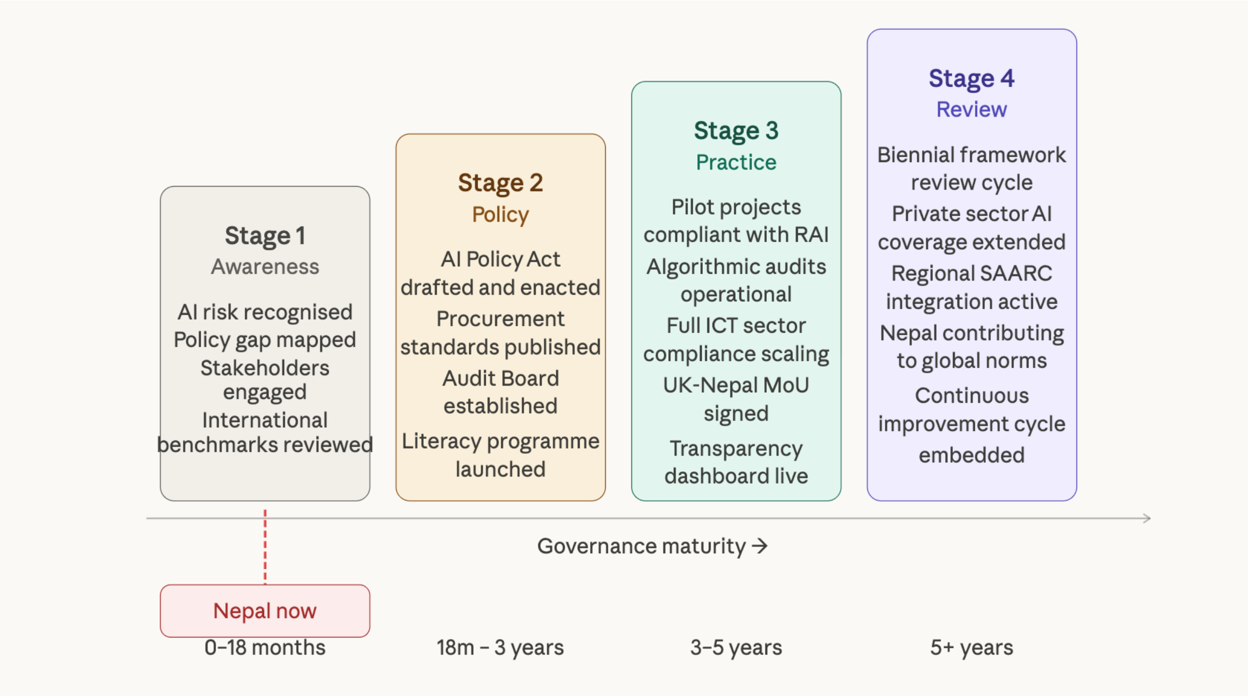


Figure 2: RAI Framework Implementation Maturity Model – Awareness → Policy → Practice → Review

6.3 Pillar 3: Stakeholder Accountability

The third pillar recognises that effective AI governance cannot be achieved by government alone. It defines accountability obligations and participation mechanisms for three stakeholder groups. The private sector including domestic and foreign technology vendors would be required to submit algorithmic impact assessments for AI systems deployed in regulated infrastructure categories, and to maintain auditable records of AI system performance and updates. Civil society and citizen bodies would be granted formal consultation rights in the development of sector-specific AI guidance, ensuring that governance reflects lived experience rather than only technical expertise. The Nepali diaspora, particularly professional networks, is recognised as a strategic governance resource: engineers and technologists working in jurisdictions with mature AI regulation can serve as knowledge bridges, technical advisors, and advocates for bilateral cooperation frameworks.

7. Implementation Pathway

To ensure operational viability, the RAI Framework is structured across a four-phase maturity model that sequences institutional investments based on their urgency and feasibility.

Table 3: RAI Framework – Phased Implementation Roadmap

Phase	Timeline	Key Actions	Responsible Actors	Success Indicators
Phase 1: Foundation	0–18 months	Draft and enact the core AI Policy Act; operationalize the baseline National AI Centre; publish unified public procurement guidelines.	MoCIT, NTA, Ministry of Law, Parliament.	Statutory Act passed; 500+ procurement officials trained; initial procurement templates integrated into state bidding processes.
Phase 2: Institution Building	18 months – 3 years	Establish a formal AI Regulation Council; execute three targeted sector pilots; implement mandatory data localization rules.	National AI Centre, MoCIT, Academic Partners, Diaspora Network.	Regulation Council staffed; 3 pilot infrastructure projects verified compliant; technical audit logs operationalized.
Phase 3: Scaling & Integration	3–5 years	Enforce full framework compliance across all public ICT procurement; initiate regional governance alignments; deploy a public transparency dashboard.	All Government Ministries, Civil Society, Tech Vendors, SAARC.	100% compliance rate for new public sector AI deployments; live public dashboard for automated systems.
Phase 4: Review & Evolution	5+ years (ongoing)	Execute a biennial framework performance review; update domestic rules based on evolving global	Independent Review Panel, International Research Partners.	Modernized regulatory framework updated for frontier models; Nepal cited as an operational model for

7.1 Designing the Phase 2 Testing Pilots

To ground the transition from policy to practice, Phase 2 relies on three specific pilot testbeds designed to stress-test the framework across different technological scopes before national scaling:

1. **Centralized E-Governance Pilot:** Applied directly to the document routing and verification modules of the *Nagarik App* to verify data handling protocols and security baselines.
2. **Critical Infrastructure Pilot:** Executed on an isolated sector of the *NTA broadband routing backbone* to build capacity for inspecting, auditing, and logging foreign network management tools.
3. **Urban Smart Systems Pilot:** Deployed within the *automated traffic management systems* in Kathmandu to establish public data privacy protections and test localized image-recognition calibration.

8. Conclusion

Nepal stands at a critical technological inflection point. The integration of artificial intelligence tools into national digital infrastructure is advancing rapidly, yet the absence of an overarching governance framework creates structural vulnerabilities regarding data sovereignty, institutional bias, and vendor lock-in. The strategic window to implement proactive safeguards is open but narrowing. The *Responsible AI Adoption (RAI) Framework* detailed in this paper provides a practical, sequenced, and internationally compatible pathway designed specifically for the institutional realities of emerging digital economies. By focusing on clear regulatory foundations, progressive capacity development, and leveraging unique external resources like the global engineering diaspora, Nepal can build an ecosystem that safely captures the efficiency gains of digital automation while preserving citizen trust and national sovereignty. Ultimately, establishing rigorous governance alongside technological deployment will demonstrate that developing nations can actively direct artificial intelligence rather than merely absorbing its external impacts.

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Reimagining the Monastic Landscape of Kapilvastu through Archaeological Findings

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Abstract

Kapilvastu, the birthplace of the historical Buddha in Nepal, has been mentioned in several Buddhist texts, including the *Saundarananda*. While South Asian archaeology has been criticised for preoccupation with textual sources compiled centuries after the events they report, findings of scientific excavations and geophysical surveys help verify some of the records, while also aiding the reimagination of the monastic landscape of the region. With a brief overview of archaeological works since 1899, this paper analyses Kapilvastu as an ancient settlement through various key aspects, including kingship and political structure, monastic architecture, urban plan, and water system.

Keywords: Kapilvastu, archaeology, Buddhist texts, *Saundarananda.*

1. Kapilvastu in Buddhist Textual Sources

1.1 Pali and Sanskrit Buddhist Texts

Kapilvastu (Pāli: *Kapilavatthu*, Chinese: *Kapilowei, Kapila-yastou*) is widely known today as the birthplace of the Buddha. Before its rediscovery 27 km west of Lumbini in Nepal (UNESCO, 2013), ancient and medieval texts remained its only record. Within the Pāli canon, the *Ambatthā Sutta* in the *Saṃyutta Nikāya* mentions *Kapilavatthu* as the city of the *Śākya*s, and the Buddha's home before renunciation (Horner, 1952). On the other hand, Indian Buddhist narrative sources also refer to the ancient city with various names, including *Kapilapura*, *Kapilāhvayapura* and *Kapilasya vastu*. *Lalitavistara*, a 1st-3rd century Mahāyāna text, describes Kapilvastu as the most prosperous city (Lamotte, 1988). *Mahāvastu*, a 2nd-4th century *Mahāsāṃghika* text, describes Kapilvastu as a royal city with the forest of Śakota trees on the slopes of the Himalayas (Lucaz, 1949). *Buddhacarita*, a Sanskrit epic poem from the 1st-2nd century CE by *Aśvaghoṣa*, associates the city with the Buddha's early life (Cowell, 1893).

1.2 Saundarananda

While the above texts have attracted wider scholarly attention, *Saundarananda* is yet another source domesticated by Newar Buddhists in the Kathmandu Valley, 300 km east of Kapilvastu. Unlike other Indian Buddhist literature, this earliest known Sanskrit poetry, also by *Aśvaghoṣa*, was not translated to Tibetan or Chinese, and was almost lost to the world, had Hara Prasad Shastri not discovered it in a Nepalese library in 1908 AD (Covill, 2007). Its primary premise revolves around Nanda, the next crown Prince following the renunciation of Siddhartha Gautama, and Janapada Kalyānī, the princess-to-be who instead joins his love interest Nanda in the Buddha's saṅgha by being ordained as a nun. Surviving in only two Sanskrit versions preserved in Nepal (Johnston, 1928), *Saundarananda* has been studied in the context of

Buddhist concepts and teachings (Arya, 1992; Feinberg, 2024), its poetic features (Regan, 2022), and kingship (Eltschinger, 2018), but not with reference to its portrayal of Kapilvastu in the Buddhist literature of ancient India, to which a full opening canto is dedicated.

Saundarananda introduces Kapilvastu as the abode of the descendants of Ishvakus, the *Śākya*s, who made their home under the *Śāka* tree[1], and the Hermitage of sage Kapila[2]. It is said to have forests with beautiful wood, and soft and smooth grasses[3], and enough fruits and flowers everywhere[4]. Among the fauna, elephants, horses, snakes and baby tigers are mentioned alongside chirping peacocks on the backdrop of the Himalayas, which can only be the outer foothills along the Siwalik range, as the other higher peaks lie too far from the Terai plain. Besides the mention of specific breeds, including the *Neem* tree (*Azadirachta indica*) and *Mādhavi* flowers (*Hiptage benghalensis*), the site with gardens and lakes is also noted for ponds with the highest quality of water[5]. Wells were also set up from all sides[6], suggesting an adequate supply of water for the populace. Lastly, it also informs about the urban planning and architecture of the beautiful city with buildings and streets, clearly paved highways and a wide moat along the river[7], and a white tower facing a well-divided market[8].

2. Beyond the Religious Texts

2.1 Chinese Travelogues

Apart from religious sources, the accounts of Chinese travellers have been another source of information on Kapilvastu. In the early 5th century, Faxian reported the city being almost uninhabited, and people feared elephants and lions while walking along the roads (Beal, 1969). It was simply a congregation of priests and about ten families of lay people in a desert-like region not under the control of a government. He further noted that twelve towers were erected at important sites, representing the life events of the Buddha. As in the early Buddhist literature, he also mentions a well, which, according to him, marked the site where the Buddha took seven steps immediately after His birth (*ibid*.).

While the earlier religious texts do not provide geographical information, the Chinese travelogues note the distance between these sites in units of *li* and *yojana*[9]. Faxian's notes also correspond to those of Hiuen Tsiang, another noted Chinese traveller from the 7th century. This is especially true for the distance between Kapilvastu and Rāmagrāma, another nearby important site with the Buddha's relics (*ibid.*), which is also mentioned in the 12th-century Pali canon, *Mahāvaṃsa* (Geiger, 1912). Besides attesting these distances, archaeological surveys in the region have provided more information on the monastic landscape of Kapilvastu and its exchanges with the lay community, which will be discussed in the following sections[10].

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[1] *śākravṛkṣapraticchannaṃ vāsaṃ … tasmādikṣvākuvaṃśyāste bhuvi śākya iti smṛtāḥ* (1.24)
[2] *kapilasya ca tasyarṣestasminnāśramavāstuni …* (1.57)
[3] *cāruvīruttaruvanaḥ prasnigdhamṛduśādvalaḥ …* (1.6)
[4] *paryāptaphalapuṣpābhiḥ sarvato …* (1.9)
[5] *… puṣkariṇīścaiva paramāgryaguṇāmbhasaḥ* (1.50)
[6] *… kūpavatīścaiva samantātpratyatiṣṭhipan* (1.51)
[7] *saridvistīrṇaparikhaṃ spaṣṭāñcitamahāpathaṃ …* (1.42)
[8] *pāṇḍurāṭṭālasumukhaṃ suvibhaktāntarāpaṇaṃ …* (1.43)
[9] The distance of 1 *li* equals 0.4 km, and 1 *yojana* equals 8-9 km.
[10] Faxian notes that from Kapilvastu, 50 *li* to the east is the royal garden of Lumbini, and 5 *yojana* to the east is Lan-mo (Rāmagrāma).

2.2 South Asian Archaeology

Archaeological research in South Asia has revealed evidence from periods ranging from the Stone and Iron Ages (Piggott, 1968) to the Mauryan era, including material traces of Emperor Ashoka's promotion of Buddhism through the erection of pillars and the distribution of relics in the 3rd century BC (Coningham & Young, 2015a). Alexander Cunningham (1814-1893) is often credited as a pioneer of Indian archaeology as he led the Archaeological Survey of India (ASI) on its establishment in 1861 (Chakrabarti, 1988). During his time, archaeology was still less distinct from anthropology, epigraphy, and numismatics (Imam, 1963). Contemporary archaeology is defined as the study of cultural systems through material remains (Binford, 1962). However, more recently, religious literature preserved through oral tradition has been termed problematic in terms of historical chronology (Thapar, 1985). Particularly, in the case of South Asia, the distinction between the immediate objects of study, text for history and material of archaeology, has been poorly defined over the last two centuries (Trautmann, 2002). In recent times, scholars have increasingly challenged the over-dependency on textual sources in the study of Buddhist antiquity, and support their arguments through archaeological evidence (Coningham, 2001).

Preoccupation with texts compiled centuries after the events they report has contributed to known problems in Buddhist studies, including the dating of the historical Buddha himself (Coningham, 2013) and the location of His birthplace in Kapilvastu. In light of this, the consultation of archaeological findings beyond the usual dependence on textual sources and oral histories can be a worthy approach to take in the case of writing histories as remote as that of Kapilvastu. Archaeology, however, is not only about chronology. By definition, it should seek the understanding of cultural aspects of the communities that lived in the past. An analysis of the historical progression is key to our understanding of urbanisation in South Asia. It has been suggested that urbanisation in India can be analysed through its three periods of pre-Buddhist, post-Buddhist, and colonial, based on their archaeological evidence (Sridharan, 2016).

2.3 Buddhist Archaeology

Buddhism formed one of the early archaeological interests of early Western explorers of the Indian subcontinent because it had already ceased to exist in the region. In Alexander Cunningham's own words, "the Rāmāyaṇa, the Mahābhārata and the Purāṇas, are all silent about Buddhism as if that religion had never flourished in India" (Imam, 1963). However, in the form of shrines and stupas, Buddhist archaeology is traced back farthest to the Buddhist conversion of Emperor Ashoka in the mid-3rd century. Along with Sanchi, Sarnath and Bairat, Lumbini also constitutes what has been termed the 'Ashokan Horizon', the first distinct Buddhist archaeological horizon that coincides with the advent of monumental royal patronage (Coningham, 2011; Coningham & Young, 2015b).

Scholars have since attempted to uncover the Buddhist influence starting from this period in urbanisation, state formation, economic change, and agricultural innovation (Shaw, 2005). In particular, our understanding of the Buddhist societies from the early history is based on 19th-20th century archaeological investigations carried out around the present-day Indo-Nepal border, - Rajgir and Vaishali in Bihar, Sarnath in Uttar Pradesh, and Kapilvastu in Lumbini, Nepal, where the excavations have continued to date, revealing a fortified settlement in the capital city of the ancient Śākya kingdom. A brief review of archaeological works carried out in the Tilaurakot-Kapilvastu site since 1899 is provided in **Appendix 1**.

3. Kapilvastu as an ancient settlement

3.1 Kingship and Political Structure

While all sources, including the Buddhist texts, Chinese travelogues and archaeological evidence, agree that Lumbini served as a pilgrimage site, they also verify that the site of Tilaurakot-Kapilvastu was once a city settlement with a royal palace of the Śākya king Suddhodana, best known as the father of Siddhartha Gautama. Suddhodana was a Kshatriya or warrior king from the Ishvaku clan or Sūryavaṃśa, the Solar race known as a major Hindu lineage (Mills, 1876). The archaeology of South Asia suggests that its cities were not tied to political territories in the early historic period before the 4th century AD, as they had not undergone political growth, warfare, and aggrandisement (Smith, 2006). The presence of royalty in an ancient South Asian city, however, does assure overall patronage for public welfare and urban development, which the city of Kapilvastu could have enjoyed.

Buddhist texts do not mention the coronation of a successor to Suddhodana, or whether a hereditary monarchy existed in Kapilvastu. On the contrary, it is noted for governance by public assembly in "common Mote Hall or *santhāgāra*" (Rhys Davids, 1903). Such a governance structure, known as *gaṇa–saṅgha,* or a republican polity similar to Vaishali, is not new in this historical region. The idea of such a political structure could have arisen a need for spacious meetings to be held within the royal complex, similar to what has been excavated in Kapilvastu. Among the excavated artefacts, while an abundance of ceramic artworks and vessels hints towards the city's cultural prosperity, none of them belonging to weaponry indicate its political stability.

3.2 Monastic Architecture

The Mahāvastu mentions the ordination of the Buddha's son Rāhula and half-brother Nanda as monks, and foster-mother Gautamī as a nun (Jones, 1949, 1952). Recalling how, in the earlier text *Saundarananda,* even His half-brother's lover Kalyānī was ordained as a nun, gives us an idea of how monasticism had an increasing influence in the then society of Kapilvastu. This leads us to assume that frequent or even mass ordination could have been the next important type of event to be held in either public or religious spaces. For these immediate family members of the Buddha, while the Mahavastu records only a brief stay in Kapilvastu before they joined His journey, less is known about the general populace. In the absence of any supporting architecture revealed through ongoing excavation, not much can be said about whether some of the inhabitants eventually shifted to monasticism.

All over India, the common plan for Buddhist monastic architecture is essentially "a quadrangle of cells around a square open space" (Pichard, 2003). Similar structures in this pattern have been identified to the east of Pushkarini pond, three of which have been classified as Mauryan, Kushan, and Gupta period, respectively (UNESCO, 2013). With four to five cells on each side, the *vihara*s provide as many as eleven rooms, all of which open to a central meeting hall. The cells could be used as a secluded space for meditation by the monks, who would convene at the centre for wider gatherings. While further archaeological work can reveal more in this region, the Chinese travelogues noted low population density by the 7th century. Since the site is historically not known for monastic teachings, it would not have required accommodation for monks in great numbers.

The monasteries can be noted on the opposite side of the stupas, where votive activities could be carried out, separated by the Maya Devi temple and Pushkarini pond. This spatial separation of the monastic quadrangle from the votive stupas should be understood as an early layout when the shrines had not yet entered the monastic premises (Sarkar, 1966). From the 5th century onwards, these shrines were frequently found inserted at the back of the monastic cells (Pichard, 2003). Stupas are also known to be the initial phase of the Buddhist objects of devotion, before transitioning into anthropomorphic forms of representing the Buddha and eventually to a statue. However, not only stupas, but images of Buddha have also been excavated from the site of Kapilvastu. Two separate findings of a terracotta bust and a head of the Buddha at Dohni in Kapilvastu, and a Seated Buddha from Saina-Maina, further 35 km northeast, are among the most prominent from the sketches provided in early reports (Mukherji, 1901). Besides representing a vast span of Kapilvastu's historical timeline, such a wide range of votive Buddhist objects suggests a changing social perception, possibly influenced by the *Bhakti* cult of Hinduism on the rise.

3.3 Urban Plan

Through a case study of South India, Pichard has argued that one of the limitations of archaeological excavations is the estimation of the size of the monastic population at a given time in history, since they go through several layers of change over a period of time (Pichard, 2003). This remains one of the key questions that remains unanswered in the case of Kapilvastu as well. While the Chinese travelogues note only a few lay families and priests, several layers of construction that were excavated, especially of the streets that crossed one another, suggest the need for moving a large number of people who travelled through the region. While Industrial activity has been detected on the site with the presence of underground metal debris, the more recent discovery of postholes is indicative of the use of timber (Coningham et al., 2018b). These archaeological discoveries are genuine contributions to the site, which otherwise stands as a remnant of layers of bricks. The detection of a moat as wide as 55 meters (*ibid.*) is yet another proof of what was limited to Sanskrit poetry in verse (1.43) of *Saundarananda*.
Kapilvastu's geographical location next to a river, the presence of wildlife and waterbodies, and its positioning in the shadow of the Himalayan range make it an attractive region for human habitation. The archaeology of the site revealed the remains of a royal palace, gardens and other open spaces, venerated stupas and temples, water tanks and streets with drainage. The discovery of structural remains of gardens, squares, and markets connected by urban roadworks suggests that it was once a livable city with recreational spaces and public movement. In agreement with the portrayal of a 'prosperous' Kapilvastu in Buddhist texts, archaeological evidence supports the idea of the city being abandoned in a later period for reasons not known. While Mahāvastu mentions a seven-walled city, geophysical surveys have revealed a centrally located five-sided central complex within the excavated fortification. The square bases of the essentially conical stupas harmonise with the polygonal theme of the overall architecture.

3.4 Water System

Surveys have revealed small fields that grew paddy, mustard and dahl in the Southern industrial area, vegetables to the east of Shivagarh, and additionally rice near the eastern Stupa (Coningham et al., 2018b). The cultivation of these lands must have responded to irrigation needs. Situated in the Terai plain, the subtropical climate of Kapilvastu makes it monsoon-wet but seasonally dry (Karki et al. 2016), which means only a single harvest would be possible annually without saving rainwater. Archaeological findings of several water tanks around the central complex fully withstand the praise for brilliant water reserves in the verses (1.50-51) of *Saundarnanada*. Given the absence of any political crisis in the region, there is less probability of any chronic food shortage or agrarian unrest as postulated by Gunawardana (Gunawardana, 1971).

While traditional texts like the Arthaśāstra credit the building and management of irrigation work to centralised state-administration, studies carried out in India and Sri Lanka show monastic contributions in the economic support of local communities in the configuration of public infrastructure (Shaw, 2005). Archaeological studies carried out in South and Southeast Asia have also challenged Wittfogel's model of hydraulic civilisations, suggesting power through central control of irrigation works that amassed forced labour whose products were confiscated by the state (Stargardt, 2018). Even when hydro-infrastructures are state-deployed, their functioning and maintenance are not necessarily institutionalised as a top-down process (Zhuang et al., 2016). While it is not yet possible to hypothesise a control mechanism for the water system of Kapilvastu, some inferences can be drawn from its similarity to the nearby Kathmandu Valley architecture related to water.

Both of the early systematic excavation reports from Kapilvastu (Mukherji, 1901; Mitra, 1972) have at least one example each of a makara-motif water conduit. Venerated as the vehicle of the water-goddess Gangā, the popular South Asian mythical creature called Makara is invariably found in all stone water spouts, several hundred of which are still functional in the Valley for more than a century (Tiwari, 2009; Joshi, 2022). Many of these conduits bear an inscription indicating royal sponsorship. Inscriptions enforcing the law for the maintenance of public water supplies have been found from the 7th century (Vajracharya, 1973) to the 17th century (Becker-Ritterspach, 1990). Public utility *guthi* system acts as a special task force within the Newar community to keep the water fountains and conduits (Gellner, 1992), which highlights their community-driven maintenance. Based on their design similarity, Kapilvastu counterparts might also have a community model in place.

4. Conclusion

The study of Kapilvastu has long relied on Buddhist texts and oral traditions preserved across centuries. While these sources remain indispensable, the archaeological investigations carried out in the region since 1899 provide an additional means of understanding the site as an ancient settlement. By bringing together references from Pāli and Sanskrit literature, including the comparatively understudied *Saundarananda*, Chinese travelogues, and the findings of excavations and geophysical surveys, this paper has attempted to reimagine the monastic landscape of Kapilvastu through multiple lines of evidence.

The archaeological record not only assists in verifying certain descriptions preserved in literary sources, but also contributes information unavailable through texts alone. The remains of fortifications, monastic structures, streets, water tanks, industrial activity, and agricultural fields help us understand Kapilvastu beyond its religious significance as the birthplace of the Buddha. Considered together, these findings suggest a settlement with a developed urban plan, organised water system, and spaces associated with both royal and monastic life. At the same time, features noted in sources such as Saundarananda, including the moat, water reserves, gardens, and wider landscape, find interesting points of correspondence within the archaeological evidence.

Rather than treating textual and material sources as separate categories of evidence, this study suggests that they can be read alongside one another to provide a fuller understanding of Kapilvastu. Such an approach contributes to ongoing discussions in Buddhist archaeology by situating the site within its wider social, political, and environmental context, while also highlighting the value of archaeology in clarifying the historical importance of one of the most significant locations associated with the early Buddhist world.

Appendix 1: Archaeology of Tilaurakot-Kapilvastu

The archaeological work carried out at the Tilaurakot site of Kapilvastu has been documented in four major phases. In the first phase conducted by the ASI in 1899 AD, Purna Chandra Mukherji located Kapilvastu with a high level of confidence following his archaeological surveys in the Terai region of Nepal, aided by the triangulation of locations from Chinese travelogues (Mukherji, 1901). He unearthed a rectangular fort with several guardrooms, one large and many smaller water tanks, octagonal and hexadecagonal stupas, a temple, an iron workshop, and a series of other brick structures. He could map the entire discovery to the known descriptions of the capital of King Suddhodana, for instance, its geographical location beside a lake and to the east of a river (Coningham et al., 2019). The site was later excavated extensively with reconstructions in the 1930s (Coningham et al., 2013).

In the second phase, the site was reinvestigated in 1962 jointly by ASI and the Department of Archaeology (DoA), Nepal, under the leadership of Debala Mitra. She excavated “a small trench across the fortifications” that unearthed fourty-eight pieces of ceramic and other artefacts, dating them to “not earlier than the 3^{rd} century BCE” (Mitra, 1972), which has been challenged as being 6^{th}-2^{nd} century BC (Erdosy, 1995a), and particularly a potentially localised form of painted grey ware that could be dated back to 9^{th}-7^{th} century BC (Erdosy, 1995b). In the fourth phase, between 1967 and 1977, Rissho University, Japan, teamed up with DoA to expose more structures, which later scholars interpreted as a palace, along with a sequence that stretched from the 1^{st} century BC to the 3^{rd} century AD, and was categorised into four periods, viz., 800-1100 BCE, 600-500 BCE, Mauryan, Sunga, and Kushan (Coningham et al., 2019).

In 1997, the fourth phase was led by Robin Coningham and Kosh Prasad Acharya for UNESCO, and determined a recalibrated radiocarbon date of 550-100 BC in developing an absolute chronology of the site. Later in 2012, DoA teamed up with Durham University and the Lumbini Development Trust to survey the southern industrial mound, dating the earliest industrial activity in the region to the 4^{th} century. In 2014, Coningham, Acharya and Manuel continued the geophysical survey of the site, leading to the identification of a large monastic complex, a series of roads, buildings and lanes, and “what looked like a brick-lined pond or tank” (Coningham et al., 2014).

Their work continued in 2015 to reveal “a very clear plan of the urban layout … with defined roads and streets .. lined with structures .. and small open areas which may represent plazas and squares” (Coningham et al., 2015c). Their survey in 2016 revealed a five-sided central walled complex with a northern gate (Coningham et al., 2016), and in 2017, postholes on the brick-laid base, suggesting the use of timber (Coningham et al., 2017). Finally, in 2018, they identified the southern gateway that defined the separable inhabitation inside and outside the central complex, and a potentially Gupta-period walled area featuring “carved and moulded bricks” (Coningham et al., 2018).

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Developing a BIM-based Framework for Sustainable Design and Construction of Residential Buildings in Nepal

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Abstract
Integrating Building Information Modelling (BIM) with the sustainability assessment models is increasingly advocated, yet a gap exists between academic key indicators and industry practice. While environmental and economic dimensions are emphasised, social dimensions remain underexplored. This paper examines this gap using Key Performance Indicators (KPIs) across all three sustainability dimensions. Using a methodology comprising a survey of forty-eight construction professionals and an examination of the social indicators in Nepal, the study evaluates practices in a low-sustainability adoption context. Results show sustainability practices remain compliance-driven, reliant on passive design strategies, with Life Cycle Assessment (LCA) tools virtually absent, with 77% of respondents having never used any LCA tool. Major barriers include client awareness and government policies. As a primary contribution, the paper proposes a four-layer BIM-integrated conceptual framework tailored to the Nepalese context, integrating environmental, economic, and social indicators. This framework enhances usability by providing a structured roadmap to integrate environmental, economic, and social indicators into a unified workflow. While currently conceptual, ongoing validation and future work involving stakeholder interviews and case study completion ensure its regional alignment.

Keywords: building information modelling; carbon emission; life cycle sustainability assessment; social life cycle assessment.

1. Introduction
A Life Cycle Assessment (LCA) is a quantitative method to evaluate environmental impacts associated with resource consumption and pollutant emissions to the environment throughout the life cycle of systems, products and processes by encompassing the entire value chain, which is from raw material extraction to waste management (Sanye-Mengual and Sala, 2022). Although LCA evaluates environmental sustainability, achieving comprehensive sustainability requires the broader application of life cycle thinking by expanding the focus beyond environmental dimensions to include economic dimension (LCC) and social dimension (S-LCA)(Soust-Verdaguer et al., 2022). The comprehensive sustainability assessment of building helps in sustainable development (Larsen et al., 2022; Llatas et al., 2022), realise the source and magnitude of lifetime costs (Jorge-Ortiz et al., 2025), minimise impacts on human health (Boje et al., 2023), and implicit gain on social aspects like job creation and retention (Larsen et al., 2022).

Although the above mentioned three sustainability dimension aids in comprehensive sustainability, but there is no standard methodology for the specific integration of these three dimensions (Soust-Verdaguer et al., 2022). However, there are individual assessment methodology of each dimension. For example, ISO 14040:2006 (defining mandatory phases in

LCA) and EN 15978 (assessing environmental performance of whole building) for LCA, ISO 15686-5:2017 for LCC of buildings, and UNEP S-LCA guidelines and EN 16309 for S-LCA assessment for a building. Unlike the standard for LCA assessment, EN 16309 for social performance assessment is not in practice (Llatas et al., 2022). The social sustainability cannot be evaluated separately by single stakeholders, it need different stakeholders and social sustainability associated with country activity contribution, (Liu and Qian, 2019). Social impacts are not in quantity form, requires normalisation and weighting to quantity the assessment scientifically, and there is a risk of inconsistency in the results due to normalisation in social LCA (Dong and Ng, 2015). Hence, due to indicator selection, quantification of indicators in sustainability ratings, and no benchmark value for comparison for comprehensive assessment of sustainability, there has been very few research which have explicitly included three dimensions of sustainability (Backes and Traverso, 2021).

In the case of Nepal, 1.2 million housed constructed in the last decade and estimated one million houses will be built in the next decade. The major issue with the built buildings is that they are being designed without considering local bio-climatic conditions which results in uncomfortable thermal environments and high carbon footprint (BEEN, 2023). In addition, there is an increasing concern about modern construction materials, their environmental impact and sustainable management of construction projects due to rapid growth in the building construction (Bhattarai et al., 2023; Kumar et al., 2024).

In terms of past research on sustainability assessment of the buildings in Nepal, hardly any contribution been noticed for social assessment. For example, Paneru et al. (2024) focused their study on embodied carbon reduction in residential building using linear optimisation techniques. Similarly, Bhochhibhoya et al. (2020) estimated total carbon foot print including operational phase of building life cycle with economic impact in hotel buildings in the Himalayan region of Nepal. The above study provided comprehensive overview of the environmental and economic for very cold climatic region (Mt. Everest region) and social factors are not included into the assessment. The existing body of research has extensively evaluated embodied carbon emissions in construction using various tools and methods. However, there is a notable research gap exists in the assessment of environmental impacts accounted with life cycle cost, and the social effect on residential building construction in Nepal. The identification of relevant indicators of sustainability in each dimension is an essential step to realise sustainable outcomes. This study aims to identify sustainability indicators and assessment approaches relevant to the whole building life cycle of building projects, examine current awareness and practice among Nepalese construction professionals. Insights from the literature and the survey, this research seeks to propose a context-specific BIM-based conceptual framework integrating environmental, economic, and social indicators for providing a pathway for sustainable development.

2. Literature Review

2.1 Identification of building KPIs

To perform sustainability assessment, the key performance indicators need to be identified. For this purpose, a literature review was conducted to identify sustainability indicators for LCA, LCC, and S-LCA the case study. The identified indicators were presented in the Pareto Chart in Figure 1. The Pareto chart is helpful in the selection of indicators in the study (Abbasi et al., 2023).

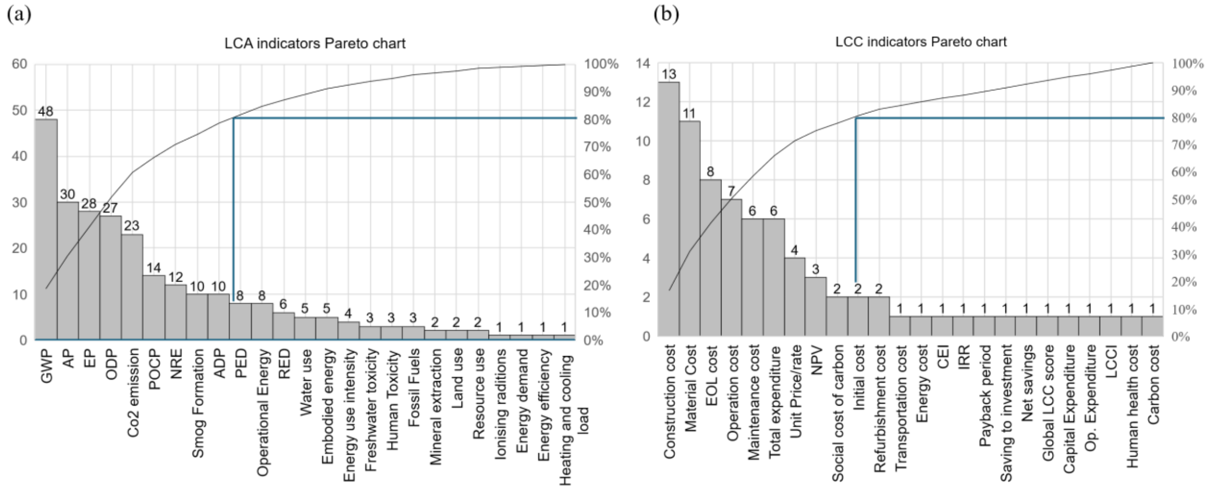

Figure 1: Identification of environmental and economic KPIs from literature

Environmental assessment largely focuses on Global Warming Potential (GWP), observed in forty-eight case study of the reviewed studies (**Error! Reference source not found.** a), Ozone Depletion Potential (ODP) follows at 27, with Acidification (30) and Eutrophication (28) as the most cited indicators. Although other indicators like renewable energy demand and water use exist, midpoint indicators like GWP are preferred for their scientific reliability (Dong and Ng, 2014). This choice is often based on data reliability and Building Information Modelling (BIM) interoperability rather than comprehensive sustainability representation. For example, the mid-point indicators like GWP have scientific reliability and global metrics like ($kgCO_2e$), which points less uncertainty, whereas endpoint indicators like damage to human health or ecosystem quality introduces high uncertainty due to assumptions and data gaps (Dong and Ng, 2014). The European standard EN 15804 for environmental product declaration provides core environmental indicators for LCA assessment. The indicators list from the Pareto (80/20) analysis (Figure 1 a, above) almost matches the EN15804 core environmental indicators. Hence, most study has included the core environmental indicators in their assessment for LCA in building projects.

The integration of Life Cycle Costing (LCC) with Life Cycle Assessment (LCA) enables evaluations that extend beyond initial costs to include all stages of a project (Schneider-Marin et al., 2022). Figure 1 *b* shows that initial investment, operational, and maintenance costs are frequently discussed. However, BIM-LCC integration faces limitations, such as simplified boundaries that neglect Net Present Value (NPV) (Sajid et al., 2024) and reliance on generic datasets (Santos et al., 2020). These issues compromise the reliability of economic assessments for sustainable design decisions. In the European standard, EN 15643-4:2012 presents a framework which include the cost and financial value together for economic assessment of building projects. Thus, economic indicators shall include cost related to the building over the life cycle and best financial value building or total economic worth of an asset, commonly represented by NPV.

For S-LCA, design and construction of buildings involve different stakeholders in different life cycle stages of the project. Ayassamy and Pellerin (2023) defined S-LCA as an assessment of social impacts of products and services throughout their project life cycle. Stakeholders have the direct influence of the social impacts. For example, fair salary, working hours, health, and safety, and forced labour are linked with workers group of stakeholders. Most of the social assessments are material centric which assess only the material production related issues but the design and construction of buildings with their related indicators are rarely assessed (Ayassamy and Pellerin, 2023). The unique social impacts generated during the design and active construction phases, such as, on-site occupational health, community integration and project delays and their impacts are rarely assessed. It is necessary to include all life cycle stages into the assessment and categorise the stakeholders based on the life cycle involvement and effect (Liu and Qian, 2019). Workplace safety and human health dominate the literature, while labour-related indicators are frequently cited (Dong and Ng, 2015). The challenges remain in quantifying social metrics due to reliance on site-specific surveys and expert judgment, making S-LCA less developed than environmental and economic assessments.

From different literatures, the social indicators were listed in the Table 5. In this table, impact indicators were observed based on the stakeholders involved. These indicators were observed in different case studies based on different life cycle stages.

Table 5: Social Indicators with life cycle stages and relative stakeholders

Life cycle stages	Impact indicators	Stakeholders	References
Material production stage, transport	Child labour, forced labour, Fair salary, Health and safety,	Workers	(Liu and Qian, 2019; Boje et al., 2023)
	Accessibility, Local Sourcing, and sustainable production methods	Community	(Figueiredo et al., 2024)
Construction stage	Child labour, forced labour, fair salary, Health and safety, Working hours,	Workers	(Liu and Qian, 2019; Bianchi et al., 2021; Llatas et al., 2022; Soust-Verdaguer et al., 2022; Boje et al., 2023)
	Health and safety, Labour hired locally	Community	(Liu and Qian, 2019; Filho et al., 2022)
Maintenance and Use stage	Health impacts, Usability and functionality, Reliability and security, Safety, Acoustic performance, Thermal comfort, Fuel poverty, Aesthetic aspects, Acoustic Performance, Social acceptance	Consumers	(Liu and Qian, 2019; Bianchi et al., 2021; Abbasi et al., 2023)
Demolition and recycling stage	Working hours	Workers	(Llatas et al., 2022; Boje et al., 2023)

2.2 Selection of KPIs

Though a wide range of sustainability KPIs has been identified in the literature, the selection and prioritisation of these indicators remain a critical challenge. Angelakoglou et al. (2023) claims that studies adopt an extensive list of KPIs without systematic screening or prioritisation, as a result, the quality of the study is often compromised. The possibility of this issue is because there is an absence of a common method for assessing the selection of a set of KPIs in a project (Kylili et al., 2016). Su et al. (2020) and Cheng et al. (2022) highlight that the definition of system boundaries and assessment objectives directly determines which life cycle stages and indicators are included.

3. Research Methodology

To evaluate the building sustainability assessment practices in Nepal, this study adopts a mixed methodology for the research design. A singular approach is insufficient to address the data scarcity and construction industry characteristics of Nepal's construction sector. First, a literature review has established a transparent, replicable, and scientifically reliable baseline of global sustainability indicators (Maeda et al., 2022). Consecutively, these theoretical insights were used to design of the survey to bridge the gap between global theory and local practice. Quantitatively, online questionnaire was deployed to gather measurable data on current understanding, perceptions, and practices related to sustainability, indicator relevance, and feasibility from industry stakeholders. By integrating these methods sequentially, the study ensures that the final framework is both theoretically robust and practically applicable to Nepal's unique built environment. A targeted sample of 200 construction professionals actively engaged in Nepalese building projects was invited to participate in the survey. Of these, only 48 professionals completed and returned the questionnaire, representing a response rate of 24%. A response rate within the 20% to 30% range is widely recognised as standard, acceptable, and typical for empirical research in the construction industry (Roshana et al., 2004).

The preliminary findings from the literature provided the foundational pool of global sustainability indicators. These identified indicators directly formulated the structural design of quantitative survey where stakeholders were asked to evaluate, rank and critique on indicator relevance, feasibility, and local implementation barriers. Consequently, while the frameworks' structure was derived from literature, its final validation and calibration were entirely driven by survey findings. The sustainability indicators identification and their selection approach were presented in previous literature review section. The key survey findings and discussion is presented in next section.

4. Survey Results and Discussions

A total of forty-eight construction professionals completed the questionnaire survey. This section presents the descriptive statistics, reliability analyses, and key findings organised by theme: respondent profile, sustainability adoption, BIM and LCA tool usage, economic assessment practices, social sustainability priorities, and barriers to sustainable construction. All statistical analyses were conducted using SPSS v26. Internal consistency was assessed using Cronbach's alpha, with values above 0.7 considered acceptable (Cho and Kim, 2015).

Respondent Profile

Table 6 summarises the demographic and professional characteristics of the sample. Most respondents possessed six or more years of construction experience, with approximately 77% possess more than six years of construction experience, with the largest group, twenty-five respondents, falling into the 6-10 years of experience. This professional maturity is further reflected in the distribution of expertise, where Architecture (47.92%) and Civil/ structural engineering (39.58%) constitute a vast majority of the sample, as shown in *Table 6*.

Table 6: Respondent Profile (n=48)

Characteristics	Category	Frequency	Percentage (%)
Years of experience	Less than 2 years	2	4.2
	2-5 years	9	18.8
	6-10 years	25	52.1
	More than 10 years	12	25
Professional role	Architect	23	47.92
	Civil/Structural Engineer	19	39.58
	Construction management	4	8.34
	BIM/ICT	1	2.08

	Academia/Researcher	1	2.08

Sustainability framework adoption and design strategies

The survey results indicate a moderate level of engagement with sustainability frameworks. While half of the respondents (47.92%) have actively used design guidelines, a combined 52.1% either have not yet adopted them or are planning to do so in the future. Local mandates dominate: the Nepal building code (43.8%) and municipal guidelines (37.5%) are the primary drivers. International frameworks show negligible adoption: EIA guidelines (22.9%), LEED (12.5%), and ISO frameworks (2.1%).

The survey result reveals a clear pattern of "low-tech sustainability" where there is heavy reliance on passive design strategies like orientation, natural ventilation, and rainwater harvesting. The mixed-use buildings and NGO projects show balanced strategies, which suggests that larger or externally funded projects are more likely to adopt diverse green technologies like solar integration and waste minimisation strategies. This pattern indicates industry readiness for sustainable building but is currently confined to the simplest methods of sustainability practice in buildings.

BIM and Life Cycle Assessment Tool Usage

Most respondents, around 39.6%, identify as somewhat familiar with the BIM and LCA tools, suggesting that there is a lack of deep, specialised expertise. The most popular tool is SketchUp Pro (35.64%), which is primarily used for 3D visualisation *Figure 2* (b). Despite the high level of awareness in sustainability, a staggering 77.08% of organisations have never used LCA tools *Figure 2* (c). This data suggests that there is a lack of workflow requirement, and adoption is blocked at the corporation level. The shallow familiarity in LCA tools, where 40% of respondents are unaware of any LCA tools, suggests that the industry lacks a standardised technical language for environmental data, *Figure 2* (d).

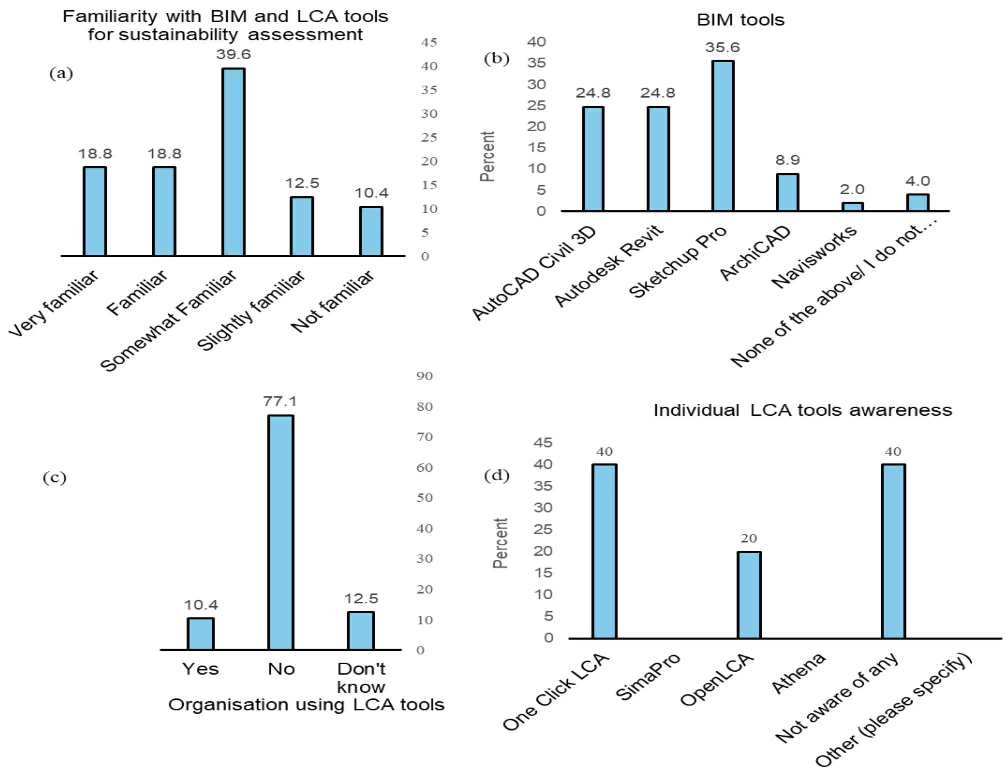

Figure 2: Bar chart on BIM and LCA tools.

Economic Assessment Practices

The result of cost-related data sources reveals that there is heavy reliance on local suppliers, government sources and consultants or cost estimators. The data on traditional unit-cost pricing (70.83%) reveal that financial decision-making remains rooted in short-term capital expenditure rather than long-term environmental value. The low frequency on LCCA (8.33%) and industry database usage (6.96%) creates a price barrier for sustainable materials, which may have a higher upfront cost but lower lifetime impacts. These cost-related data indicate that economic assessment is limited to locally available and immediately affordable, failing to include the assessed model to prove the long-term viability of high-performance sustainable buildings.

Social Sustainability Practices

For social indicators, reliability analysis was conducted to assess the internal consistency of the Likert-Scale items used to measure sustainability indicators. The result indicated a Cronbach's alpha value of 0.87(>0.7) (*Table 7*), suggesting a good reliability among the eleven items. The results indicate that fire services received the highest mean score of 3.93 (*Table 7*), suggests that respondents perceive safety-related aspects as important. Indicators such as accessibility for persons with disabilities and cultural heritage receives higher attention. In contrast, community engagement in design and planning recorded the lowest mean score (3.04). The standard deviation values ranged between 1.11 and 1.37, demonstrating moderate variability in responses and suggesting a reasonable level of agreement among participants. The respondents have prioritised the safety and physical accessibility rather than community participation or labour practices.

Table 7: Social Indicators statistics

Social Indicators	Mean	Std. Deviation	Reliability statistics	
Fire services	3.93	1.116	Cronbach's alpha 0.870	N of items 11
Accessibility for persons with disabilities	3.67	1.348		
Cultural heritage preservation	3.67	1.261		
Visual Comfort	3.60	1.372		
Ventilation and indoor air quality	3.56	1.253		
Thermal comfort	3.40	1.268		
Working hours	3.38	1.284		
Escape routes	3.29	1.375		
Local employment and labour practices	3.22	1.126		
Waste disposal	3.16	1.127		
Community engagement in design/planning	3.04	1.205		

Barriers to Sustainable Construction

The reliability analysis of the six barrier variables produced a Cronbach's alpha value of 0.771, indicating acceptable internal consistency among the items. The mean score reveals that the most significant barriers to sustainable building construction adoption are the lack of client awareness and the absence of clear government policies, with a mean value of 4.30. Other important barriers include inadequate technical knowledge or training and resistance to change from traditional practices, whereas the excessive cost of sustainable materials and limited availability of eco-friendly materials are ranked lower. These results suggest that policy support, stakeholder awareness ad capacity building are essential to promote sustainable construction practices.

5. Conceptual Framework for Sustainability Assessment

The peer-review literature and inferential statistics from local engineers, architects, and project managers, the framework minimises academic bias and maximised the real-world project applicability. The literature synthesis established a rigorous baseline of global building sustainability frameworks and their corresponding life cycle indicators, and questionnaire survey provides empirical feedback loop, which is critical in defining functional requirements and boundary constraints of the framework. Ultimately, the finalised components were mapped into sequential, interdependent layers, establishing a systematic data-routing and decision support mechanism capable of navigating building sustainability assessment. The framework systematically structures the flow of data from raw inputs to multi-criteria decision making through four distinct, interdependent layers and establish an iterative design optimisation loop, as presented in *Figure 3*.

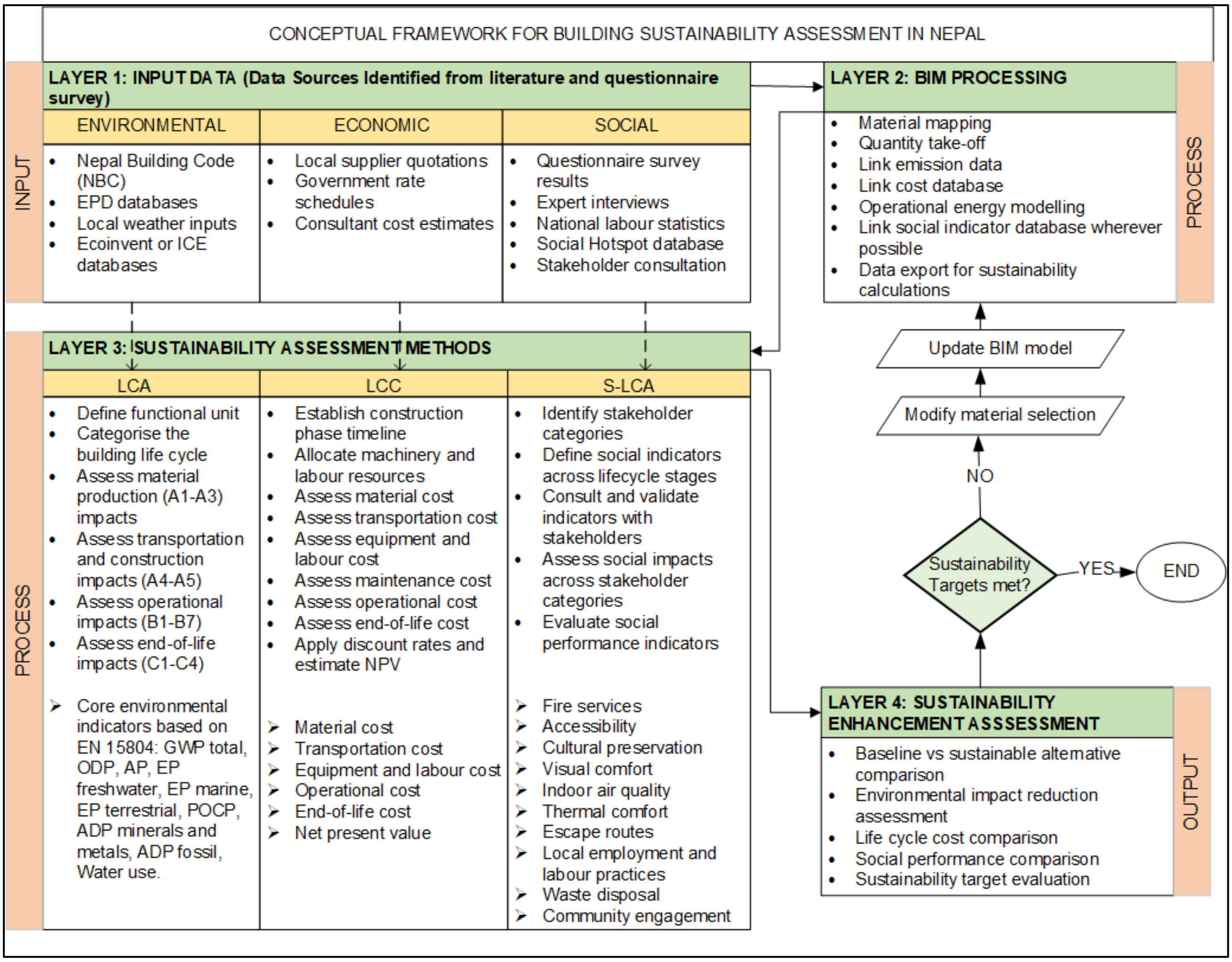

Figure 3: Proposed framework for sustainability assessment.

Layer 1: Input Data

The foundational layer establishes the data necessary to perform the assessment within the geographic and socio-economic boundaries of Nepal. Data sources are divided into three streams: Environmental, Economic, and social data. All data layer streams feed into Layer 2 and Layer 3 for BIM processing and sustainability assessment.

Layer 2: BIM Processing

Layer 2 functions as the primary BIM model computation for material mapping and geometric modelling of the building. Furthermore, Layer 2 executes operational energy modelling based on the climatic data from layer 1 through energy modelling software.

Layer 3: Sustainability Assessment Methods

This layer is the core evaluative process of the framework, where three independent sustainability dimensions are assessed in parallel across all building life cycle phases. In LCA environmental emissions across phases A1 to C4 are quantified. Outputs are mapped to core environmental indicators mandated by standard EN 15804. In LCC, cash flows in all building life cycle phases are calculated. Future expenditures are mathematically calculated using discount rates to estimate project net present value. In S-LCA, the indicators identified from literatures and survey will be validated with stakeholders. Stakeholder categories are identified (Workers, society, consumers, etc) and relevant indicators were defined across all life cycle phases. Qualitative stakeholder feedback is translated into quantifiable metric by mathematical weighting methods after stakeholder validation of indicators.

Layer 4: Sustainability Enhancement Assessment and the optimisation loop

This layer acts as a decision support system. It performs a structured comparison between the baseline building design and one or more sustainable material design alternatives across three sustainability dimensions. The sustainability target is set prior to decision making based on literature derived benchmarks or experts defined thresholds. If sustainability target for the sustainable alternative do not meet the target, then framework activates an iterative optimisation loop, directing the workflow back to Layer 2. In this case, designers must modify material selection, alter building geometry, and recalculate the inventory matrices until compliance is achieved. Ultimately, in positive validation “YES”, the framework concludes the assessment.

6. Conclusion and Future Study

This study identified whole-building sustainability indicators from the literature and examined current practice among 48 Nepalese professionals. The findings reveal a critical gap: sustainability practice remains compliance-driven, relying on passive design, with 77% never using LCA tools and only 8% employing LCC assessment. Critically, primary barriers are not material costs but the absence of policy and client awareness. In addition to the findings, this study has validated a set of social indicators for building sustainability assessment.

Based on these findings, this study makes three contributions. First, it provides empirical evidence from developing country context, challenging assumptions that barriers are primarily economic and technical. Second, it presents a context-specific four-layer BIM-based framework designed for environments with limited data availability, low technological maturity, and low

stakeholder awareness. Third, it provides insight into the social indicators been tested based on Nepalese context through questionnaire survey.
The ongoing validation includes stakeholders' interviews (n=15-20) and case study application to a residential building in Nepal, assessing relevance and feasibility rather than numerical benchmarking against non-Nepalese databases. Furthermore, this is ongoing research; the next stage of study focuses on improving interoperability between BIM and sustainability assessment tools, developing localised embodied emission databases. These efforts will contribute to bridging the gap between research and practice and support the broader adoption of sustainable construction practices in emerging economies.

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Assessing the Feasibility of Clay Resources for LC³ Cement as a Low-Carbon Construction Pathway in Nepal: A Review

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Abstract
This review assesses the feasibility of using clay resources to produce limestone calcined clay cement (LC³) as a low-carbon construction pathway in Nepal. The study adopts a literature-based approach with two linked components. First, it reviews published research on LC³ performance, focusing on mechanical strength, hydration behaviour, microstructure, durability, and environmental and economic advantages relative to ordinary Portland cement (OPC). Second, it examines the availability, distribution, and mineralogical suitability of Nepali clay deposits, with particular focus on kaolinite-bearing clays and their relevance for calcination for production of LC³ cement. The review indicates that LC³ can achieve performance comparable to OPC while reducing clinker consumption and carbon emissions, making it feasible for countries seeking lower-carbon cement systems. Evidence from Nepal shows that clay resources are geographically widespread and that several deposits have promising mineralogical characteristics for LC³ production, although suitability varies with clay quality, associated minerals, accessibility, and calcination response. The review also finds that LC³ may be compatible with existing cement manufacturing infrastructure in Nepal with limited modification, offering potential economic and implementation advantages. However, further work is required on systematic clay characterisation, calcination optimisation, local mix design, pilot-scale production and standards development. Overall, the paper concludes that Nepal has strong potential to adopt LC³ technology, but successful implementation will depend on coordinated research, industrial validation, and policy.

Keywords: LC³ cement, limestone calcined clay cement, Nepal, clay resources, low-carbon construction, supplementary cementitious materials, kaolinite, sustainability

1. Introduction
The global cement industry is responsible for approximately 8%of anthropogenic carbon dioxide (CO_2) emissions, making it one of the most significant contributors to climate change (Scrivener et al., 2017). With the construction sector experiencing unprecedented growth, particularly in emerging economies, the demand for cement continues to rise. This growth presents a critical challenge: meeting infrastructure development needs while simultaneously reducing the carbon footprint of cement production. Traditional SCM such as `fly ash and ground granulated blast furnace slag approaches to reducing CO_2 emission has been utilised till now. However, the availability of these materials is declining globally due to the phase-out of coal-fired power plants and changes in steel production technologies (Barbhuiya et al., 2023).

In this context, Limestone Calcined Clay Cement (LC^3) has emerged as a promising low-carbon alternative that can achieve clinker replacement levels of up to 50% while maintaining performance comparable to ordinary Portland cement (OPC) (Martirena et al., 2018). The LC^3 cement typically consists of 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum, offering a carbon emission reduction of approximately 25-40% compared to OPC (Martirena, 2023). Unlike conventional SCMs, the raw materials for LC^3, clay and limestone, are abundantly available in most regions of the world, making this technology particularly attractive for developing countries with limited access to industrial by-products.

Nepal presents a compelling country for LC^3 cement adoption. The country possesses abundant clay resources distributed across various geological formations. Nepal's cement industry currently relies heavily on clinker-intensive production, contributing substantially to the nation's carbon emissions. The country's commitment to sustainable development and climate change mitigation, coupled with its rich clay deposits, creates an opportunity for LC^3 technology adoption. However, the feasibility of this transition depends on several critical factors: the suitability of local clay resources for calcination, compatibility with existing cement manufacturing infrastructure, economic viability, and the technical capacity to implement this technology.

Therefore, this review paper systematically examines the potential for producing LC^3 cement as a low-carbon construction pathway in Nepal. First, it synthesises the current understanding of LC^3 cement performance, including mechanical properties, hydration behaviour, microstructure development, and durability properties, with particular emphasis on comparisons with OPC. Second, it evaluates the geological and mineralogical characteristics of Nepali clay resources, assessing their suitability for LC^3 production. Finally, it examines the feasibility of implementing LC^3 technology in Nepal's existing cement manufacturing infrastructure, considering technical, economic, and practical implementation challenges. By bridging the gap between material science and resource availability, this review aims to provide a comprehensive assessment that can guide future research, policy decisions, and industrial adoption of LC^3 cement in Nepal.

2. LC^3 Cement

As shown in Figure 1, LC^3 differs from OPC mainly in its composition, with a substantial proportion of clinker replaced by calcined clay and limestone. This reduced clinker factor is central to the environmental and economic significance of LC^3, as it lowers both calcination energy demand and CO_2 emissions while making use of widely available supplementary raw materials. Despite this reduction in clinker content, LC^3 cement has shown mechanical performance comparable to, and in some cases better than, OPC. Kanagaraj et al. (2023) reported a 28-day compressive strength of 46.2 MPa at 50% clinker replacement, while Hernández (2017) found that industrially produced LC^3 in Cuba achieved strength comparable to P35 cement at both 7 and 28 days. Huang et al. (2024) further showed that the optimum calcined clay-to-limestone ratio varies with target strength, and Blouch et al. (2023) demonstrated that even low-grade kaolinite can be suitable for LC^3 production. In practical applications, Wali et al. (2018) reported that LC^3 can replace OPC by weight using conventional construction methods, while Martirena (2023) observed that LC^3 matches the properties of OPC at all ages.

As illustrated in Figure 2, the performance of LC^3 is closely linked to its hydration behaviour. Clinker hydration produces C-S-H and portlandite (CH), while reactive alumina from calcined clay reacts with CH and limestone to form additional C-S-H, carboaluminate phases, and stratlingite (Scrivener et al., 2017; Blouch et al., 2023; Barbhuiya et al., 2023). These additional hydration products refine the pore structure, reduce porosity, and enhance load transfer within the cement matrix, thereby enabling LC³ to achieve comparable, and in some cases higher, strength than OPC despite its lower clinker content. The formation of additional C-S-H, carboaluminates, and stratlingite also results in a denser microstructure, characterised by fewer weak porous zones and greater matrix compactness, which further contributes to improved mechanical performance (Hernández, 2017; Scrivener et al., 2017; Blouch et al., 2023; Adegbemileke et al., 2024). This refined microstructure also contributes to improved durability, particularly against chloride ingress and carbonation, while the lower clinker content and modified hydration products may improve sulfate resistance; overall, LC³ has been identified as a durable and sustainable alternative to conventional OPC with lower energy demand and greenhouse gas emissions (Hernández, 2017; Barbhuiya et al., 2023; Kanagaraj et al., 2023).

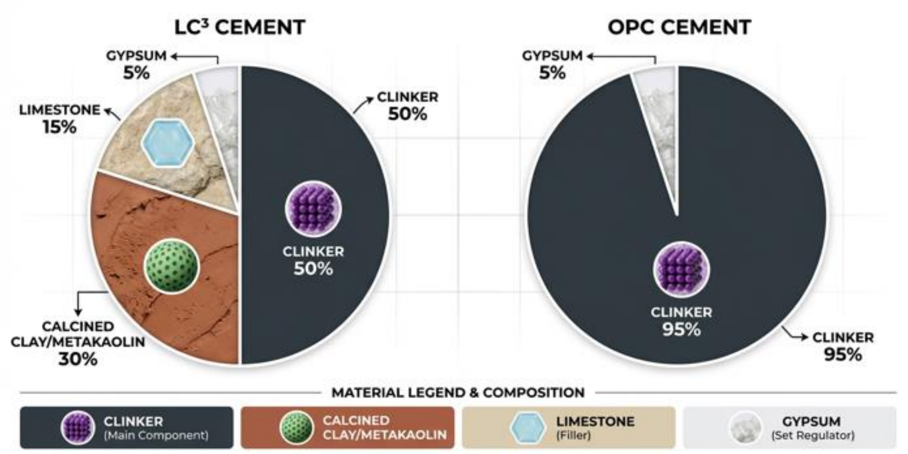

Figure 1: Comparison of LC³ and OPC cement compositions, showing the reduced clinker content in LC³ through partial replacement with calcined clay, limestone, and gypsum.

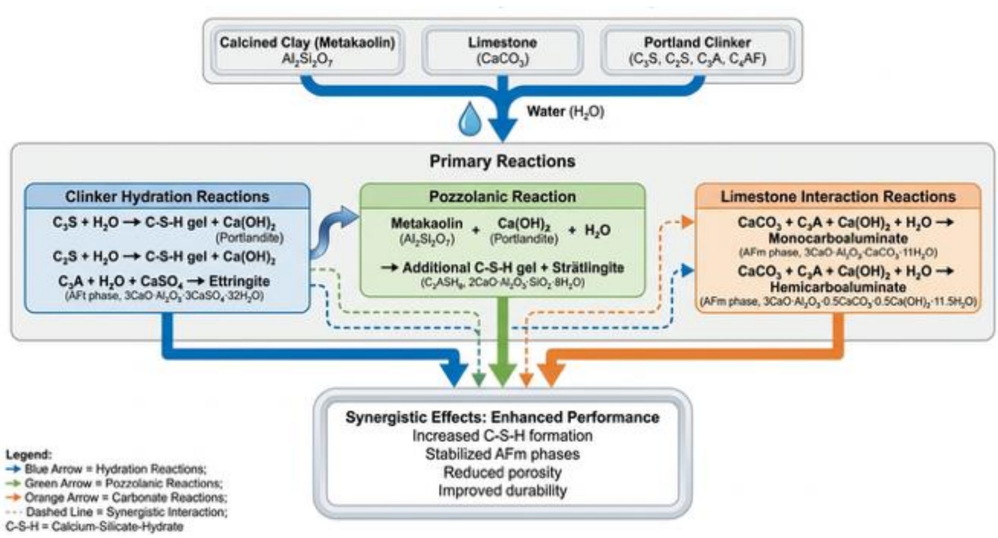

Figure 2: Schematic illustration of the hydration process of LC³ cement, showing clinker hydration, pozzolanic reaction, limestone interaction, and their synergistic effects on performance.

3. Geological and Mineralogical Analysis of Clay Resources in Nepal

3.1 Availability and Distribution

Nepal's location within the Himalayan belt has created a wide distribution of clay deposits across the country. Assessing their availability and spatial distribution is essential for evaluating the feasibility of LC^3 cement production. Tao et al. (2022) studied clay samples from 25 locations in Nepal and showed that clay resources are widely available across the country, which could support regional LC^3 production and reduce transport costs and environmental impacts. As shown in Figure 3, kaolinite-rich clay deposits occur across western, central, and eastern Nepal, including areas around Surkhet, Dang, Palpa, Dhading, Hetauda, Makwanpur, Chitwan, Bara, Parsa, Rautahat, Sindhuli, and Udayapur. Figure 3 also shows that many of these deposits are concentrated in the Hills and Valleys and the Terai belt, where better access to infrastructure and transport networks may provide practical advantages for LC^3 production.

The distribution of these deposits also reflects Nepal's complex geology and topography. Neupane et al. (2025) identified white clay soils containing kaolinite and halloysite across altitudinal gradients in Central Nepal. In Kaltari, Gorkha, albite was associated with halloysite formed by weathering and hydrothermal alteration, whereas in Daman, Makawanpur, soils are mainly suitable for LC^3 production than others. Baumler et al. (1997) also showed mineralogical variation in the Langtang valley, where illite altered to interstratified minerals and hydroxy-Al interlayered minerals or pedogenic chlorite with increasing soil development. Although these illite mineral-dominated clays may be less suitable for LC^3 production, they highlight the diversity of Nepal's clay assemblages. Although kaolinite-rich deposits are available in Nepal (Figure 3), their practical use for LC^3 production will depend on factors such as accessibility, topography, infrastructure, and land use, since some deposits are located in remote mountainous areas with limited road access.

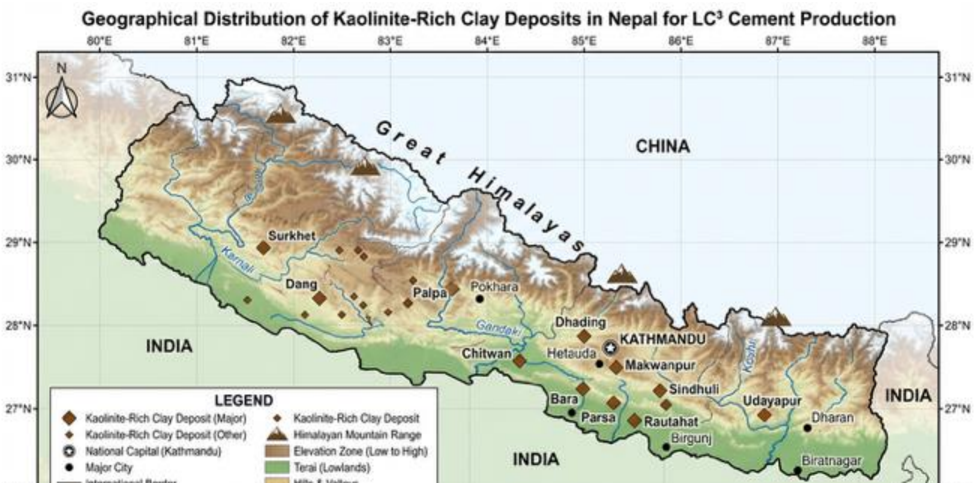

Figure 3: Geographical distribution of kaolinite-rich clay deposits in Nepal relevant to LC^3 cement production, showing major and minor deposit locations, major rivers, elevation zones, and key urban centres (prepared by the author based on Bäumler, Madhikermi and Zech (1997), Bhattarai et al. (2021), Dhakal et al. (2021), Dubey (2023), Huyghe et al. (2011), Neupane and Adhikari (2011), Neupane et al. (2025), Paudel (2014), Regmi et al. (2014), and Tao et al. (2022)).

3.2 Mineral Composition and Suitability for LC³ Production

The mineralogical composition of clay deposits is a key factor in determining their suitability for LC³ production, with kaolinite content being the most important indicator of potential reactivity after calcination. Tao et al. (2022) characterised Nepali clays using XRD, SEM, and BET analyses and confirmed that several deposits have suitable mineralogical properties for supplementary cementitious use, providing strong evidence that Nepal possesses promising clay resources for LC³ production. Earlier, Jha (1978) also confirmed the presence of kaolinite in Nepali clays, particularly in Daman, Panchmane, and Dalcap, with Daman clay showing stronger kaolinite-related peaks. More recently, Neupane et al. (2025) identified both kaolinite and halloysite in Central Nepal, indicating that clay mineralogy varies with location, parent rock, and weathering conditions. Halloysite is also important because, like kaolinite, it may develop pozzolanic reactivity after calcination, although its reactivity may differ.

Associated other minerals must also be considered when assessing clay suitability. Neupane et al. (2025) reported that Daman and Makawanpur soils contain muscovite, albite, montmorillonite, and halloysite alongside kaolinite. These associated minerals can influence calcination behaviour and reactivity, showing that suitability depends not only on the presence of kaolinite but also on the overall mineral assemblage. Tao et al. (2022) further highlighted the relevance of Nepali clays for cementitious applications, although detailed mineral quantification remains limited.

Some studies suggest that even moderate- to low-grade kaolinitic clays may still be suitable for LC³ production. Blouch et al. (2023) reported good performance with clays containing 40–55% kaolinite, while Babafemi et al. (2022) found 29.5–41.6% kaolinite satisfactory after calcination at 650°C for 1.5 h. In addition to kaolinite content, chemical composition and calcination conditions are also critical in determining suitability. Díaz et al. (2018) proposed screening criteria of Al_2O_3 > 18.0%, Al_2O_3/SiO_2 > 0.3, LOI > 7.0%, CaO < 3.0%, and SO_3 < 3.0% for identifying suitable kaolinitic clays. Calcination conditions are equally important: Tau et al. (2023) reported that 700–850°C is generally effective, while Gebremariam (2015) showed that excessive temperature can promote mullite formation and reduce pozzolanic reactivity. Vásquez-Torres et al. (2022) likewise showed that geological characteristics and mineralogy directly affect performance.

Overall, the available evidence suggests that Nepal has many promising clay resources with rich kaolinite content for LC³ production, including some deposits such as Panchmane and Dalcap that may be suitable even with moderate kaolinite grades. In addition to this, suitability will depend not only on mineralogical composition and calcination treatment, but also on practical factors such as deposit size, accessibility, proximity to cement plants, environmental regulations, and economic feasibility.

4. Feasibility Assessment

4.1 Infrastructure Compatibility and Calcination Requirements

LC³ has a practical advantage because it can be produced using much of the existing cement manufacturing infrastructure, which may reduce implementation cost. Krishnan (2014) demonstrated this through pilot-scale LC³ production in India, where the material was successfully produced under industrial conditions with lower kiln temperature requirements than clinker and in compliance with Indian standards. This is relevant to Nepal, where similar industrial conditions suggest that LC³ could be introduced with limited modification to existing cement plants. Martirena et al. (2020) further noted that clay calcination can be integrated into cement plants either by refurbishing old clinker kilns or by using rotary or flash calciners, depending on capital cost. They also identified grinding strategy as an important issue, since separate grinding provides better control of particle size and reactivity, whereas co-grinding is simpler but less flexible. For Nepal, this means that the most suitable production route will depend on the age, configuration, and technical capacity of existing cement plants.

Industrial experience also suggests that LC³ is compatible with current construction practice. Wali et al. (2018) reported that LC³ produced by JK Lakshmi Cement in India could replace OPC by the same weight without loss of performance and could be used with standard construction procedures. Shao et al. (2025) also highlighted pilot industrial production in Gujarat, India, confirming that LC³ has moved beyond laboratory-scale study.

The Calcination process remains the key technical requirement. Tau et al. (2023) reported that kaolinitic clays are generally calcined at 700–850°C, which is much lower than the 1450°C required for clinker production and therefore offers energy and CO_2 savings. They also showed that flash calcination is more energy efficient than industrial kiln calcination. Scrivener et al. (2017) noted that clay calcination may be carried out using flash calciners, fluidised beds, roller hearth kilns, or static tunnel kilns, depending on raw material characteristics, production scale, and available capital. Gebremariam (2015) further showed that flash calcination can rapidly produce optimum metakaolin at 1173–1200 K, although it requires fine particles and careful process control. Tau et al. (2023) also suggested that underutilised wet-process kilns can be refurbished for clay calcination, which may offer a lower-cost entry point for some plants in Nepal. Temperature control is especially important because it directly affects clay reactivity. Dhar et al. (2023) showed that kaolinite transforms to metakaolin by about 800°C, whereas at 1000°C it begins to convert to a spinel phase unsuitable for cementitious use. Bruno et al. (2024) also showed that electrified calcination could outperform conventional systems under carbon pricing, although this may be more relevant for future application in Nepal as renewable energy infrastructure develops.

However, practical challenges remain. Martirena et al. (2020) noted that the high specific surface area of calcined clay can increase water demand and reduce workability, which may require mix optimisation and admixture use. In addition, clay preparation, moisture removal, particle size, and material handling must be considered when selecting calcination systems for Nepali resources.

4.2 Economic Considerations

The economic feasibility of LC³ in Nepal will depend on whether it can compete with conventional cement while still delivering environmental benefits. Evidence from other countries suggests that LC³ can be cost-competitive under suitable conditions. Joseph et al. (2015) found that LC³ was significantly more economical than OPC and often competitive with PPC in India, even when higher quality kaolinitic clays were used. Similarly, Habert et al. (2016) reported that LC³ in Cuba reduced carbon emissions by about 30% and costs by around 10% compared with OPC, mainly because of lower clinker content, lower energy demand, and the use of local raw materials.

Further evidence from Cuba also highlights the economic practicality of LC³. Hernández (2017) found that LC³ production was economically viable and could be introduced using existing clinker infrastructure with only modest short-cycle investment, although transport costs could reduce this advantage. Sánchez-Berriel et al. (2020) also showed that local LC³ production had economic advantages over industrial LC³, OPC, and PPC, particularly because of the use of local materials, lower cost, and easier storage. This suggests that decentralised or regional LC³ production may also be attractive in Nepal, especially where suitable clay resources are located far from major cement plants. In addition, Díaz et al. (2018) examined retrofit costs and return on investment for LC³ over 15 years, emphasising the importance of long-term planning for industrial adoption.

Economic performance will also depend on the optimisation of the mix design and production strategy. Huang et al. (2024) proposed a multi-objective optimisation framework for LC^3 that integrates compressive strength and market-based cost, allowing mix proportions to be selected on the basis of both technical performance and economic efficiency. Their study achieved strong predictive accuracy for mechanical performance and showed that the optimum calcined clay-to-limestone ratio varies with target strength: for high-strength applications (≥65 MPa), a ratio of about 1:1 to 1.6:1 was recommended, while for lower-strength mixes (<65 MPa), the optimum ratio shifted to about 1.6:1 to 2:1. This is important because it shows that cost-efficient LC^3 formulations should be tailored to the required performance level rather than relying on a single fixed proportion. Kanagaraj et al. (2023) likewise noted that LC^3 concrete can achieve high compressive strength in a cost-effective manner while also reducing energy demand and greenhouse gas emissions.

However, the economic feasibility of LC^3 in Nepal will ultimately depend on site-specific factors such as clay extraction, processing, calcination, transport distance, and market acceptance. Policy measures such as carbon taxes, subsidies for low-carbon technologies, supportive building codes, and public procurement strategies could further improve the competitiveness of LC^3 and accelerate its adoption in Nepal's cement sector.

5. Challenges and Limitations

Although LC^3 shows strong potential as a low-carbon cement option for Nepal, its practical adoption is likely to face a combination of technical, economic, and implementation challenges.

A major technical limitation is the variability of Nepali clay resources. Since clay deposits differ in mineralogical composition and quality, a single calcination condition or mix design may not be suitable for all sources. This means that consistent LC^3 production will require careful clay characterisation, source selection, and quality control. Calcination is another critical challenge, because clay reactivity depends strongly on temperature control; insufficient or excessive heating can reduce pozzolanic performance. In addition, the choice of calcination system, grinding method, and process configuration will need to match the conditions and capacity of existing cement plants. The high specific surface area of calcined clay may also increase water demand and reduce workability, potentially requiring admixture use and further optimisation of the concrete mix design before use of LC3 cement.

Economic limitations are also important. While LC^3 has the potential to reduce clinker use and energy demand, its financial viability in Nepal will depend on the cost of clay extraction, processing, calcination, transport distance, and production scale. These costs may become significant where suitable deposits are remote or poorly connected to cement plants. Initial investment in calcination equipment and supporting infrastructure may also be a barrier, particularly for smaller producers. In addition, limited market familiarity with LC^3 may affect pricing and demand during early adoption.

Implementation challenges extend beyond material and cost issues. Nepal still lacks the standards, certification pathways, and regulatory framework needed for large-scale LC^3 deployment. Market acceptance may also be slow unless supported by pilot production, field demonstration, and long-term performance evidence. Capacity building will therefore be essential in clay characterisation, calcination control, cement formulation, and concrete production. Environmental and social issues related to clay extraction, together with weak coordination among industry, researchers, and government, may further delay implementation.

Overall, the main limitation is not the potential of LC³ itself, but the gap between promising laboratory and literature evidence and reliable industrial application under Nepali conditions. Bridging this gap will require coordinated technical validation, economic assessment, institutional support, and practical demonstration.

6. Conclusions and Future Directions

Overall, this review indicates that LC³ could provide a feasible and sustainable pathway for reducing the carbon intensity of cement production in Nepal. The main conclusions are as follows,

- LC³ is a promising low-carbon cement option for Nepal, as it can reduce clinker demand, lower CO_2 emissions, and offer potential economic benefits through lower calcination temperature and the use of locally available raw materials.
- Nepal appears to have sufficient clay resources for LC³ production, with kaolinite-bearing deposits reported in places such as Daman, Makawanpur, Surkhet, Dang, Palpa, Dhading, Bara, Parsa, Rautahat, Sindhuli, and Udayapur. In addition, studies from 25 locations suggest that several of these clay resources have promising mineralogical characteristics for supplementary cementitious use.
- Not only high-grade clays, but also some moderate- to low-grade kaolinitic clays are suitable after calcination, which widens the possible raw material base for Nepal low kaolinite clay deposits; however, this still requires detailed confirmation through local mineralogical and reactivity testing.
- LC³ appears technically feasible within Nepal's existing cement plants, since it could be produced using current cement infrastructure with limited modification, although plant-level compatibility and calcination optimisation remain essential.
- The main barrier is not the concept of LC³ technology itself, but its reliable industrial implementation in Nepal. This will require pilot-scale production, clay-to-limestone proportion optimisation, and field performance monitoring.
- Successful adoption will depend on more than just suitable clay resources. Economic viability, transport, standards, quality control, technical training, coordination between institutions, and supportive policies will all be needed before LC³ can be used on a large scale in Nepal.

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3D FEM Analysis of Geosynthetically Reinforced Road Pavements for Mitigating Surface Distresses and Structural Deficiencies in Heavily Loaded Bend and Uphill Sections

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Abstract
Road pavements constructed on inadequate subgrade are highly susceptible to rutting, cracking, and settlement under heavy traffic, particularly in heavily loaded highway lanes where 33–42 ton trucks induce repeated stresses, especially at bends and upgrade sections. In such conditions, several observed sections are beyond repair, where conventional rehabilitation methods such as overlays are ineffective, and even rigid pavement solutions (e.g., at Piplamode) have not performed satisfactorily due to persistent subgrade inadequacy and severe loading. This highlights the need for improved reinforcement strategies rather than conventional repair approaches. However, the relative influence of geogrid stiffness and placement location under such loading remains unclear. This study evaluates geosynthetically reinforced flexible pavements using a 3D finite element model. The design follows the IIT Pave approach for an 80 kN standard axle over 30 MSA, while simulating a 33-ton, 12-wheel truck. Geogrids with stiffness ranging from 400 to 1600 kN/m are placed at key interfaces. Results show that the Service Life Ratio (SLR) varies from 1.12 to 1.90, with maximum improvement under optimal or combined reinforcement. Stiffness has a negligible effect, whereas placement location governs performance. Subgrade–base reinforcement reduces compressive and vertical strains with SLR ≈ 1.5-1.85, while base–asphalt or combined reinforcement improves fatigue life with SLR up to 1.9. The findings emphasize that optimal reinforcement depth is more critical than stiffness for enhancing pavement performance under heavy loading.

Keywords: Finite Element Method; Geo-synthetic reinforcement; Vehicle load Configuration, Vehicle load dynamics; Service life; Bend and uphill pavements

1. Introduction
Surface distress in flexible pavements-manifested as cracking, rutting, and settlement-commonly reflects deficiencies in the underlying subgrade, particularly under heavy truck loading conditions (Huang, 2004). Along major corridors such as the Prithvi Highway in Nepal, these problems are more pronounced in the left lane, which carries heavily loaded trucks with gross vehicle weights of approximately 33 tons (Figure 1). Critical locations such as Piplamod near Nagdhunga, Galchhi in Dhading, Richoktar near Malekhu, and Bishaltar near Mugling frequently exhibit pavement distress, including depressions, rutting, and asphalt deterioration (Figure 2). These site-specific variations in terrain, moisture, and repeated heavy loading

generate localized stress concentrations, which accelerate the structural degradation of the pavement system.

High-stress pavement sections are highly prone to distress due to the combined action of heavy axle loads and inadequate subgrade conditions; however, their coupled influence is often overlooked, resulting in limited understanding and the absence of unified design guidelines for such scenarios. Under these conditions, conventional solutions like subgrade replacement become impractical, particularly for heavily loaded roads. Geosynthetics, including geogrids and geotextiles, offer a more efficient approach by improving structural stability through enhanced confinement, separation, and load transfer mechanisms (Koerner, 2012; Giroud and Han, 2004; Leng and Gabr, 2002) (Figure 3). These improvements directly address key distress mechanisms-such as rutting, cracking, and settlement-by limiting subgrade deformation and controlling stress distribution. Numerical studies further indicate that the effectiveness of reinforcement depends on factors such as stiffness, placement depth, and subgrade characteristics, with optimized configurations significantly reducing deformation under repeated loading (Kim and Lee, 2014; Yin et al., 2022; Chhetri and Deb, 2024; Hegde and Palsule, 2020; Tiwari et al., 2025). In this context, the present study evaluates stress–strain response, deformation, and load distribution to quantify the contribution of geosynthetics to improved pavement performance and durability (Leonardi and Suraci, 2022; Namir et al., 2017; Poudel and Tiwari, 2022).

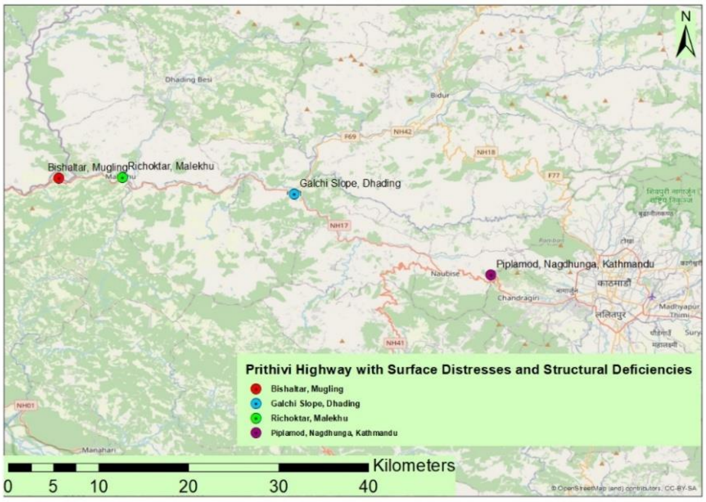

Figure 1: Typical locations of surface distresses and structural deficiencies identified on the Nagdhunga - Mugling section of the Prithvi Highway

Figure 2: Rutted and depressed road surfaces in the heavily loaded truck lane of Prithvi Highway: Piplamod, Kathmandu (First Figure), Galchhi Height, Dhading (Second Figure), Richoktar, Malekhu, Dhading (Third Figure), and Bishaltar, Chitwan (Fourth Figure)

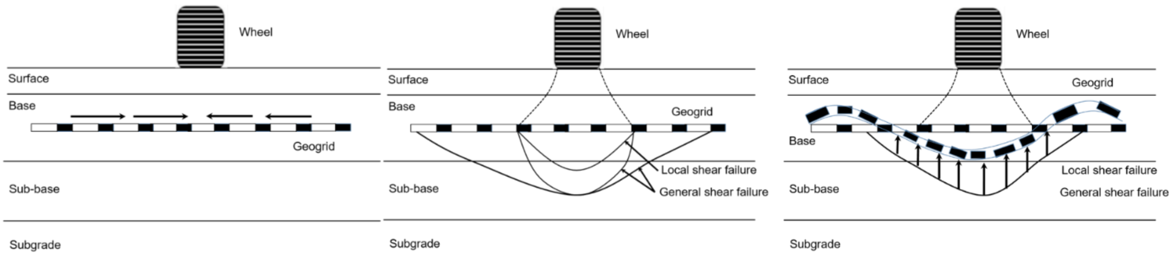

Figure 3: Influences of Geosynthetic Reinforcement: Lateral restraint mechanism (Left Figure), Increased bearing capacity mechanism (Middle Figure), and Tension membrane mechanism (Right Figure)

The problem was made based on field investigations on the Prithvi Highway portion from Mugling (Chitwan) to Nagdhunga (Kathmandu). For the uphill journey, heavy duty trucks mostly utilize the left lane whereas the return journey vehicles use the right lane. The right lane consists of mostly light loaded or even empty trucks. Due to their low speeds and continuous wheel loads and extra strains caused by curvatures and gradient in the left lane, the damage due to pavement wear is comparatively more severe in the left lane compared to the right lane. From the field surveys, surface damage was visible in the left lane, but no such damage was visible in the right lane.

2. Methodology

This study adopts a numerical approach to evaluate the performance of geosynthetically reinforced pavements under heavily loaded trucks. The methodology integrates 3D finite element modeling and data analysis to assess stress–strain behavior, load distribution, and deformation in curved, uphill, and combined sections under realistic traffic loading conditions (30 MSA). Numerical modeling is carried out using PLAXIS to simulate the continuum behavior of pavement systems (PLAXIS V8 Dynamics Manual, 2025). Curved sections are analyzed for additional lateral stresses induced by vehicle turning, while uphill sections are evaluated for the effects of acceleration on pavement distresses. Combined sections are examined to understand the interaction of curvature and gradient on pavement response. Pavement structures for unreinforced cases are designed using IITPave in accordance with IRC and DoR guidelines (IRC, 2018; DOR, 2021), while 3D PLAXIS is employed to model geosynthetic–soil interaction beyond the limitations of conventional design approaches. Material behavior is represented using linear elastic models for the geosynthetics, base layer, and surface layer, while appropriate constitutive model (e.g., Mohr–Coulomb) is used for the subgrade layer. The performance of the reinforcement is evaluated in terms of improved load distribution, enhanced lateral confinement in curved sections, and reduction of shear deformation and rutting in uphill and combined sections. The results are interpreted with reference to established engineering standards to ensure practical applicability and reliability. The overall methodological flowchart is presented in Figure 4. The material models are prepared as per Tables 1-4. The research methodology has been previously validated by Tiwari et al. (2025), with field verification conducted by the same author on the Arughat–Okhale Road section of the Mid-Hill Highway, Nepal.

Geometric design data for the five road sections were obtained from the Department of Roads, Pulchowk, Nepal. Curved flexible pavement sections were identified, and key parameters- including horizontal radius of curvature (R), carriageway width (W), super elevation rate (e), and longitudinal gradient (G) - were extracted and systematically organized in a structured Excel database (Table 1).

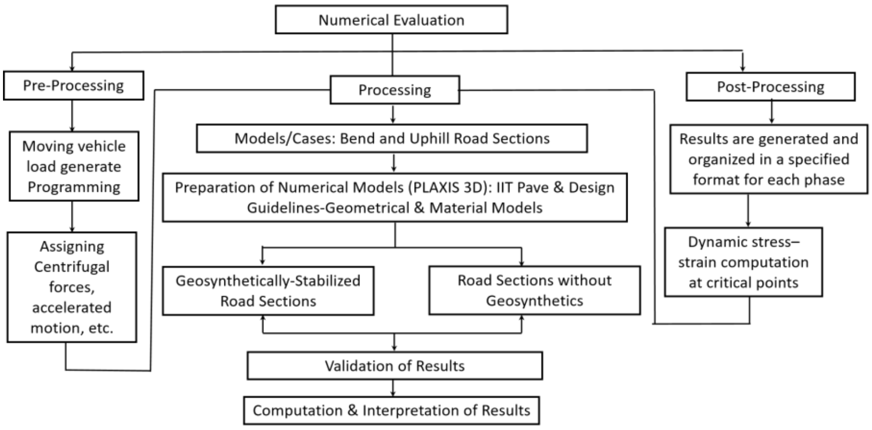

Figure 4: Methodology flow chart for numerical modelling

Table 1: Geometric parameters of the selected curved pavement sections

Site	Radius (m)	Width (m)	Super-elevation (%)	Long. Grade (%)
Pipalamod Upper	50	7.6	6	5.02
Pipalamod Lower	32	9	2.50	6.14
Galchhi Height	110	17	5.30	3
Richoktar	205	16	4	2.96
Bishaltar	40	12	6.80	4.56

The testing program determined all parameters required for the Mohr-Coulomb material model, as summarized in Table 2. The values reported in Table 3 are used in order to represent the behavior of the subgrade soil and facilitate the choice of the suitable material model and whether the soil should be considered drained or undrained in this study. A Mohr-Coulomb model was chosen in this study and the effect of those values was not studied individually.

Table 2: Mohr-Coulomb material parameters determined from laboratory testing

Parameter	Symbol	Test Standard	Unit	Relevance to Model
Unit weight	γ	IS 2720 Part 2	kN/m³	Body force
Cohesion	c	IS 2720 Part 13	kPa	Mohr-Coulomb yield
Friction angle	φ	IS 2720 Part 13	degrees	Mohr-Coulomb yield
Young's Modulus	E	CBR correlation (IRC 37)	MPa	Elastic stiffness
Poisson's ratio	v	Literature correlation	—	Lateral deformation
CBR	CBR	IS 2720 Part 16	%	Pavement thickness design

Table 3: Material model

Location	LL (%), PL (%) & PI	G_s	OMC (%) &MDD (gm/cc)	CBR (%) (@2.5mm & @ 5.0mm)	Φ (◦) & c (kg/cm2)	Grain size (%) (< 0.075mm)	q_u (kPa) & c_u (kPa)	Cc

Piplamode Upper	35.620, 27.767, 7.852	2.81	0.12, 1.39	1.42, 3.03	35.17, 0.1713	90.77	92.32, 46.16	0.040
Piplamode Lower	32.753, 25.130, 7.623	2.71	0.10, 1.56	3.31, 5.86	31.43, 0.1793	79.20	82.32, 41.66	0.0443
Galchi Height	27.319	2.67	0.12, 1.70	6.81, 8.89	39.40, 0.1501	39.20		
Richoktar	20.193	2.87	0.16, 1.64	1.70, 3.03	36.64, 0.1121	23.60		
Bishaltar	32.949, 17.193, 15.756	2.83	0.20, 1.80	2.55, 2.83	45.27, 0.1587	85.20	116.20, 58.10	0.0741

Table 4: Summary of flexible pavement design for 30 MSAL (IRC:37-2018, IIT Pave)

Site	Location	CBR (%)	GSB (mm)	WMM (mm)	DBM (mm)	BC (mm)	Total (mm)	E_asphalt (MPa)	E_base (MPa)
1	Piplamode Upper	3.03	350	150	150	50	700	3000	99.31
2	Piplamode Lower	5.86	250	150	150	50	600	3000	161.77
3	Galchi	8.89	200	150	150	50	550	3000	198.92
4	Richoktar	3.03	350	150	150	50	700	3000	99.31
5	Bishaltar	2.83	400	150	150	50	750	3000	96.823

Figures 5-7 present typical snapshots of the 3D finite element modeling of the curved and uphill road section at Piplamode Lower in PLAXIS. Figure 5 shows different vehicle load positions (Positions 1-3), the quasi-static displacement of the vehicle along the route alignment, accounting for the horizontal curvature as well as longitudinal grade of the alignment. The loading effect of the vehicle is modeled using progressive displacements on the pavement surface, where the existing load effect is first stripped off and a new load is placed on the pavement. Such an analysis accounts for the changes in the pavement behavior due to changing load effects but ignores any dynamic effects. Figures 6 and 7 illustrate the model configuration, including geogrid placement with interface conditions and the layer-wise structure (subgrade, base, and asphalt). These are typical representations, and similar diagrams can be obtained for other sites. Table 5 shows the IIT Pave strain verification comparing obtained strain with allowable strains.

Table 5: IIT Pave strain verification: obtained vs. allowable strains

Site	Location	εv obtained (GSB check)	εv allow (0.00243)	εv obtained (final)	εv allow (0.000416)	εt obtained
1	Piplamode Upper	0.00213	✓	0.000369	✓	0.0001787
3	Galchi	0.002097	✓	0.0002785	✓	0.0001411
4	Richoktar	(= Site 1)	✓	(= Site 1)	✓	(= Site 1)
5	Bishaltar	0.001851	✓	0.0003556	✓	0.0001790
Note: εt, allow = 0.000219 for all sites; all tensile strain checks pass. ✓ All obtained strains are less than allowable strains at 90% reliability for 30 MSAL design traffic. The proposed pavement sections satisfy both rutting and fatigue Failure criteria as per IRC: 37-2018.						

A twelve-wheeled TATA truck was selected as the design vehicle. Field measurements were used to obtain axle and wheel spacing, and axle load was determined using static equilibrium, resulting in −31 kN per point load for the front axles and −26 kN for the rear axles (Table 6).

Table 6: Vehicle load Configuration

Parameter	Measured Value
Number of axles	4
Number of wheels	12
Axle 1–2 spacing (m)	3
Axle 2–3 spacing (m)	1.74
Axle 3–4 spacing (m)	1.45
Wheel spacing - front axle (m)	0.7568
Wheel spacing - rear axles (m)	Left and right set-0.7568, between adjacent wheels-0.08
Total gross vehicle weight (kN)	332
Fz per point load - front two axles (kN)	−31
Fz per point load - rear two axles (kN)	−26

Mesh generation has been performed using the automated meshing facility incorporated within the PLAXIS 3D software, resulting in an unstructured mesh comprising 10-node tetrahedrals. Mesh sensitivities were checked and the optimal mesh configuration has been chosen when no more than 2% variation in strain occurred during subsequent mesh refinements. Coarsening factors allocated to each layer are listed in Table 7 (PLAXIS Knowledge Base, 2015). Similarly, Mesh scheme and boundary conditions are respectively shown in Table 8 and 9.

Table 7: Local coarseness factors assigned to each model component

Layer / Component	Element Type	Local Coarseness Factor	Mesh Density	Justification
Subgrade	10-noded tetrahedra	1.0 (coarsest)	Standard	Deep layers: Coarse mesh
Granular base course	10-noded tetrahedra	0.75	Medium-fine	Transition zone: Moderate mesh
Bituminous asphalt layer	10-noded tetrahedra	0.5	Fine	Loading zone: Fine mesh
Point load locations	10-noded tetrahedra	0.1 (finest)	Very fine	Critical zone: Very fine mesh.

Table 8: Mesh statistics for the five study site models

Site	Total Elements	Total Nodes (approx.)	Phases per Model
Pipalamod Upper	24599	50446	20
Pipalamod Lower	28490	58712	20
Galchhi Height	27387	56812	24
Richoktar	17866	38684	21
Bishaltar	24228	49917	29

Table 9: Boundary Conditions

Bottom face (base of subgrade)	Fully fixed (Ux = Uy = Uz = 0)	Rigid base assumption
Side faces (transverse)	Normally fixed	Prevents rigid body motion; roller boundary

Side faces (longitudinal)	Normally fixed	Prevents rigid body motion along traffic direction
Top surface (pavement surface)	Free- point loads applied at tire contact coordinates	Load application surface

All calculation phases used plastic analysis calculation method in PLAXIS 3D through Newton-Raphson method of incrementation and iteration (PLAXIS Scientific Manual, 2025). The K0 method was utilized in the first phase to determine the geostatic condition of stress. The complete phase sequence is summarized in Table 10.

Table 10: Calculation phase sequence for each PLAXIS 3D simulation

Phase No.	Phase Type	Activated Components	Description
1	Initial (K0 procedure)	Subgrade	Initial phase: Geostatic stresses established.
2	Plastic analysis	Base course	Base phase: Base layer activated.
3	Plastic analysis	Asphalt layer	Surfacing phase: Asphalt layer activated.
4	Plastic analysis	Point load set 1 (12 loads)	Loading phase: Vehicle load applied at initial position.
5-22	Plastic analysis	Successive point load sets	Moving load phase: Vehicle advances incrementally; loads updated at each steps

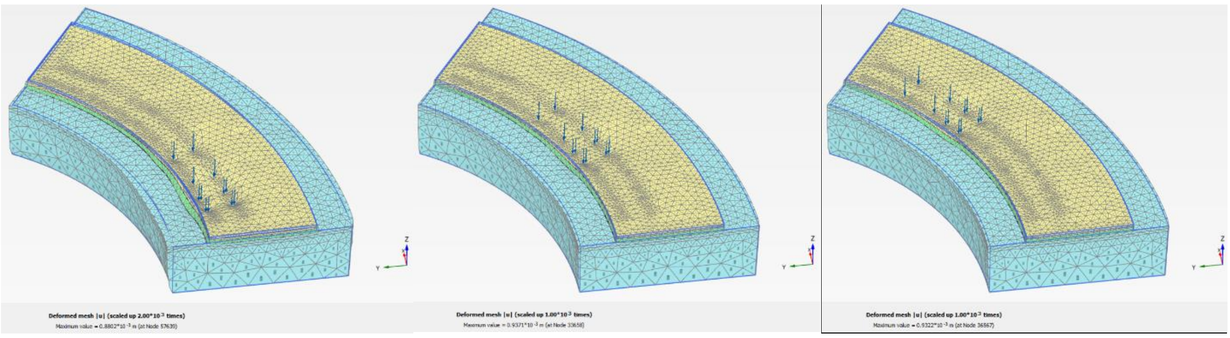

Figure 5: 3D model of curved and uphill road section of Piplamode Lower in Plaxis: Vehicle load position 1 (Left Figure), Vehicle load position 2 (Middle Figure), and Vehicle load position 3 (Right Figure)

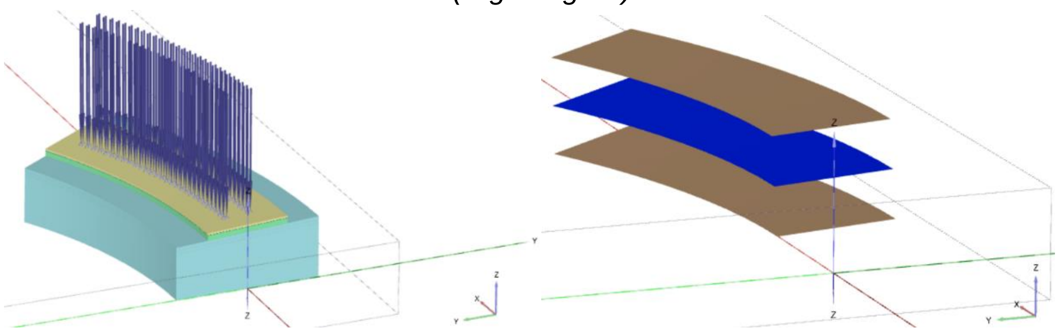

Figure 6: 3D model of curved and uphill road section of Piplamode Lower in Plaxis (Left Figure) and Geogrid placement with positive and negative interfaces (Right Figure)

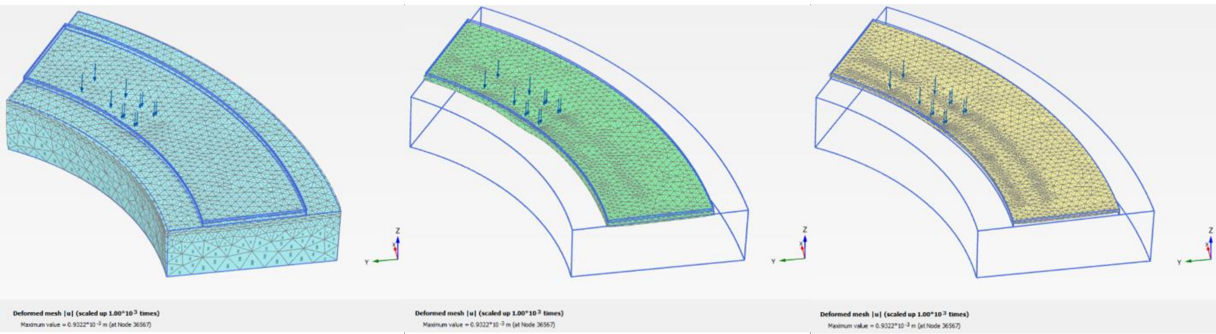

Figure 7: 3D model of curved and uphill road section of Piplamode Lower in Plaxis: Subgrade layer (Left Figure), Base layer (Middle Figure), and Asphalt layer (Right Figure)

2.1 Service Life Ratio (SLR) based on Rutting and Fatigue criteria

The Service Life Ratio (SLR) is defined as the ratio between the service life of a reinforced pavement and that of an unreinforced pavement. It provides information regarding the effectiveness of reinforcing in increasing the durability of pavements. If SLR exceeds unity, it implies that the service life of pavements has been extended owing to less fatigue and rutting. Rutting is considered a failure when the average rut depth reaches 20 mm. Rutting life (N_R) is the number of standard 80 kN axle load repetitions the pavement can withstand before reaching this limit. It is calculated using the following formulas (IRC-37, 2018).

80% Reliability:

$$N_R = 4.1656 \times 10^{-8}(1/\varepsilon_v)^{4.5337} \quad (1)$$

90% Reliability:

$$N_R = 1.4100 \times 10^{-8}(1/\varepsilon_v)^{4.5337} \quad (2)$$

Where, N_R = Rutting life (in standard 80 kN axle loads), and ε_v = Vertical compressive strain at the top of the subgrade, calculated using linear elastic layered theory

Fatigue failure is said to occur when 20% or more of the surface area develops interconnected cracks. The fatigue life (N_f) is the number of standard axle load repetitions until this condition is reached. The fatigue life is calculated using the following equations (IRC-37, 2018):

80% Reliability:

$$N_f = 1.6064 \times C \times 10^{-4}(1/\varepsilon_t)^{3.89}\,(1/M_{Rm})^{0.854} \quad (3)$$

90% Reliability:

$$N_f = 0.5161 \times C \times 10^{-4}(1/\varepsilon_t)^{3.89}\,(1/M_{Rm})^{0.854} \quad (4)$$

Where, N_f= Fatigue life (in standard 80 kN axle loads), ε_t= Horizontal tensile strain at the bottom of the bituminous layer, M_{Rm} = Resilient modulus (in MPa) of the bituminous mix

$$C = 10^M \quad (5)$$

$$M = 4.84\left(\frac{V_{be}}{V_a+V_{be}}-0.69\right) \quad (6)$$

Where, C = Adjustment factor accounting for the volumetric properties of the bituminous mix V_a- Air Voids: The percentage of air spaces in the compacted bituminous mix. The recommended range of design air voids is 2–2.5%. The maximum in-place air voids is taken as less than 4%. The low air voids help reduce moisture damage and aging. The proper compaction ensures mix durability and resistance to environmental damage. V_{be}- Effective Bitumen Content: The percentage of bitumen that effectively coats and binds the aggregates, excluding bitumen absorbed into aggregate pores. The recommended range is 4–5%.

2.2 Automation of FEM- Pre-Processing and Post-Processing

The PLAXIS 3D Remote Scripting API, which is an HTTP interface based on Python language, makes it possible for other Python scripts to communicate with the program to perform various operations such as geometry creation, property assignment, phase definition, and output acquisition (Brinkgreve et al., 2019; Bentley Systems, 2022). The use of automation via such interfaces has been widely used in recent literature for automatic execution of repeated geotechnical model tasks. In this current work, automation using Python was used in the pre-processing phase (curved path point load and dynamic load assignment) and in the post-processing phase (extraction of pavement response parameters from 65 models).

3. Results

Figure 8 presents a typical stress plot of the curved and uphill road section at Piplamode Lower, showing total principal strain along the longitudinal section at the subgrade top (left) and along the transverse section at the rear wheel axle (right). Similar results can be obtained for other sections.

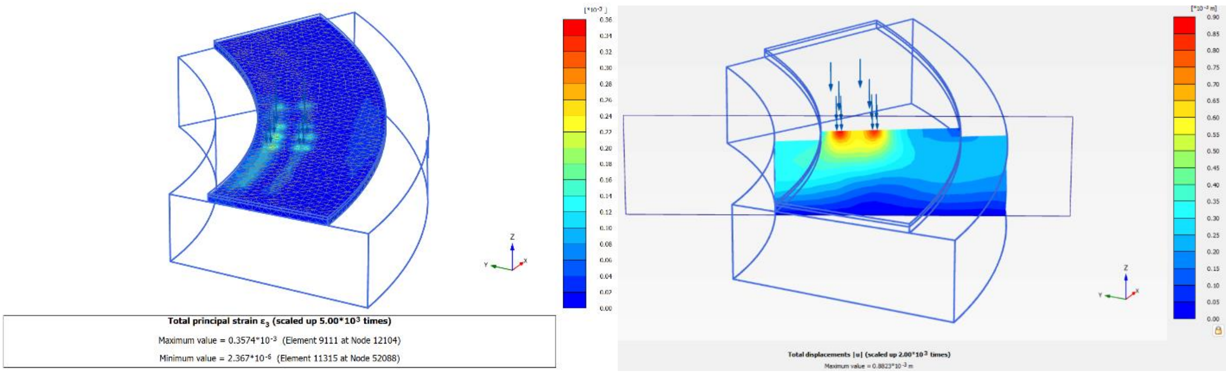

Figure 8: Stress Plots of curved and uphill road section of Piplamode Lower: Total Principal Strain along Longitudinal Section at Subgrade Top (Left Figure), Total Principal Strain along Transverse Section at rare wheel axle (Right Figure)

The analysis of the Service Life Ratio (SLR) at the Piplamode Lower curve section, as illustrated in Figures 9 and 10, reveals a consistent and significant trend: the effectiveness of geogrid reinforcement is governed primarily by its placement depth rather than its tensile stiffness (K). Across all three strain metrics-principal compressive strain (E1), Cartesian compressive strain (EZZ), and principal tensile strain (E3)-here focusing on E1 and E3, the nearly horizontal trends between 300 kN/m/m and 1600 kN/m/m indicate that increasing geogrid stiffness provides negligible additional structural benefit.

For surface-level compressive strains (E1), Figure 9 shows that placing the geogrid at the subbase level (subgrade–base configuration) is the most effective strategy. This configuration yields a substantial extension in service life, with SLR values reaching approximately 1.75 for E1, representing an improvement of up to 75% compared to unreinforced sections. In contrast, base-level reinforcement and other configurations remain around an SLR of 1.0, offering no measurable advantage in mitigating these surface-level strains. For fatigue-related tensile strains at the bottom of the asphalt layer (E3), a different trend is observed. As shown in Figure 10, base-level reinforcement (base–asphalt configuration) is more effective, achieving an SLR of approximately 1.5. While subbase reinforcement still provides a modest improvement (SLR ≈ 1.2), placing the geogrid closer to the asphalt layer better reduces tensile stresses associated with fatigue cracking. Overall, the results confirm that the optimal reinforcement location depends on the targeted distress mechanism. However, both surface compression and asphalt fatigue can be effectively mitigated even with lower-stiffness geogrids, as the primary structural benefit arises from strategic placement within the pavement layers. Similar trends are observed in the remaining sections, as summarized in Table 7.

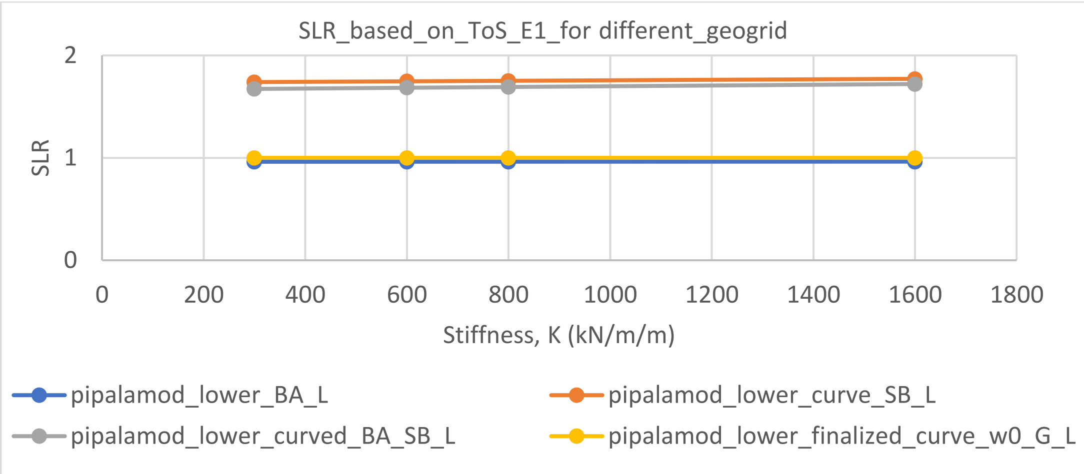

Figure 9: Service Life Ratio (SLR) versus geogrid stiffness, K (kN/m/m), considering the principal compressive strain (E1) at the top of the asphalt layer at the Piplamode Lower curve section, left lane

Table 11 shows that SLR is controlled by geogrid placement, not stiffness. Subgrade–base reduces compressive strains, while base–asphalt or combined placement improves tensile and fatigue performance, with minimal benefit from higher stiffness. Overall, optimal reinforcement depth is key to enhancing pavement service life.

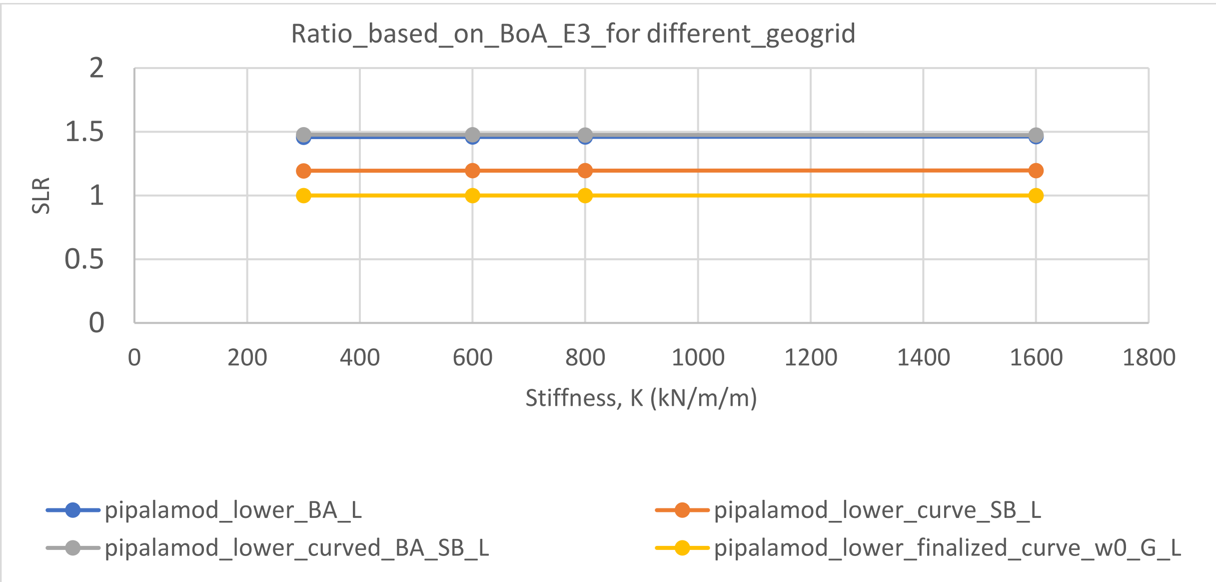

Figure 10: Service Life Ratio (SLR) versus geogrid stiffness, K (kN/m/m), considering the principal tensile strain (E3) at the bottom of the asphalt layer at the Piplamode Lower curve section, left lane.

Table 11: Comparative Summary of SLR Performance

Curve Section	Strain Type	Best Reinforcement Location	SLR Range	Effect of Stiffness (K)	Key Observation
Piplamode Upper	E1 (Top of Subgrade, compressive)	Subgrade-Base	1.7–1.75	Negligible (flat trend)	Placement depth governs performance; stiffness insignificant
Piplamode Upper	EZZ (Top of Subgrade, Vertical compressive)	Combined Subgrade-Base and Base-Asphalt	~1.5	Nearly zero effect	Lower layer reinforcement controls vertical strain
Piplamode Upper	E3 (Bottom of Asphalt , tensile)	Combined Subgrade-Base and Base-Asphalt	1.8–1.9	No significant effect	Base reinforcement highly effective for fatigue life
Piplamode Lower	E1 (Top of Subgrade)	Subgrade-Base	~1.75	Negligible	Subbase placement most effective for compressive strain reduction
Piplamode Lower	EZZ (Top of Subgrade)	Subgrade-Base	1.70 – 1.85	No meaningful effect	Maximum benefit for vertical strain reduction, Reinforcement depth dominates performance
Piplamode Lower	E3 (Bottom of Asphalt)	Base-Asphalt	~1.5	Negligible	Base reinforcement improves fatigue life, Base layer controls tensile fatigue behavior
Galchhi Curve	E1 (Top of Subgrade)	Combined Base-Asphalt and Subgrade-Base	1.8–1.85	Insignificant	Subbase controls surface deformation, Subbase reinforcement significantly extends service life
Galchhi Curve	EZZ (Top of Subgrade)	Combined Base-Asphalt and Subgrade-Base	~1.85	No effect	Depth of reinforcement is critical
Galchhi Curve	E3 (Bottom of Asphalt)	Base–Asphalt	1.50 – 1.55	Negligible	Base layer essential for tensile strain control, fatigue crack control
Bishaltar Curve	E1 (Top of Subgrade)	Subgrade-Base	~1.6	Negligible	Moderate improvement in rutting resistance
Bishaltar Curve	EZZ (Top of Subgrade)	Subgrade-Base	~1.55	No effect	Stiffness increase does not improve performance
Bishaltar Curve	E3 (Bottom of Asphalt)	Combined Base-Asphalt and Subgrade-Base	1.7–1.75	No effect	Strong fatigue resistance improvement, Base reinforcement significantly improves fatigue life
Richoktar curve	E1 (Top of Subgrade)	Subgrade-base	1.45 – 1.60	Slight but limited	Diminishing returns with increasing stiffness
Richoktar curve	EZZ (Top of Subgrade)	subgrade-base and base-asphalt	1.48 – 1.57	Low sensitivity	Initial inclusion more important than stiffness
Richoktar curve	E3 (Bottom of Asphalt)	Base-Asphalt	1.12 – 1.55	Almost constant	Acts as strain-relief layer; stiffness insignificant

The heat map shows that BA reinforcement reduces asphalt bottom strain by up to 39.7% but slightly increases subgrade strain (~+3.8%), while SB reinforcement reduces subgrade strain by over 46%. The combined (SB+BA) case performs best, achieving up to 93.9% reduction in lateral strain, indicating a strong synergistic effect (Figure 11). These results confirm that reinforcement effectiveness is greatly influenced by its position within the pavement layers; therefore, the recommendation for appropriate reinforcement depth selection based on pavement performance is justified.

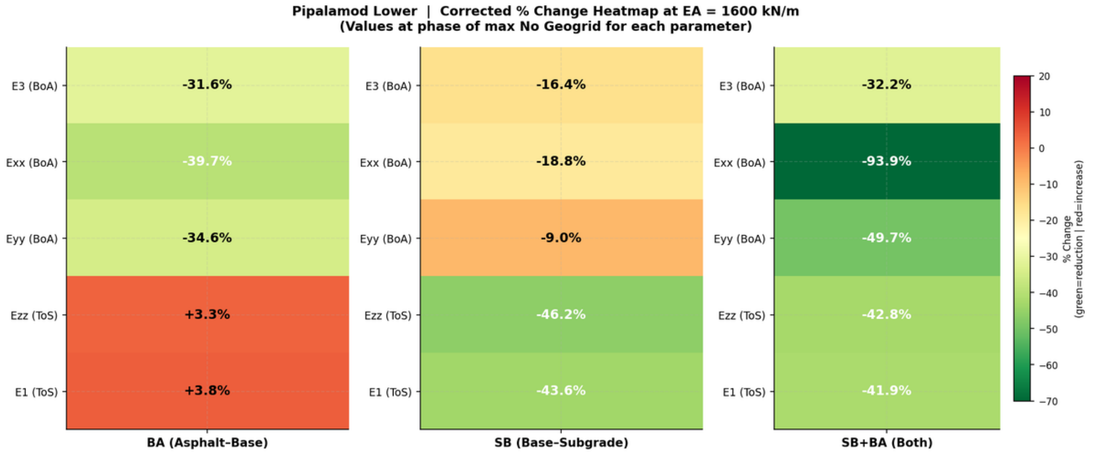

Figure 11: Pipalamod Lower - SLR heat map — all configurations and stiffness levels

The values of the geometric variables (Radius, Width, Super-elevation, and Gradient) in the present investigation were used to simulate practical curved and uphill pavement loads, and not for studying the effect of their variations individually on the SLR. This effect is implicitly included in the response and the SLR computations. Nonetheless, an independent study of the effects of each geometric variable is not performed in this work, since such a study goes beyond the present investigation scope.

4. Conclusion and Recommendation

The Service Life Ratio (SLR) ranges approximately from 1.12 to 1.90, with the highest improvements observed in sections subjected to combined reinforcement (up to ≈1.9), while lower gains are noted in weaker sections such as Richoktar (≈1.12-1.55). The influence of geogrid stiffness (K) is consistently negligible to insignificant, indicating that increasing stiffness provides minimal additional benefit. In contrast, reinforcement location is the controlling factor, where placement at the subgrade-base interface significantly improves compressive and vertical strain performance (SLR ≈1.5-1.85), and placement at the base–asphalt interface or in combination enhances tensile strain resistance and fatigue life. It is therefore recommended to prioritize optimal reinforcement depth and location over stiffness selection, adopting subgrade-level reinforcement for rutting and deformation control, and base-level or combined reinforcement for fatigue resistance, ensuring a more efficient and economical pavement design under heavy loading conditions.

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Exploring the Determinants of Foreign Direct Investment in the Construction Industry in Nepal

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Abstract
To attract Foreign Direct Investment (FDI), many countries embarked on various reforms. Nepal like many South Asian Countries, has taken some steps and introduced measures aimed at improving the FDI regulatory framework. Realizing the comparative and locational advantages of Nepal, the targeted growth requires substantial investment from both bilateral and multilateral sources, as well as active participation from the private sector. In this context, the role of FDI becomes pivotal, not only for sustaining developmental efforts but also for alleviating poverty. This study examines the key determinants of FDI commitment in the construction industry in Nepal. The FDI model is specified using identified determinants of FDI and several variables characterizing economic, financial and environmental indicators. A twenty-five-year dataset spanning from 1996 to 2021 A.D. is analyzed using multiple regression method. The explanatory variables include Gross Domestic Product (GDP) per capita, Gross National Income (GNI) per capita, doing business index, national wholesale price index, construction material price index, infrastructure development measured by Blacked Topped Road (BTR), the Nepal Stock Exchange (NEPSE) index and CO_2 emissions per capita are considered as independent variables in the research. The study concludes that GDP per capita, CO2 emissions per capita, and the NEPSE index, which serves as an indicator of market stability and size, are the key determinants of FDI commitment within the construction industry in Nepal. However, this study does not incorporate the FDI realization and a sectoral-level analysis of FDI determinants of Nepal.

Keywords: Foreign Direct Investment, GDP per capita, $C0_2$ emission per capita, NEPSE index, National wholesale price index.

1. Introduction
Foreign direct investment (FDI), which is the investment in physical assets (such as land, buildings, or even existing factories) in foreign enterprises, acquisition of foreign firms, and the creation of new overseas subsidiaries are common ways for multinational corporations (MNCs) to take advantage of international economic prospects. When correctly handled, any of these types of FDI can produce significant profits. However, as FDI calls for a sizable investment, a lot of money may be at risk. Additionally, if the investment doesn't work as well as anticipated, MNCs can find it challenging to sell the foreign enterprise it helped to build. Given these FDI return and risk characteristics, MNCs often do a thorough cost and benefit analysis prior to implementing any sort of FDI. It is conventionally defined as a form of international inter-firm cooperation that involves a significant equity stake in, or effective management control of foreign firms (Mello, 1997).

FDI is advantageous to both the host country and the Multi-National Companies (MNC), making it a win-win situation, FDI can be classified as vertical, horizontal, or conglomerate in nature. When an MNC invests in a host nation to conduct identical production operations to those it undertakes in its own nation, this is referred to as horizontal FDI. In contrast to conglomerate FDI, which occurs when an MNC invests in a completely unrelated industry that is not directly related to its existing business, vertical FDI involves an MNC fragmenting its production process globally by deploying each stage in the host country where it can be executed at the lowest possible cost (Protsenko, 2004).

While FDI can offer additional benefits and ultimately eliminate the need for foreign help, development aid alone cannot restore destroyed economies to healthy, self-sufficient systems (Turner et al., 2008). Using panel data, Khachoo & Khan (2012) look at the main factors that influence FDI influx in developing nations. The results demonstrate that FDI flows are closely correlated with market size, labor costs, overall reserves, and infrastructure. The trade openness variable, however, is not significant.

2. Literature Review

Jadhav & Katti (2012) examined various factors that influence FDI inflows. They look at the institutional and political factors that attract foreign investors to specific nations. The role of infrastructure is prominent in attracting FDI in the host country (Mohammad, vandnahidi et al., 2012).

Panel data was utilized by Imai, Gaiha, Ali, and Kaicker (2014) to examine how FDI affected economic development in 24 countries between 1980 and 2009. The factors taken into account included the GDP, remittances, inflation, civil wars, natural resource availability, investment, financial development, and capital account openness. Remittances are seen to have a greater impact on economic growth than FDI and ODA.

Mohammed and Mahfuzul (2016) conducted a study using annual time series data covering the years 1973 to 2014. They employed the cointegration method to examine the impact of Foreign Direct Investment (FDI) on the economy of Bangladesh. Similarly, Abdouli and Hammami (2017) utilizing panel data and a dynamic model studied to investigate the influence of economic growth, human capital, and the environment on FDI inflows in four African Mediterranean countries.

One of the main sources of a nation's GDP is FDI. The growth of the economy is boosted by foreign direct investment, according to empirical studies (Azam & Feng 2021; Carbonell et al., 2018). Through the use of effective fiscal policies, FDI increases investment in the economy, which may subsequently be used to create jobs and end poverty (Anand 2019). FDI causes major economic swings in developing nations (Anetor 2019).

Various models were propounded regarding FDI determinants by Sahoo (2006), Mottaleb and Kalirajan (2010), and Phung (2016). Economou and Hassapis (2015) used the Arellano-Bover/Blundell-Bond dynamic panel model to examine correlation and endogeneity issues.

$$FDI_{it} = \alpha i + \beta 1 * FDI_{it}\text{-}1 + \beta 2 * GDP_{it} + \beta 3 * x_{it} + \beta 4 * M_{it} + \beta 5 * Infl_{it} + \beta 6 * ULC_{it} + \beta 7 * Z_{it} + \epsilon_{it}$$

in which FDI_{it} represents FDI inflows, GDP_{it} represents GDP per capita, x_{it} for goods and service exports, M_{it} for goods and service imports, for inflation $Infl_{it}$ and ULC_{it} for unit labor cost, Z_{it} as a vector of individual control variables (institutional quality, openness, exchange rate, infrastructure, etc., depending on the specification) and ϵ_{it} denotes the idiosyncratic. The subscripts indicate:

- $i=1,2,\ldots, N$: countries (cross-sectional units)
- $t=1,2,\ldots,T$ (Time periods)

3. Methodology

This research adopts a quantitative explanatory design using secondary sources of data. To explore the relationships among variables, a quantitative explanatory approach based on secondary annual time-series data spanning from 1996 to 2021 is employed. The dataset is obtained from several credible sources, including Nepal's Department of Industry, Nepal Rastra Bank, the World Bank, and the World Development Indicators.

All statistical analyses are conducted using STATA software. Based on the OLI framework and previous empirical literature the model specification was developed. Before estimating the regression model, the stationarity of the time-series data is assessed using the Augmented Dickey-Fuller (ADF) test. Non-stationary variables were transformed into first differences prior to regression estimation.

3.1 Research Conceptual Framework

The theoretical literature review revealed various theories aimed at elucidating the determinants of FDI. The major theories are the Mercantilism theory, Eclectic Paradigm theory, Absolute Advantage theory, and theory based on Imperfect Market Competition. The Eclectic Paradigm theory by Dunning follows the OLI framework as shown in Figure1 below. The major pillars of this OLI framework are ownership, location and internalization.

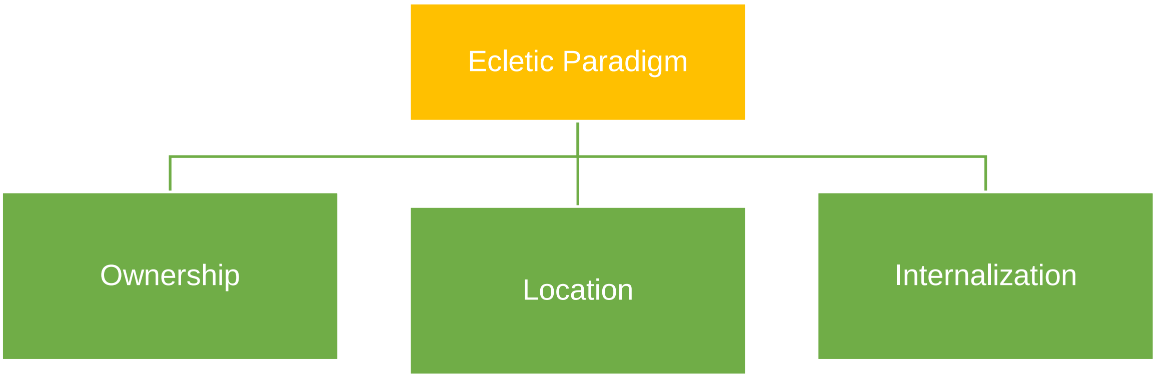

Figure 1: Conceptual breakdown of the Eclectic (OLI) Paradigm (adapted from Dunning, 1979).

This study is theoretically grounded in John Dunning's (1977) Eclectic Paradigm (the OLI framework). The OLI Framework (Eclectic Paradigm) explains why multinational companies or firms invest internationally based on three advantages .This paper utilizes the location advantages of Nepal, assessing how the localized economic variables, financial market indicators and environmental risk indicators such as $C0_2$ emission per capita, attract or deter the foreign capital. For this, time series data of the variables is analyzed with the help of regression equations.

*Table 1: Comparative Study of Various Theoretical Framework **on** Determinants of FDI*

Author(s)	Type of Data	Sample	Variables	Methodology	Main Results
Blomstrom, and Kokko (2000)	Panel data	Europe	GDP growth, cost of labor, openness,	Auto regressive model and integration	Significant and positive relationship between dependent and independent variables
Asiedu (2006)	Time series	Africa	Infrastructure, GDP per capita, consumption, Expenditure.	OLS model	Market size is the positive function of FDI inflows
Coleman, and Tettey (2008)	Time series	Ghana 1970 – 2002	Transportation, communication, cost of energy supply, GDP, trade policy	OLS model	Market size is a significant determinant of FDI
Hussain, and Kimuli (2012)	Time series	57 Developing countries 200 -2009	GDP, per capita, cost of labor, business policy	Instrumental variable approach	Market size is important determinant of FDI
Phung (2016)	Time series	Latin America and African developing countries 1990- 2014	GDP, GDP per capita, trade policy, infrastructure	Three stage least squares methods	Market size is a significant determinant of FDI inflows.

Dunning (1977) identified four types of activities by Multi-National Companies: (a) Market–seeking investment, (b) Natural resource–seeking investment, (c) Strategic assets –seeking investment, and (d) Efficiency–seeking investment (Dhungel,2022).

The Growth Identification and Facilitation Framework (GIFF) framework provides pragmatic strategies for developing nations to pursue their comparative advantage in development through actionable development paths. In determining the FDI determinants, various researchers used different models like linear regression model, and Auto Regressive Distributive Lag (ADRL) model. The literature revealed the various economic, financial, and political and risk analysis, and environmental variables used in analyzing the FDI determinants. Agarwal (1980) used time series data, and variables used are Market size, GDP, GNI, Per capita income. Hussain, and Kimuli (2012) also used time series data and instrumental variable approach in determining FDI determinants.

3.2 Conceptual Framework of the study

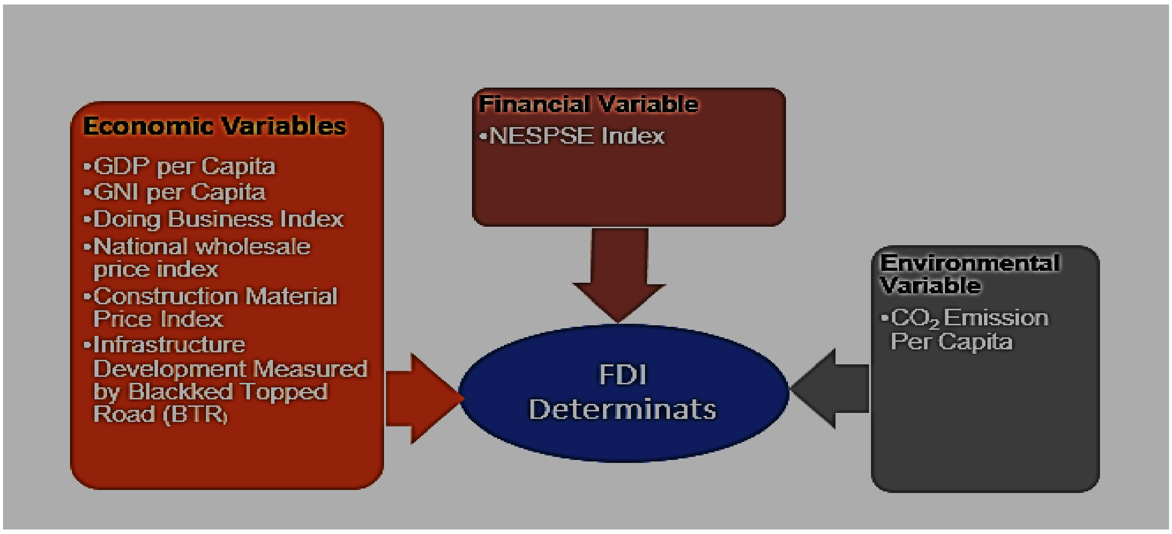

Figure 2: Conceptual Framework

Figure 2, illustrates the conceptual framework developed to examine the factors influencing foreign direct investment (FDI) in Nepal's construction industry. Three sets of variables were identified to examine the key determinants of FDI inflows in construction and infrastructure sector in Nepal. The variables were categorized into the economic variables, financial variables and the environmental variables. Economic variables include GDP per capita, GNI per capita, the Doing Business Index, the national wholesale price index (NWPI), the construction material price index (CMPI), and infrastructure development measured by the length of Black Topped Roads (BTR). These indicators capture the overall economic conditions, market potential, business environment, and infrastructure availability which may affect investors' decisions. Financial market conditions are represented by the NEPSE Index that reflects the level of development and performance of the country's capital market. The environmental variable is represented by CO_2 emissions per capita, which serves as an indicator of environmental and industrial activity. The framework assumes that each of these factors may directly influence the inflow of foreign direct investment into Nepal's construction sector.

3.3 Sources of Secondary Data and Variable Definition

To analyze the determinants of Foreign Direct Investment in Nepal's construction industry, a comprehensive dataset is compiled from authoritative national and international repositories. The variables, along with their operational definitions, are shown in table 2 below. The dependent variable, (FDI_infra) represents the total foreign direct investment commitments in the construction sector, measured in millions of Nepalese Rupees which is sourced from the industrial statistics published by the Department of Industry (DoI). To model the macroeconomic

environment of the host country, GDP per capita, the Construction Material Price Index (CMPI) and the National Wholesale Price Index (NWPI) are utilized as indicators of market capacity and inflationary pressure, extracted from the data source of Nepal Rastra Bank (NRB).
Market stability and size are instrumented through NEPSE index, while physical infrastructure development is assessed using the total length of Black Topped Roads in kilometers, both retrieved from the NRB database. To account for institutional and regulatory quality, the World Bank's Doing Business Index is employed as a proxy measure for the ease of doing business. Finally, environmental risk and sustainability factors are controlled for using carbon dioxide emissions per capita, obtained from the World Bank's World Development Indicators (WDI).

Table 2: Variable Definition

Variables	*Variable definition*	*Data sources*	*Data retrieved from*
GDP_percap	Gross domestic Product per capita of host country measured in current USD	Nepal Rastra Bank (NRB)	https://www.nrb.org.np/category/current-macroeconomic-situation/?department=red&fy=2078-79&subcategory=annual
DBI	DBI is the Doing business index of host country (Nepal) as a proxy measure for business environment,	World bank	https://archive.doingbusiness.org/en/data/exploreeconomies/nepal
CMPI	Construction material price index	NRB	https://www.nrb.org.np/category/current-macroeconomic-situation/?department=red&fy=2078-79&subcategory=annual
NEPSE	NEPSE index as a proxy measure of market stability and size	NRB	https://www.nrb.org.np/category/current-macroeconomic-situation/?department=red&fy=2078-79&subcategory=annual
BTR	Black Topped Road as a proxy measure of infrastructure development of host country measured in Km	NRB	https://www.nrb.org.np/category/current-macroeconomic-situation/?department=red&fy=2078-79&subcategory=annual
CO2_PerCap	proxy for environmental risk measured by C02 emission metric tons per capita,	World Bank, World Development Indicator	https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?locations=NP
NWPI	National wholesale price index	NRB	https://www.nrb.org.np/category/current-macroeconomic-situation/?department=red&fy=2078-79&subcategory=annual
FDI_infra	Total FDI commitment in construction sector (Million NRs.)	Department of Industry (DoI), Industrial statistics	https://www.doind.gov.np/industrial-statistics

3.4 Analysis and Validity of Model

3.4.1 Dickey Fuller Test

Augmented Dickey Fuller Test (ADF) is performed to gauges how stochastic is a time series data of FDI determinants and variables used in this study. The t-statistic produced by the Dickey Fuller test is compared to pre-set or predetermined critical values. Being below that the critical value permits the rejection of the null hypothesis and accepts the alternative hypothesis.
The null hypothesis of the ADF test is that the series contains a unit root and is non-stationary. So, if the p value of the test is less than the significance level (0.05) then the null hypothesis is rejected indicating stationarity.

3.5 Model Specification

The regression model is developed theoretically based on Dunning's Eclectic Paradigm (OLI Framework), particularly the location-specific factors that influence foreign investors' decisions is considered in this paper. Based on the theoretical framework and previous empirical studies, the potential determinants of Foreign Direct Investment (FDI) in Nepal's construction industry are categorized into three groups: economic variables (GDP per capita, Doing Business Index, Construction Material Price Index, Black Topped Road, and National Wholesale Price Index), financial variables (NEPSE Index), and environmental variable (CO_2 emissions per capita).
Before estimating the regression model, the stationarity of the time-series data was tested using the Augmented Dickey-Fuller (ADF) test. The results indicated that most variables were non-stationary at their original levels but became stationary after first differencing. Therefore, the first-differenced values of the variables are used in the regression analysis to avoid spurious results and improve the reliability of the estimates. An alternative specification replacing GDP per capita with GNI per capita is used to test robustness of the model specification. The coefficients of the regression model are computed using STATA 15.The model is developed based on the literature reviewed, primarily the macroeconomic frameworks of FDI determinants established by Sahoo (2006), Mottaleb and Kalirajan (2010), and Phung (2016). Furthermore, the regression model is designed conceptually aligned with model a utilized by Economou and Hassapis (2015).Drawing theoretical foundation from the model developed by Economou and Hassapis (2015) and adapting them to the specific context of the host country's infrastructure construction industry, the relevant vector of control variables is expanded for the model development in this paper.

Model Specification

The regression equation is specified as follows:

$$\Delta FDI\_{infra} = \beta_0 + \beta_1 \Delta GDP\_percap + \beta_2 \Delta DBI + \beta_3 \Delta CO_2\_percap + \beta_4 \Delta CMPI + \beta_5 \Delta BTR + \beta_6 \Delta NWPI + \beta_7 \Delta NEPSE + \varepsilon it$$

The operator Δ represents the first difference of the variables. β_0 is the intercept term, β_1 to β_7 are the coefficients of the explanatory variables, and ε is the error term. The variables are defined in Table 2.

4. Result and Discussion

The ADF test results of the variables are summarized in table 3.1.

Table 3.1: Empirical Results of Augmented Dickey Fuller Test for Model Specification

Variable	ADF Test Statistics Intercept	Mac Kinnon P -value
GDP_percap	1.257	0.9964
DBI	-1.398	0.5834
CO2_PerCap	0.339	0.9791
CMPI	0.118	0.9673
BTR	-1.796	0.9983
NWPI	-5.288	1
NEPSE	0.62	0.9881
ΔGDP_percap	-3.709	0.004
ΔDBI	-4.277	0.005
ΔCO2_PerCap	-4.267	0.005
ΔCMPI	-4.929	0
ΔBTR	-4.078	0.0011
ΔNWPI	-0.432	0.0003
ΔNEPSE	-2.737	0.0479
ΔFDI_infra	-3.87	0.0023
FDI_infra	-6.255	0

The empirical results from different model specifications of regression equation to explore the determinants of FDI commitment in the construction industry in Nepal are illustrated in table 3.2.

Table 3.2: Determinants of FDI in Construction Sector in Nepal

VARIABLES	(1) ΔFDI_infra	(2) ΔFDI_infra
ΔGDP_per cap	4.984*	
	(2.517)	
ΔCMPI	5.039	2.216
	(41.950)	(41.681)
ΔBTR	0.139	0.144
	(0.199)	(0.197)
ΔDBI	-103.227	-106.581
	(68.833)	(68.319)
ΔCO2_PerCap	-7,254.815*	-7,611.034*
	(4,001.313)	(4,001.574)
ΔNWPI	-36.210	-41.371
	(47.288)	(47.374)
ΔNEPSE	0.802**	0.801**
	(0.368)	(0.364)

ΔGNI_percap		5.384*
		(2.574)
Constant	-84.605	-65.607
	(236.104)	(232.781)
Observations	25	25
R-squared	0.395	0.408
Adj. R squared	0.146	0.164

Robust Standard Errors in parentheses
*** p<0.01, ** p<0.05, * p<0.10

The final specification of the regression model developed is as follows.

$$\Delta FDI\_{infra} = -84.605 + 4.984\Delta GDP\_percap - 103.227\Delta DBI - 7254.815\ \Delta CO2\_percap + 5.039\ \Delta CMPI + 0.139\Delta BTR - 36.210\Delta NWPI + 0.802\Delta NEPSE + \varepsilon it$$

Regression model incorporates several independent variables, including GDP per capita, CO_2 emissions per capita, and the Nepal Stock Exchange (NEPSE) index, GNI per capita, BTR as Black Topped Road as a proxy measure of infrastructure facility of host country measured in KM, NWPI as the National wholesale price index, NEPSE as the NEPSE index as a proxy measure of market stability with first differences taken as variables in the regression equation.

3.1 Validity and Robustness of the Model Specification

It is observed that there is consistency of the estimated coefficients of independent variables across different samples or under variations in the dataset. In regression analysis, it's desirable for the signs (positive or negative) of coefficients to remain consistent across different model specifications or when similar variables are added or removed. In model specification, replacing the independent variable GDP per capita with GNI per capita, it is found that there is no significant change in the coefficient and the sign also remains consistent which validates the model specification.

3.2 Determinants of FDI in Construction Industry in Nepal

GDP per Capita

While the coefficient is positive (4.984), indicating a positive relationship between changes in GDP per capita and FDI, it is statistically significant at 10% level. The result of the regression model suggests that there is a positive relationship between changes in GDP per capita and Foreign Direct Investment (FDI) commitment in construction sector. In this model, for every increase in GDP per capita by one USD, the FDI in construction sector in Nepal is increased by 4.984 million Nepali Rupees (NRS).

GDP per capita is a crucial determinant of Foreign Direct Investment (FDI) in Nepal's construction sector. A higher GDP per capita signifies a more prosperous economy, indicating a larger and more affluent consumer base. This, in turn, creates increased demand for residential, commercial, and infrastructure projects, making Nepal an attractive destination for FDI. Additionally, countries with higher GDP per capita often boost better infrastructure, political stability, and regulatory frameworks, reducing investment risks. Investors seek opportunities for growth and profit in stable environments, making Nepal's efforts to raise its GDP per capita pivotal in attracting FDI and fostering growth in the construction sector.

CO_2 Emissions per Capita

The coefficient for CO2 emissions per capita is negative (-7254.815), suggesting that higher CO_2 emissions per capita are associated with lower FDI inflows in construction industry in Nepal. This relationship is statistically significant at the 10% level (p=0.088). In regression model analyzing the relationship between CO_2 per capita emissions and FDI, a negative coefficient for CO_2 per capita suggests an inverse association between environmental pollution and FDI. Furthermore, we can say that FDI commitment in construction industry is highly sensitive to environmental issues. This negative relationship may imply that investors are drawn to countries with cleaner, more sustainable environments, where they perceive lower environmental risk. Alternatively, governments implementing stricter environmental regulations might deter FDI due to compliance costs and the result of this finding is fairly consistent with Cole et al., (2017), and Saqib et al., (2023).

NEPSE Index

The NEPSE index exhibits a positive and statistically significant relationship. This relationship is statistically significant at the 5% level. (p=0.044). The coefficient for NEPSE index is positive (0.802), suggesting an increase in the NEPSE index is associated with higher FDI inflows into construction industry in Nepal. This finding highlights the importance of a strong and thriving stock market in attracting FDI in Construction sector in Nepal. And the result of this finding is fairly consistent with recent literature (Hussain & Kimuli, 2012; Smith et al., 2017; Chen & Wang, 2020; Mapendo et al., 2025).

5. Conclusions

The findings of the regression analysis provide valuable insights into the determinants of FDI in construction industry of Nepal. The time-series data for the dependent and independent variables is analyzed from the period of 1996 to 2021A.D to find the key determinants of FDI in construction industry. Through regression model analysis, using STATA 15 software, the study uncovered key determinants of FDI commitment in construction sector. From the model specification, it is concluded that the GDP per capita, $C0_2$ emission per capita, and the NEPSE index as a measure of market stability and size are the significant determinants of FDI in construction sector in Nepal. Thus, the results from the developed regression model provides an evidence-based framework and serves as an essential predictive tool for policymakers. It proves that the future growth of foreign investment in Nepal's construction industry depends on maintaining capital market stability, enhancing per-capita income and reducing environmental risk.

6. Recommendations

Based on the findings of this research, several recommendations can be made to enhance FDI in the construction industry of Nepal.

- **Promote economic growth:** Nepal should focus on policies and strategies that promote sustainable economic growth and increase GDP per capita. This can be achieved through infrastructure development, diversification of the economy, and investments in education and technology. There is casual linkage between GDP per capita and FDI flow.
- **Environmental sustainability:** Recognizing the negative impact of CO_2 emissions on FDI in the construction industry, Nepal should prioritize sustainable and eco-friendly

construction practices. Implementing environmental regulations and offering incentives can attract responsible foreign investors.

- **Simplify the FDI approval process:** Ease the FDI approval process, profit repatriation procedure and develop the strategic plan for specific investment incentives. Maintain political stability and security to instill confidence in foreign investors to attract more FDI in construction sector in Nepal.
- **Financial market stability:** The positive relationship between the NEPSE index and FDI highlights the importance of a stable financial market. Nepal should make efforts to maintain a secure and growing stock market, which can attract foreign investors and Non-Resident Nepalese (NRN).
- **Price stability:** In a regression equation, the negative relationship between the national wholesale price index (NWPI) which is often an indicator of inflation or price levels in the country, and overall Foreign Direct Investment (FDI) commitment means that as the NWPI increases, the overall FDI tends to decrease, and vice versa. This indicate the monetary and financial policy should align to balance the inflation for more FDI attraction.

7. Limitation

This study subject to several limitations. First, the analysis is fully based on FDI commitment rather than FDI realization. Furthermore, this research does not cover sectoral-level cross-country analysis. Additionally, further investigation into the wider effects of FDI would be valuable, particularly in area of employment creation, skill development including knowledge and technology transfer. These areas could provide a deeper understanding of the long-term benefits and implications of foreign investment in Nepal’s construction industry.

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Tracking Evolution of Land Use and Land Cover in Kathmandu Valley: Insights from 1984 to 2024

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Abstract

In the last four decades the Kathmandu valley has experienced rapid urbanization, population growth, expansion of infrastructure and socio-economic transformation. These developments have drastically altered the land use and land cover (LULC) patterns, resulting in the conversion of agricultural land, forests and barren areas into built-up urban settlements. Such changes impact environmental sustainability, biodiversity conservation, food security, water resources and overall ecosystem health. Therefore, understanding the spatio-temporal dynamics of LULC change is critical for sustainable land management and evidence-based urban planning. Remote sensing and geographic information system (GIS) technologies are useful tools for the monitoring and quantification of these changes over time. The main objective of this study was to assess and analyse land use and land cover change in Kathmandu Valley from 1984 to 2024 using GIS and Remote Sensing techniques. The study was designed to identify major trends in urban expansion, agricultural land conversion, forest cover dynamics and other landscape changes in different time periods. The study was quantitative in nature, based on secondary geospatial data. Multi spatial and temporal data of the years 1984, 2000, 2010, 2019 and 2024 were collected and processed. The GIS and Remote Sensing techniques were used for data processing, clipping, classification, overlay analysis and change detection analysis. Spatial and statistics analysis was conducted to measure the changes in different land cover categories. The interpretation of the findings was to understand long-term landscape transformations and to support informed decision making for sustainable urban development, environmental conservation and land management in the Kathmandu Valley.

Keywords: Land Use and Land Cover (LULC), GIS, Remote Sensing, Kathmandu valley.

1. Introduction

Land use and land cover (LULC) change has become one of the most significant indicators of environmental transformation worldwide, particularly in rapidly urbanizing regions. Changes in land use patterns directly influence ecosystem services, biodiversity, hydrological processes, climate regulation, agricultural productivity, and human well-being Devkota et al. (2023). In developing countries, accelerated urban growth and population expansion have intensified pressure on natural resources, resulting in substantial landscape modifications Shrestha et al. (2022). Kathmandu valley, the political, economic, and cultural center of Nepal, has experienced remarkable urban expansion over recent decades, leading to significant transformations in agricultural land, forests, wetlands, and other natural ecosystems Lama and Kumpakha. (2023). Despite extensive studies on land use and land cover change (LULC) in the Kathmandu valley, critical gaps persist in addressing the interconnected socio-environmental dynamics and their long-term implications. While prior research has mapped urban expansion Bajracharya et al. (2010), agricultural conversion Rimal et al. (2018), and ecological degradation Sarif et al. (2020), these studies often focus on isolated drivers (e.g., urbanization, population growth) without holistically integrating environmental, economic, and social dimensions Maharjan et al. (2020); Lama & Kumpakha. (2024).

Advanced geospatial tools for real-time monitoring and predictive modelling of future LULC trajectories under climate change scenarios remain underexplored Tiwari et al. (2019); Devkota et al. (2024). Quantitative assessments of ecosystem service losses (e.g., water regulation, carbon sequestration) and their socio-economic costs are also limited, hindering evidence-based policy frameworks Sarif et al. (2020). Furthermore community participation in adaptive land management and governance strategies is marginal in existing literature, despite its critical role in addressing informal urban transitions Chapagain et al. (2018). Bridging these gaps requires interdisciplinary approaches that combine high-resolution spatial analysis, participatory governance, and climate resilience frameworks to support sustainable planning. The analysis draws on a plethora of research studies and reports that have investigated LULC in the Kathmandu valley. These findings highlighted the alarming rate of urban expansion, agricultural land conversion, and the depletion of natural vegetation. Furthermore, Maharjan et al. (2020) emphasized the impact of socio-economic drivers on LULC in the Kathmandu valley. This finding underscores the interconnectedness of human activities and environmental transformations in this region.

In addition to this, Gautam et al. (2003) and Tiwari et al. (2019) have contributed valuable information on the spatial patterns and trends of land cover change in this valley. Bajracharya et al. (2010) focused on mapping and analysing urban growth, while Tiwari et al. (2019) investigated into the impacts of land use changes on hydrological processes. Continuing with the exploration of land use and land cover change, it is essential to consider the broader environmental consequences and the potential implications for local communities. The loss of green spaces, such as forests and wetlands, not only jeopardizes biodiversity but also diminishes the valley's capacity to provide essential ecosystem services like water regulation, soil fertility, and climate regulation Sarif et al. (2020)**.** Chapagain et al. (2018) investigates into the socio-economic implications of urban expansion in the valley, highlighting issues related to housing, infrastructure, and the overall quality of life for the valley's residents. In addition to the studies mentioned earlier, the research conducted by Lama & Kumpakha. (2024) on the spatial and temporal analysis of land use changes in the broader context of Nepal provides valuable insights. Their findings underscore the need for adaptive strategies that consider the dynamic nature of LULC and its intricate relationship with socio-economic factors Haack & Rafter. (2006). As we explore into the complexities of LULC in the Kathmandu, it is imperative to recognize the interconnectedness of environmental, social, and economic dimensions. The synthesis of findings from various studies, coupled with a focus on community engagement and sustainable development practices, will contribute to a comprehensive understanding of the challenges and opportunities posed by land use and land cover change in this dynamic region Lama & Kumpakha. (2024).This paper aims to synthesize and build upon these existing studies to present a comprehensive understanding of LULC in the Kathmandu valley. By incorporating recent data and advanced geospatial techniques, we intend to update the knowledge base on this critical issue and contribute to the ongoing discourse on sustainable land management in Nepal. Through this endeavour, we aim to inform policy decisions that promote sustainable development and environmental conservation in the valley and, by extension, contribute to the broader discourse on LULC change in Nepal Devkota et al. (2024).

1.1 Case Study Background

The study area is located in the central part of Nepal at coordinates 85°12'0" to 85°34'0" E longitude and 27°32' 30" N to 27°45' 30" N latitude which is most densely populated region in the country. Nestled within the central hill region, it encompasses three districts: Kathmandu, Bhaktapur, and Lalitpur, covering areas of 395 km², 119 km², and 385 km², respectively Haack & Rafter. (2006). The Kathmandu district includes eleven municipalities, Lalitpur has six municipalities, and Bhaktapur comprises four municipalities. The valley, which resembles a bowl, is encircled by hills ranging in elevation from 1,500m to 2,800m Gurung et al. (2017). Historically known for its cool climate and fertile soil, the valley has been highly productive in agriculture Bournay et al. (2012). The valley floor is intensively cultivated, with terrace farming in the hilly areas, primarily growing crops like rice, wheat, and barley. The Bagmati River watershed drains the valley, and a 27 km ring road connects Kathmandu and Lalitpur, blending industrial zones with residential and commercial districts. This place hosts various industrial businesses, including cement and brick factories. It is the fastest-growing metropolitan region in South East Asia, with an annual growth rate of 4%, as reported by the World Bank. Despite this rapid population increase, essential amenities, such as infrastructure and employment opportunities, are not keeping pace Chitrakar et al. (2014). In 1991, the total population of this valley was approximately 1,185,468 Thapa. (2020). By 2021, the population of the valley had increased to around 3,006,329, with Kathmandu district alone recording a population of 2,017,532 Pokhrel and Baral. (2023)**.** This dramatic growth reflects the valley's transformation into a highly urbanized and economically dynamic region. Migration from rural areas in search of better opportunities, as well as natural population growth, have both contributed to this trend.

The rise in population poses challenges for urban planning, environmental management, infrastructure development, and service delivery, while also providing opportunities for investment and innovation in urban governance. Similarly, the central core of this valley has stabilized in terms of population, the peripheral areas are experiencing unchecked growth.

2. Methodology

The methodology employed for analysing LULC in the Kathmandu valley follows a meticulous, step-by-step process, combining Remote Sensing, GIS tools, and extensive validation techniques as demonstrated in Figure 2.

2.1 Data Collection

Similarly, LULC data for the years 2000, 2010, and 2019 were extracted from the ICIMOD Geo-portal, an open-access platform developed by the International Centre for Integrated Mountain Development (ICIMOD) Joshi et al. (2021). The extracted data were downloaded in Geo-TIFF format and analysed using GIS tools for spatial pattern interpretation and change detection across decades. After downloading clipping vector over raster and spatial adjustment were done to give final dataset of Kathmandu valley. In parallel, the land use and LULC data of 2024 was downloaded from global land cover from ESRI site Turner and Meyer. (1994).

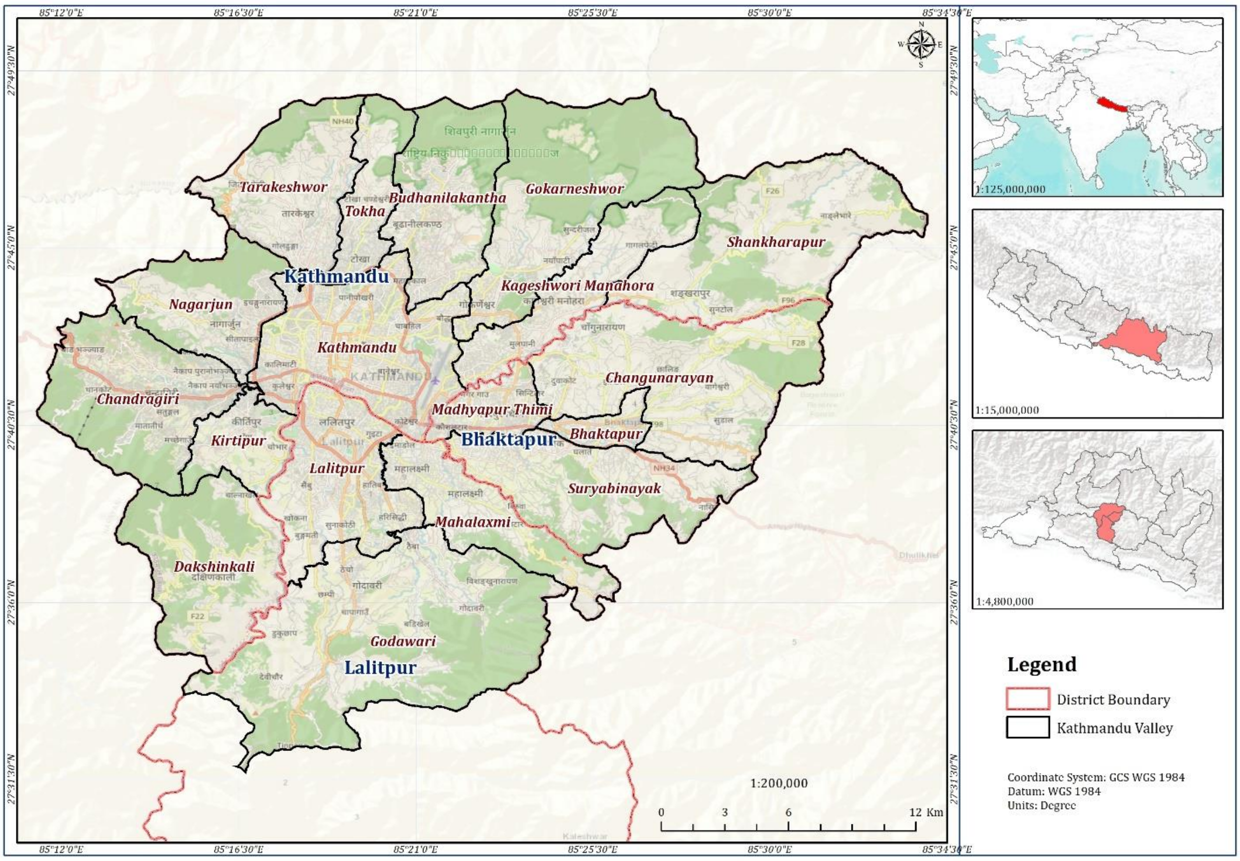


Figure 1: Study Area, Kathmandu valley

2.2 Data Analysis Interpretation

After downloading all the raster data from 1984 to 2024, vector boundary data of Kathmandu valley was used to clip the LULC raster layers, isolating the study area. This was followed by spatial adjustment and projection correction to ensure uniformity across datasets and alignment with the national coordinate system. The final clipped and adjusted LULC datasets were then used for temporal analysis to assess land cover changes over two decades Shanuj et al. (2020). After downloading, vector boundary data of Kathmandu valley was used to clip the LULC raster layers, isolating the study area. This was followed by spatial adjustment and projection correction to ensure uniformity across datasets and alignment with the national coordinate system. The final clipped and adjusted LULC datasets were then used for temporal analysis to assess land cover changes over four decades Shanuj et al. (2020). After clipping the data specific to the valley, geo-processing tools were employed—particularly the intersection algorithm—to extract precise data layers corresponding to the year 1984, 2000, 2010, 2019 and 2024.

Figure 2: Methodology Flowchart

2.3 Land Cover Classification and Change Detection

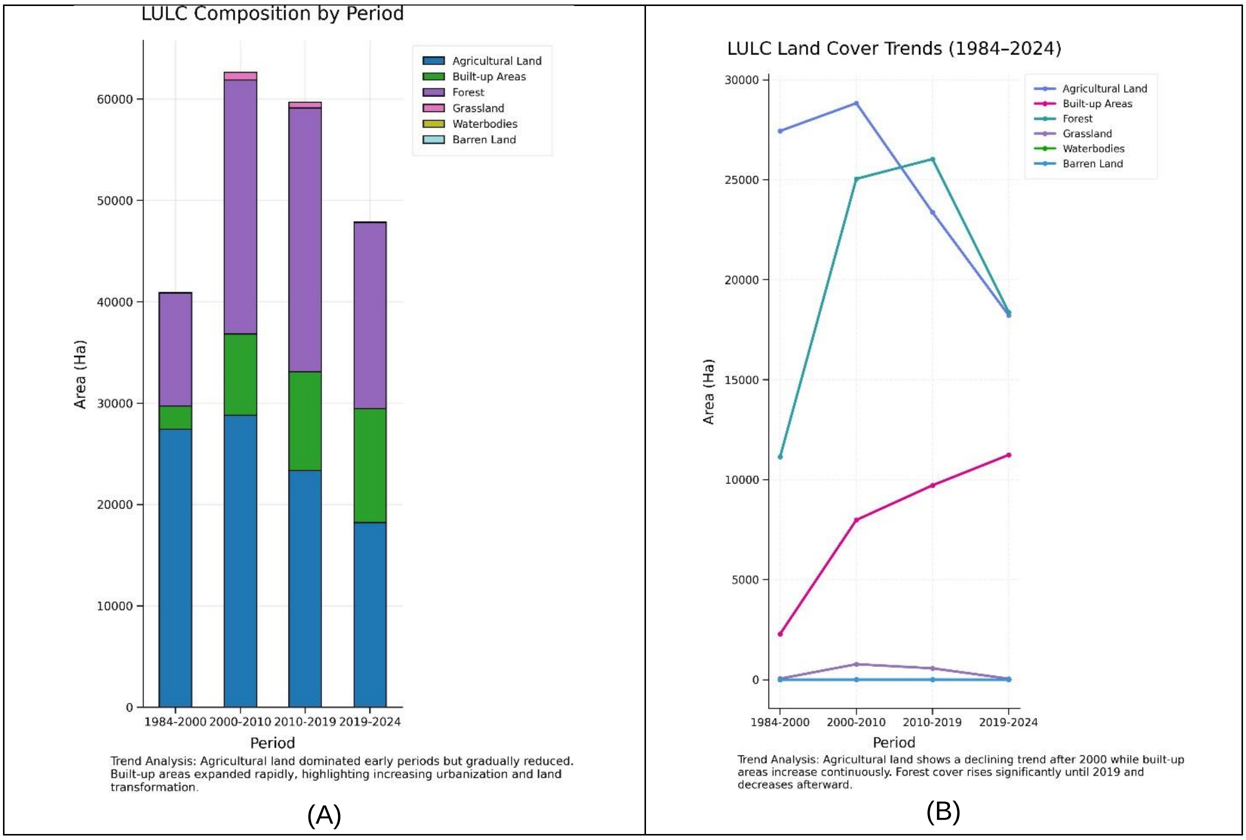
Land use and land cover classes are defined based on established schemes and the unique characteristics of the Kathmandu valley. The classes typically include Agricultural Land, Forest, Barren Land, Built-up Areas, Waterbodies and Grassland Shrestha et al. (2022). Training subsets of imagery with known land cover types are incorporated into the classification process to improve its precision. Once the classification process is complete, post-classification change detection is conducted. This pivotal step quantifies the changes in land use and land cover between the selected years. This process is carried out by converting the KML file and check it out in google earth application. From this step calculating the land use and land cover detection is carried out. This process involves converting the KML file into a compatible format and then visualizing it in the Google Earth application for verification and spatial inspection. Following this step, land use and land cover (LULC) analysis is conducted, where different surface features are identified, classified, and quantified to support further spatial assessment and decision-making. The changes are categorized into conversion, persistence, and emergence of land cover classes, providing valuable insights into the dynamic transformations of the landscape over time Lamichhane et al. (2021).

3. Result

The Kathmandu valley has undergone significant land use and land cover (LULC) changes over the past four decades. These transformations reflect the rapid pace of urbanization, population growth, infrastructural development, and changing land management practices. Among the most notable trends observed during the periods 1984–2000, 2000–2010, 2010–2019, and 2019–2024 is the persistent decline of agricultural land and the expansive growth of built-up areas Thapa and Murayama. (2008); Ishtiaque et al. (2017); Maharjan et al. (2020). Agricultural land has traditionally dominated the Kathmandu valley landscape. In the earliest period (1984–2000), a significant area of 27,436.2 hectares remained classified as agricultural. While there was a slight increase to 28,827.2 hectares during the 2000–2010 period, the trend reversed dramatically thereafter. By 2010–2019, agricultural land had decreased to 23,369.7 hectares, and by 2019–

2024, it further declined to 18,221.6 hectares Maharjan et al. (2017). This downward trend signifies that a large portion of fertile agricultural land has been transformed into built-up areas and, to a lesser extent, into forests and barren land. The reasons behind this transformation are rooted in urban expansion, rising land prices, and infrastructural development driven by population pressure and economic activities Thapa and Murayama. (2010); Paudel et al. (2016). Simultaneously, the built-up area has shown a remarkable and consistent increase, signalling rapid urbanization. The transition from agricultural land to built-up areas grew modestly during the earlier periods (287.2 ha in 1984–2000 and 298.9 ha in 2000–2010), but surged significantly between 2019 and 2024 with a leap to 2,456.2 hectares.

Additionally, the built-up areas that remained in the same category increased from 2,284.5 ha in 1984–2000 to a notable 11,239.4 ha in 2019–2024. This increase not only highlights the expansion of settlements but also indicates densification of already urbanized zones. The increase in built-up area reflects the high demand for housing, commercial establishments, roads, and public infrastructure, a trend that is both a result and a driver of economic transformation in the valley Ishtiaque et al. (2017).



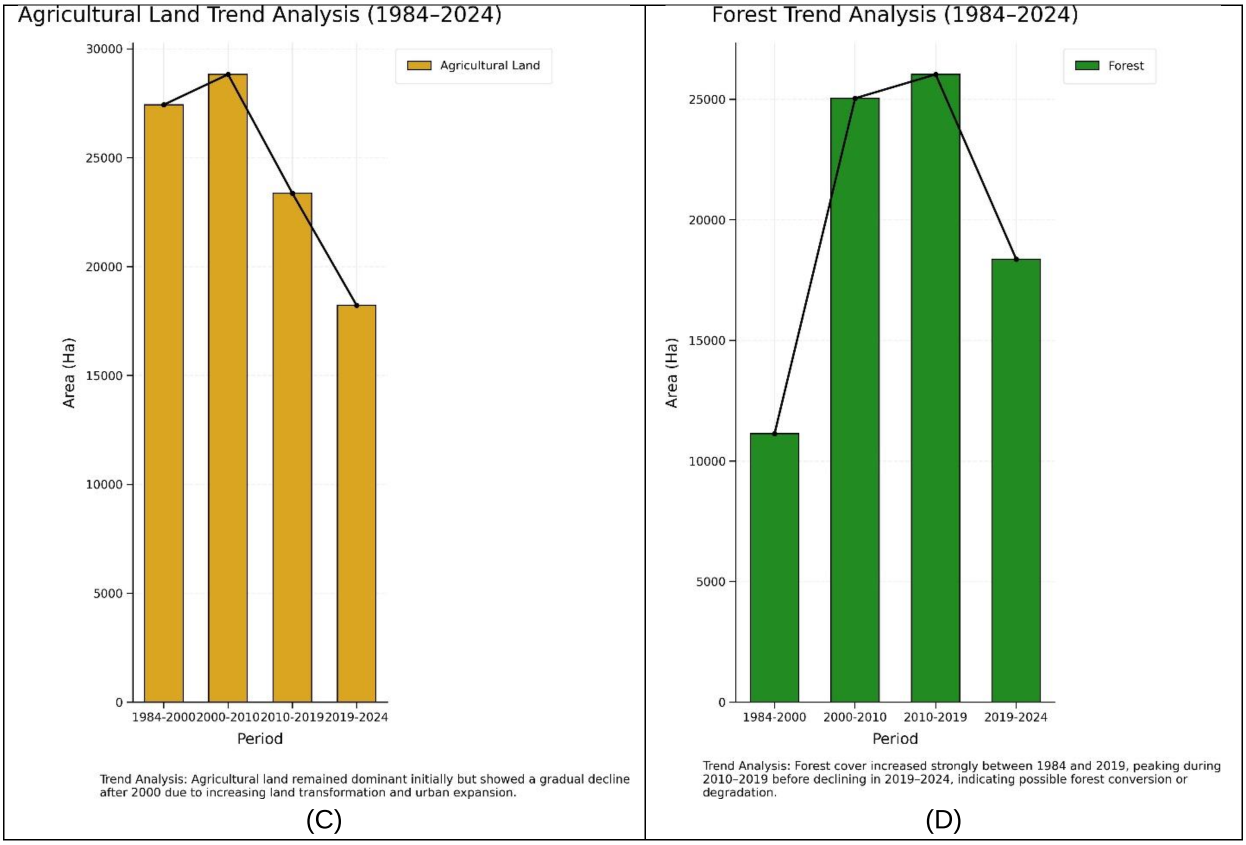


Figure 3: (A) LULC composition by Period, (B) Overall LULC Land Cover Trend (1984 – 2024), (C) Agricultural Land Trend Analysis (1984 – 2024), (D) Forest Trend Analysis (1984 – 2024)

Forest areas in the Kathmandu valley have demonstrated both degradation and recovery trends over the study period. The early years (1984–2000) saw considerable conversion of forest land to agriculture (10,520.9 ha), a trend that can be linked to the expansion of farming and encroachments. However, forest cover improved significantly in later years, with 26,032.5 ha remaining forested between 2010 and 2019. Interestingly, 2,794.2 ha of agricultural land transitioned into forest during the 2019–2024 period, indicating a positive shift toward reforestation or natural succession Paudel et al. (2016). Despite this, the conversion of 916.8 ha of forest to built-up area in the most recent period underscores continued pressure on forest resources due to urban development. Grassland, though a smaller land use category, has also experienced significant changes. During 1984–2000, 4,270.8 ha of grassland converted to forest, possibly due to conservation or succession. Over time, the area of grassland steadily decreased, with only 49.9 ha remaining grassland between 2019 and 2024. This reduction reflects the growing scarcity of open spaces as they are converted to agricultural or built-up areas.

The most significant conversion occurred between 1984 and 2000, when 331.4 ha of agricultural land turned into barren land, possibly due to land degradation or extraction activities. However, the barren land category showed signs of stabilization in the later years, with some areas converting back to agriculture or being built upon. This trend indicates either rehabilitation efforts or land revaluation for urban use. Nonetheless, the relatively low share of barren land overall points to the active utilization of most available land in the valley Maharjan et al. (2020).

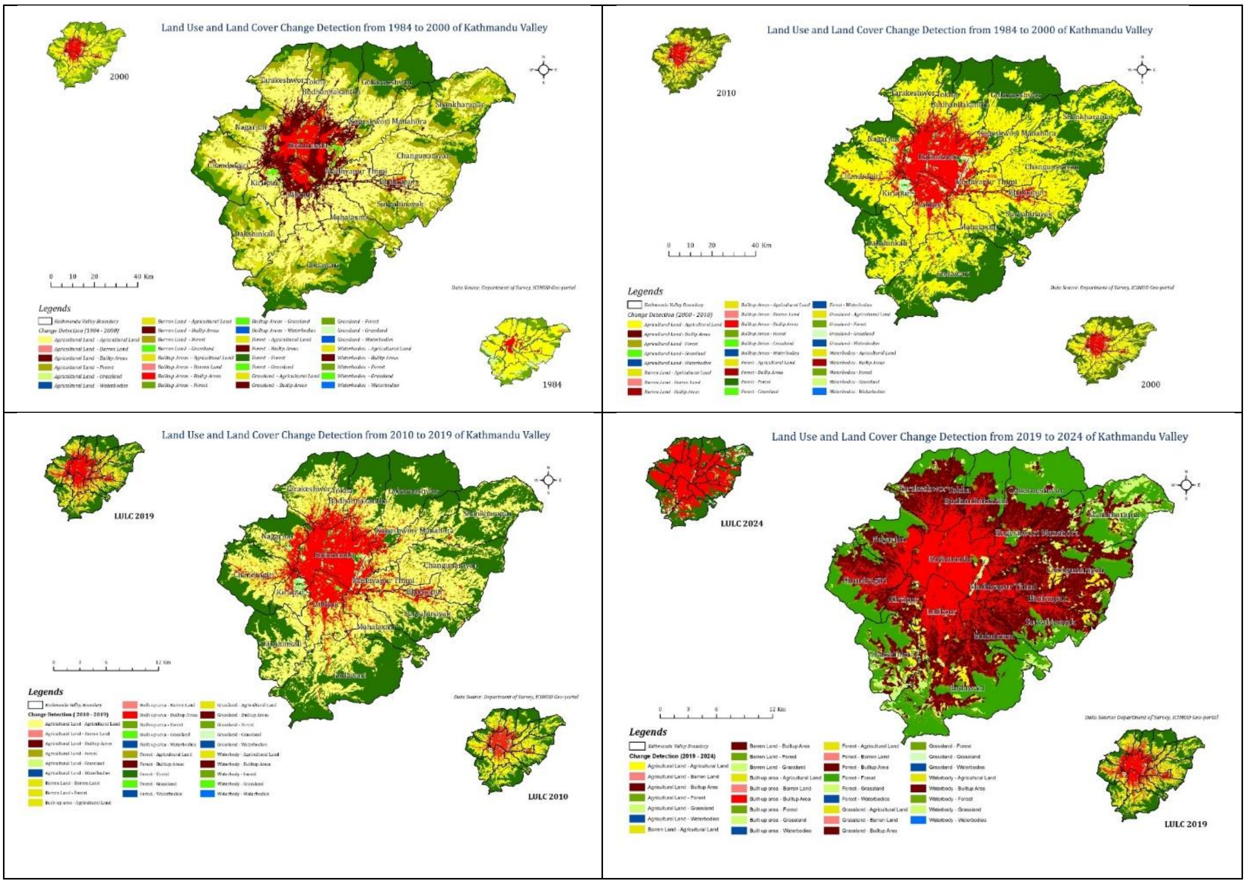


Figure 4: Land Use and Land Cover Change Detection from 1984 to 2000, 2000 to 2010, 2010 to 2019 and 2019 to 2024

Waterbodies, although the smallest category, also exhibited important transitions. From 1984 to 2024, small yet consistent conversions from and to waterbodies took place, particularly with agricultural, forest, and grassland areas. One concerning trend is the conversion of waterbodies to built-up areas, such as the 6.7 ha converted between 2019 and 2024. This development suggests encroachment and filling of ponds, riversides, or wetlands for construction purposes, a trend that can have negative implications for ecological balance and water resource management. The most recent period (2019–2024) revealed several striking land use changes. Notably, there was a significant conversion of 2,794.2 ha of agricultural land into forest, which may reflect either genuine reforestation programs or abandonment of farmland. Another unusual trend was the conversion of 5,527.4 ha of built-up area back into forest. This could be the result of reclassification, rewilding efforts, or inaccuracies in categorization. However, if accurate, it represents a rare and positive example of urban greening. On the other hand, 916.8 ha of forest land was lost to urban development in this same period, indicating that conservation gains remain vulnerable to urban pressure Acharya et al. (2023).

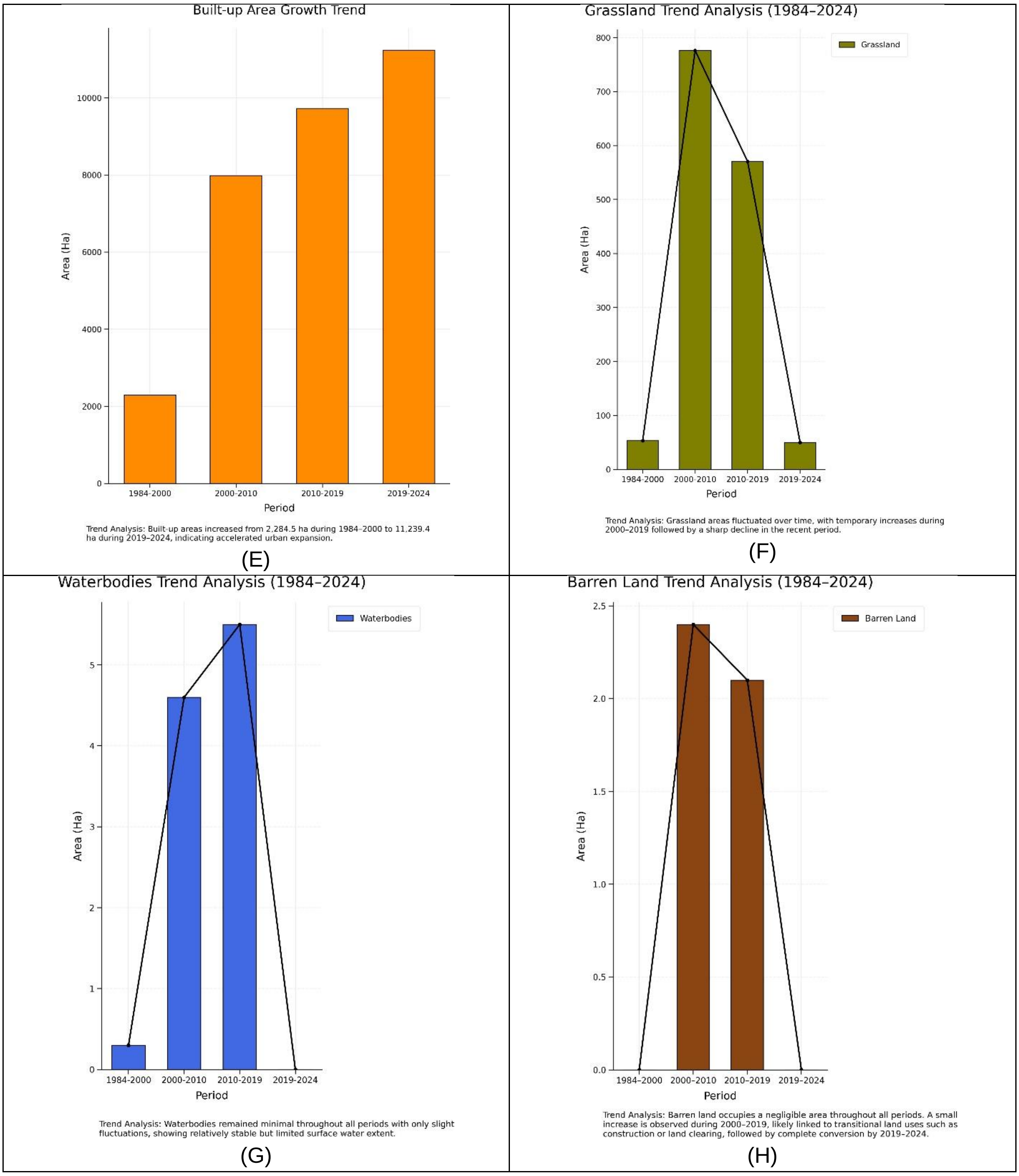


Figure 3: (E) Builtup Area Growth Trend, (F) Grassland Trend (1984 – 2024), (G) Waterbodies Trend Analysis (1984 – 2024), (H) Barren Land Trend Analysis (1984 – 2024)

At end, the Kathmandu valley has undergone a profound transformation in its land use and land cover over the last four decades. Urban expansion has been the dominant force reshaping the landscape, often at the cost of agricultural and forest lands. The continuous decline in agricultural areas poses risks to local food security, while forest fluctuations reveal both the potential for restoration and the threat of urban encroachment. Grasslands and waterbodies are shrinking, further emphasizing the need for integrated land management strategies. These trends highlight the urgency for sustainable urban planning, enforcement of environmental regulations, and conservation efforts to preserve the ecological integrity and liability of the Kathmandu valley in the years to come Tiwari et al. (1999).

Table 2: Land Use and Land Cover Change Detection from 1984 to 2024 ([https://rds.icimod.org/& ESRI Global Landcover 2024)]

LULC Change 1984 - 2000	**Area (Ha)**	**LULC Change 2000- 2010**	**Area (Ha)**		**LULC Change 2010 - 2019**	**Area (Ha)**	**LULC Change 2019 to 2024**	**Area (Ha)**
Agricultural Land-Agricultural Land	27436.2	Agricultural Land - Agricultural Land	28827.2		Agricultural Land - Agricultural Land	23369.7	Agricultural Land - Agricultural Land	18221.6
Agricultural Land-Barren Land	331.4	Agricultural Land – Built-up Areas	298.9		Agricultural Land - Built-up Areas	82.4	Agricultural Land - Barren Land	1.9
Agricultural Land-Forest	3193.8	Agricultural Land - Forest	1045.4		Agricultural Land - Forest	2324.8	Agricultural Land - Built-up area	2456.2
Agricultural Land-Waterbodies	458.6	Agricultural Land - Grassland	48.4		Agricultural Land - Grassland	26.3	Agricultural Land - Forest	2794.2
Agricultural Land-Grassland	2163.1	Agricultural Land - Waterbodies	1		Agricultural Land - Barren Land	0	Agricultural Land - Grassland	85.8
Agricultural Land-Built-up Areas	287.2	Built-up Areas - Agricultural Land	1722.3		Agricultural Land - Waterbodies	0.4	Agricultural Land - Waterbody	6.3
Built-up Areas-Agricultural Land	5712	Built-up Areas – Built-up Areas	7984.3		Built-up area - Agricultural Land	5380	Barren Land - Agricultural Land	76.5
Built-up Areas-Barren Land	20.4	Built-up Areas - Forest	40.9		Built-up area - Built-up Areas	9718.6	Barren Land - Built-up area	26.4
Built-up Areas-Forest	119.2	Built-up Areas - Grassland	66.4		Built-up area - Forest	129.9	Barren Land - Forest	48.1
Built-up Areas-Waterbodies	238.1	Built-up Areas - Barren Land	0.6		Built-up area - Grassland	282.9	Barren Land - Grassland	3.8
Built-up Areas-Grassland	10.8	Built-up Areas - Waterbodies	2.6		Built-up area - Barren Land	1.6	Barren Land - Waterbody	0.01
Built-up Areas-Built-up Areas	2284.5	Forest - Agricultural Land	3327		Built-up area - Waterbodies	0.7	Builtup Areas - Agricultural Land	4.6
Forest-Agricultural Land	10520.9	Forest – Built-up Areas	7.2		Forest - Agricultural Land	1441	Builtup Areas - Barren Land	5
Forest-Barren Land	129.8	Forest - Forest	25042.2		Forest - Built-up Areas	2.7	Builtup Areas - Built-up area	11239.4
Forest-Forest	11140.4	Forest - Grassland	185.1		Forest - Forest	26032.5	Builtup Areas - Forest	5527.4
Forest-Waterbodies	23.7	Forest - Waterbodies	0.4		Forest - Grassland	46.3	Builtup Areas - Grassland	442.9

Forest-Grassland	4270.8	Grassland - Agricultural Land	25.5		Forest - Waterbodies	0	Builtup Areas - Waterbody	6.7
Forest-Built-up Areas	29	Grassland – Built-up Areas	100.7		Grassland - Agricultural Land	21.8	Forest - Agricultural Land	5509
Grassland-Agricultural Land	591.9	Grassland - Forest	24.3		Grassland - Built-up Areas	11.3	Forest - Barren Land	0.5
Grassland-Barren Land	13.2	Grassland - Grassland	776.1		Grassland - Forest	74	Forest - Built-up area	916.8
Grassland-Forest	83	Grassland - Waterbodies	1.1		Grassland - Grassland	570.5	Forest - Forest	18377.6
Grassland-Waterbodies	23	Barren Land - Agricultural Land	0		Grassland - Waterbodies	0.6	Forest - Grassland	95.7
Grassland-Grassland	53.2	Barren Land – Built-up Areas	1.3		Barren Land - Forest	0.9	Forest - Waterbody	1.4
Grassland-Built-up Areas	311.3	Barren Land - Barren Land	2.4		Barren Land - Barren Land	2.1	Grassland - Agricultural Land	1988.7
Barren Land-Agricultural Land	2.8	Waterbodies - Agricultural Land	0.3		Waterbody - Agricultural Land	2.7	Grassland - Built-up area	874.9
Barren Land-Built-up Areas	0.3	Waterbodies – Built-up Areas	0		Waterbody - Built-up Areas	1.9	Grassland - Forest	755
Waterbodies-Agricultural Land	7.2	Waterbodies - Forest	1.4		Waterbody - Forest	4	Grassland - Grassland	49.9
Waterbodies-Waterbodies	0.3	Waterbodies - Grassland	0.8		Waterbody - Grassland	1.7	Grassland - Waterbody	1.3
Waterbodies-Grassland	1.1	Waterbodies - Waterbodies	4.6		Waterbody - Waterbodies	5.5		
Waterbodies-Built-up Areas	1.1							

4. Discussion

The LULC changes in the Kathmandu valley over three periods—1984 to 2000, 2000 to 2010 and 2010 to 2019—show a vibrant picture of how human activities and the natural environment interact. The first period, from 1984 to 2000 saw changes in land cover types mainly due to urbanization, farming practices and somehow conservation efforts. Agricultural land changed into categories like barren land, built-up areas, forest, grassland and waterbodies. These changes showed an equilibrium between keeping farming practices and obliging growth as well as preserving natural ecosystems. The second period, from 2000 to 2010 showed a trend of urbanization with more built-up areas. Agricultural land changed, contributing to urban spaces, forest cover and changes in other land cover types. The conservation of forested areas became important to keep the valleys balance amid development pressures. This shows the relationship between land cover types during this period showed how human activities and natural integrity are connected. Similarly, the analysis of the period from 2010 to 2019 showed more urbanization, forest conservation efforts and changes in other land cover categories. Built-up areas expanded significantly showing urban development due to demographic and economic factors. Likewise, farming practices continued alongside changes to land cover types highlighting the complex nature of land use changes in the Kathmandu valley. The recent data from 2019 to 2024 shows ongoing growth in urban areas and positive forest conservation trends as well as adaptable use of barren land. The study findings also stress the need for sustainable land management strategies in the Kathmandu valley. Given the expansion of built-up areas at the expense of agricultural land policymakers should focus on comprehensive land use zoning regulations to control unplanned urban sprawl and protect productive agricultural areas. Strengthening infrastructure like urban forests, parks and ecological corridors can help reduce the environmental impacts of rapid urbanization while enhancing ecosystem services and climate resilience. Promoting modernization and sustainable farming practices can enhance productivity on existing agricultural lands and reduce pressure for land conversion.

The integration of geospatial technologies into land monitoring systems can support decision-making and enable timely interventions. Collaboration among governments urban planners, environmental agencies and community stakeholders will be essential to achieve a balanced approach that harmonizes economic development, urban growth and environmental conservation. This study has limitations as it relies primarily on time series data with varying spatial and temporal resolutions. Future studies can build upon this research by utilizing higher-resolution satellite imagery and advanced machine learning algorithms. Integrating variables population growth trends and policy interventions can better understand the driving forces behind land use change. Scenario-based modelling approaches can predict land use trajectories and assess the impacts of alternative planning strategies. Investigations into the implications of land use changes on ecosystem services, urban heat islands and climate resilience would provide a comprehensive understanding of the environmental and societal consequences of landscape transformation in the Kathmandu valley. Continuous monitoring using near-time geospatial data and periodic assessments will be critical, for supporting sustainable urban planning and adaptive land management in the future.

Despite these perceptions, the study has certain limitations that must be acknowledged. The analysis is primarily based on multi-temporal secondary data with low spatial and temporal resolutions, which may inconsistencies in classification and change detection results. Moreover, the study focuses mainly on spatial land cover changes without incorporating detailed socioeconomic, demographic, policy, or institutional factors that strongly influence land use dynamics. Limited availability of reliable ground-truth data for historical periods further constrains validation of earlier land cover conditions. In near future, such research can be performed by using higher-resolution satellite imagery such as RapidEye, GeoEye, or UAV-based data to improve classification accuracy and spatial detail. Likewise, advanced machine learning and deep learning techniques like Random Forest, Support Vector Machine, and Convolutional Neural Networks (CNN) can further enhance classification performance. Future studies should also integrate socioeconomic drivers, population growth, infrastructure development, and policy frameworks to better understand the underlying causes of land use change. In addition, scenario-based modeling approaches such as CA-Markov, ANN, and Land Change Modeler can be used to predict future land use trajectories and evaluate alternative planning strategies. Further research on the impacts of land use change on ecosystem services, urban heat islands, climate resilience, disaster risk, water resources, and food security will provide a more holistic understanding of environmental and societal implications. Continuous monitoring through near-real-time geospatial data and periodic assessments will be essential for supporting adaptive and sustainable urban planning in the Kathmandu Valley.

5. Conclusions

The findings of this research emphasize the urgent need for integrated, holistic and sustainable land management strategies in Kathmandu valley, particularly as built-up expansion continues at the cost of agricultural land. Policymakers as well as local bodies should prioritize strict land use zoning regulations and enforce planned urban development to control unplanned sprawl and protect productive agricultural zones. In addition, promoting sustainable agricultural practices and modernization is essential to improve productivity and reduce pressure on land conversion, while the integration of geospatial technologies like GIS and remote sensing into regular planning systems can support evidence-based decision-making and timely intervention. Effective collaboration among government bodies, urban planners, environmental agencies, and local communities is also critical to achieving a balanced approach between development and conservation.

In spite of this awareness of the need for balanced environmental and social development, Kathmandu valley continues to face severe land use challenges due to multiple interconnected factors. One major issue is unplanned and weakly enforced urban governance, where land use zoning regulations exist but are often inconsistently implemented due to institutional fragmentation and limited coordination among agencies. Rapid rural-to-urban migration and population concentration in the valley have intensified housing demand, leading to informal settlements and uncontrolled urban sprawl. Economic pressure and land speculation have further encouraged the conversion of fertile agricultural land into residential and commercial plots, often prioritizing short-term financial gains over long-term sustainability. In addition, insufficient integration of scientific planning tools into decision-making, limited use of updated geospatial data in policy enforcement, and insufficient monitoring capacity have contributed to ineffective land management. Political instability and frequent policy discontinuity have also weakened long-term urban planning implementation. Strengthening green infrastructure through the expansion of urban forests, green belts, ecological corridors, and protected river systems is critical for maintaining ecological balance and climate resilience. The adoption of smart city planning tools, including GIS-based monitoring systems, real-time land use tracking, and satellite-based change detection, should be institutionalized within local and national planning agencies for evidence-based decision-making.

Equally important is the integration of participatory planning approaches, ensuring that local communities are actively involved in land use decisions, which improves accountability and reduces conflicts. Agricultural land protection policies should be strengthened through incentives for farmers, restrictions on farmland conversion, and promotion of high-value and climate-resilient agriculture to maintain food security. Institutional coordination among municipal governments, federal agencies, and environmental authorities must be improved through a unified land management framework to avoid overlapping responsibilities and policy gaps.

Future planning should also prioritize data-driven scenario modeling to anticipate urban growth patterns and evaluate alternative development pathways. This includes integrating socioeconomic forecasting, population dynamics, and infrastructure demand into spatial planning models. Continuous capacity building of urban planners, engineers, and decision-makers in modern geospatial technologies and sustainable planning principles is also essential.

Overall, the Kathmandu Valley's land use challenges are not solely the result of technical limitations in urban planning, but also arise from governance weaknesses, economic pressures, institutional fragmentation, and enforcement gaps. Addressing these issues requires not only better planning tools but also stronger political commitment, coordinated governance, and a shift toward long-term sustainability-oriented development thinking.

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Poster Presentations and Summary

An Agentic AI Framework for Enhancing Data Trustworthiness in Blockchain Systems Addressing "Garbage In, Garbage Out" Problem in Blockchain Systems

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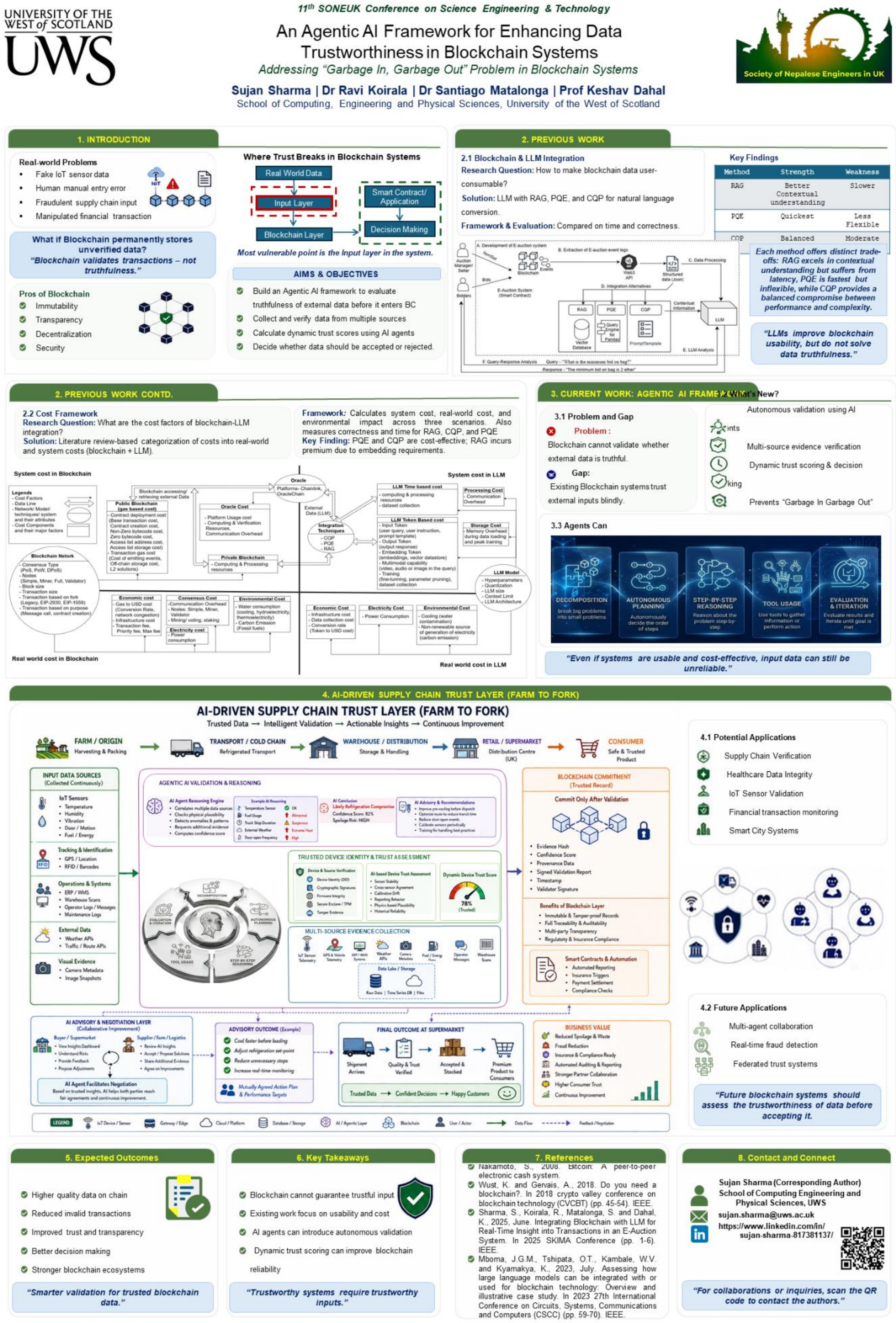
Abstract

Blockchain technology offers immutability, transparency, decentralisation, and security, making it a robust platform for secure data management. However, in real-world applications, the quality of data entering the blockchain remains a critical challenge, as the blockchain itself cannot verify the truthfulness of external data before it is permanently recorded. This limitation creates the "Garbage In, Garbage Out" (GIGO) problem, where inaccurate or manipulated data can undermine the reliability of blockchain applications. Although recent research has integrated Large Language Models (LLMs) with blockchain to improve usability and cost efficiency, little attention has been given to validating the trustworthiness of input data. This research addresses this gap by proposing an Agentic AI conceptual framework for a strawberry supply chain that evaluates external data before it is stored onto the blockchain.

The proposed framework employs autonomous AI agents to collect evidence from multiple trusted sources, perform contextual reasoning, calculate dynamic trust scores, and record both the validated data and its associated trust score on the blockchain. This enables stakeholders to negotiate based on trusted information and quickly identify the source of errors or inconsistencies when disputes arise. By introducing an intelligent validation layer before blockchain storage, the framework aims to improve data integrity, reduce invalid transactions, and strengthen trust in blockchain-based systems. Although demonstrated using a strawberry supply chain, the framework is applicable to other supply chains, healthcare, IoT sensor networks, financial transactions, and smart city applications, where trustworthy data is essential for reliable decision-making.

Key Worlds:
Data trustworthiness, Blockchain, Large Language Models, Agentic AI, supply-chain.



11th SONEUK Conference on Science Engineering & Technology

An Agentic AI Framework for Enhancing Data Trustworthiness in Blockchain Systems

Addressing "Garbage In, Garbage Out" Problem in Blockchain Systems

Sujan Sharma | Dr Ravi Koirala | Dr Santiago Matalonga | Prof Keshav Dahal
School of Computing, Engineering and Physical Sciences, University of the West of Scotland

1. INTRODUCTION

Real-world Problems
- Fake IoT sensor data
- Human manual entry error
- Fraudulent supply chain input
- Manipulated financial transaction

What if Blockchain permanently stores unverified data?
"Blockchain validates transactions – not truthfulness."

Pros of Blockchain
- Immutability
- Transparency
- Decentralization
- Security

Where Trust Breaks in Blockchain Systems

Real World Data → Input Layer → Blockchain Layer → Smart Contract/ Application → Decision Making

Most vulnerable point is the Input layer in the system.

AIMS & OBJECTIVES
- Build an Agentic AI framework to evaluate truthfulness of external data before it enters BC
- Collect and verify data from multiple sources
- Calculate dynamic trust scores using AI agents
- Decide whether data should be accepted or rejected.

2. PREVIOUS WORK

2.1 Blockchain & LLM Integration
Research Question: How to make blockchain data user-consumable?
Solution: LLM with RAG, PQE, and CQP for natural language conversion.
Framework & Evaluation: Compared on time and correctness.

Key Findings

Method	Strength	Weakness
RAG	Better Contextual understanding	Slower
PQE	Quickest	Less Flexible
CQP	Balanced	Moderate

Each method offers distinct trade-offs: RAG excels in contextual understanding but suffers from latency, PQE is fastest but inflexible, while CQP provides a balanced compromise between performance and complexity.

"LLMs improve blockchain usability, but do not solve data truthfulness."

2. PREVIOUS WORK CONTD.

2.2 Cost Framework
Research Question: What are the cost factors of blockchain-LLM integration?
Solution: Literature review-based categorization of costs into real-world and system costs (blockchain + LLM).

Framework: Calculates system cost, real-world cost, and environmental impact across three scenarios. Also measures correctness and time for RAG, CQP, and PQE
Key Finding: PQE and CQP are cost-effective; RAG incurs premium due to embedding requirements.

3. CURRENT WORK: AGENTIC AI FRAMEWORK

3.1 Problem and Gap

Problem: Blockchain cannot validate whether external data is truthful.

Gap: Existing Blockchain systems trust external inputs blindly.

3.2 What's New?
- Autonomous validation using AI agents
- Multi-source evidence verification
- Dynamic trust scoring & decision making
- Prevents "Garbage In Garbage Out"

3.3 Agents Can
- DECOMPOSITION – break big problems into small problems
- AUTONOMOUS PLANNING – Autonomously decide the order of steps
- STEP-BY-STEP REASONING – Reason about the problem step-by-step
- TOOL USAGE – Use tools to gather information or perform action
- EVALUATION & ITERATION – Evaluate results and iterate until goal is met

"Even if systems are usable and cost-effective, input data can still be unreliable."

4. AI-DRIVEN SUPPLY CHAIN TRUST LAYER (FARM TO FORK)

AI-DRIVEN SUPPLY CHAIN TRUST LAYER (FARM TO FORK)
Trusted Data → Intelligent Validation → Actionable Insights → Continuous Improvement

FARM / ORIGIN (Harvesting & Packing) → TRANSPORT / COLD CHAIN (Refrigerated Transport) → WAREHOUSE / DISTRIBUTION (Storage & Handling) → RETAIL / SUPERMARKET (Distribution Centre (UK)) → CONSUMER (Safe & Trusted Product)

4.1 Potential Applications
- Supply Chain Verification
- Healthcare Data Integrity
- IoT Sensor Validation
- Financial transaction monitoring
- Smart City Systems

4.2 Future Applications
- Multi-agent collaboration
- Real-time fraud detection
- Federated trust systems

"Future blockchain systems should assess the trustworthiness of data before accepting it."

5. Expected Outcomes
- Higher quality data on chain
- Reduced invalid transactions
- Improved trust and transparency
- Better decision making
- Stronger blockchain ecosystems

"Smarter validation for trusted blockchain data."

6. Key Takeaways
- Blockchain cannot guarantee trustful input
- Existing work focus on usability and cost
- AI agents can introduce autonomous validation
- Dynamic trust scoring can improve blockchain reliability

"Trustworthy systems require trustworthy inputs."

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"For collaborations or inquiries, scan the QR code to contact the authors."

Experimental Investigation of the Influence of Fibre Volume Fraction on the Mechanical Behaviour of Concrete and Validation of Finite Element Models.

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Abstract

This research studies the effect of fibre volume fraction (Vf) on compressive strength, flexural strength, residual strength, flexural toughness, and ductility of steel fibre reinforced concrete (SFRC). Low fibre volume fractions of 0.2% and 0.4% were studied using normal strength concrete. 5D hooked-end steel fibres with aspect ratio 65 and tensile strength 2300 MPa were used. The tensile stress-strain properties of fibre reinforced concrete (FRC) were determined by means of a direct tensile test with the use of steel plates bonded to dog-bone specimens. Direct tensile and flexural beam tests were performed on a Zwick Roell Z250 universal testing equipment. Compressive strength and third point bending tests were conducted according to BS EN 12390-3 and BS EN 12390-5, respectively.

The modulus of elasticity and tensile strength of concrete were determined according to provisions of Eurocode 2 and compared with the experimentally obtained values. The experimental results were somewhat lower because of the constraints of direct tensile testing and measurement of strain. The Eurocode 2 predictions offered more credible estimates of the mechanical characteristics of concrete and so these values were used for the subsequent numerical analysis. A finite element model was developed in LUSAS using experimental and derived data. As the softening curve in LUSAS is mesh dependent, a mesh-objective analysis was carried out by considering the strain localisation to get a constant energy dissipation during the fracture process regardless of the mesh size. The results showed that the addition of fibres greatly enhanced the compressive strength, flexural strength, residual strength, toughness and ductility. The mean compressive strength of the 0.4% SFRC specimen increased by 11.83% compared to the control mixture, whereas mean flexural strength rose dramatically by 20.87% over the control mixture. The mean flexural toughness of 0.4% SFRC specimen at L/150 was 2.42 times higher than that of 0.2% SFRC specimen. Moreover, the mean ductility index of 0.4% SFRC mixture increased by 7.64 times and 1.70 times than 0% and 0.2% SFRC specimens respectively Furthermore, the finite element model exhibited a good agreement with the experimental results with regression value of 0.8741, which confirms the trustworthiness of the constructed numerical model to forecast the behaviour of SFRC with low fibre volume percentages.

Keywords
Steel fibre, Fibre volume fraction, Compressive Strength, Flexural Strength flexural toughness, Ductility.

UNIVERSITY OF PORTSMOUTH

Experimental Investigation of the Influence of Fibre Volume Fraction on the Mechanical Behaviour of Concrete and Validation of Finite Element Model.

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Shyam Sundar Subedi, MSc Civil Engineering

INTRODUCTION

Concrete is widely used in construction but is brittle and weak in tension. Steel fibres can enhance tensile strength, flexural performance, ductility, toughness, and crack resistance. While some studies report significant improvements with small fibre additions [1], others found negligible gains at a fibre volume fraction of 0.35% [2]. These conflicting findings highlight the need for further investigation.

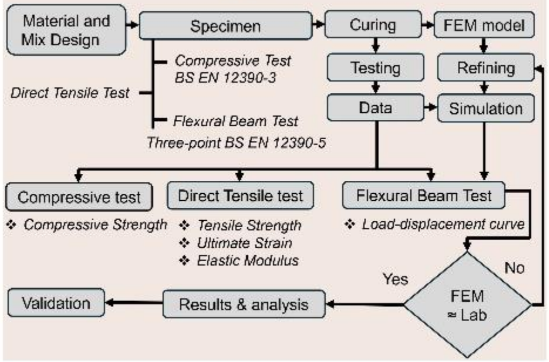
(a) 5D Hooked End Steel Fibre (b) Crack Bridging action

Source: Bekaert (a) and Sika UK (b)

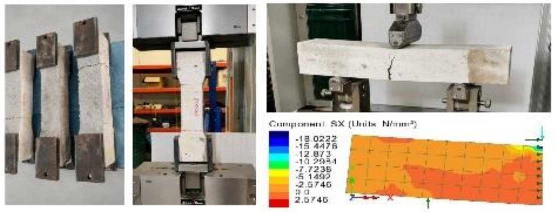
RESEARCH OBJECTIVE

- To analyse the effect of fibre volume fractions (0.2%, 0.4%) on key mechanical parameters compressive strength, flexural strength, ductility and flexural toughness.
- To develop and validate the finite element models of SFRC specimens using **LUSAS** software.

METHODOLOGY



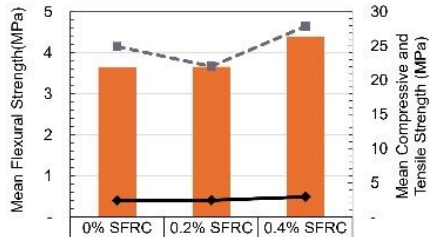
DATA COLLECTION



(c) Direct tensile test's Dog bone specimen and its test arrangement, Three-point bending test and FEM Model in LUSAS (Left to Right).

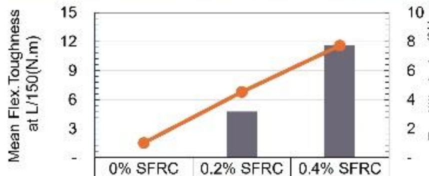
RESULT AND ANALYSIS

1. Mean Strength



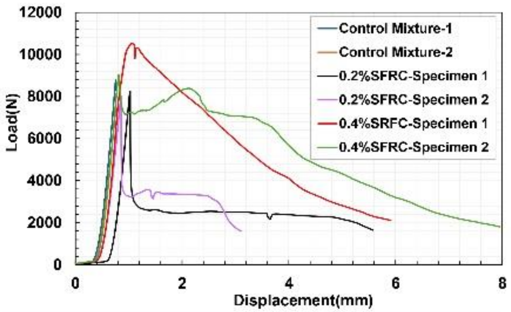
	0% SFRC	0.2% SFRC	0.4% SFRC
Mean Flexural Strength	3.64	3.66	4.40
Mean Com. Strength	24.93	22.02	27.88
Mean Tensile Strength	2.43	2.44	2.93

2. Flexural Toughness and Ductility Index

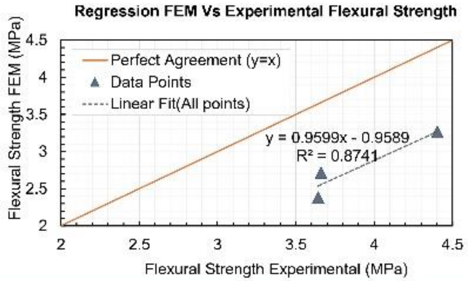


	0% SFRC	0.2% SFRC	0.4% SFRC
Mean Flex. toughness at L/150 (N.m)	-	4.77	11.59
Mean Ductility Index(%)	1.01	4.53	7.72

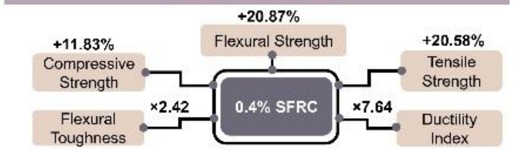
3. Load Displacement Curve



VALIDATION



CONCLUSION



- 87.41 % of the experimental variation was captured by the FEM.

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Green Fuels from Nepal's Surplus Electricity: A Pathway to Global Decarbonization & National Economic Growth

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Abstract

Nepal generates almost all its electricity (99.7%) from hydropower. During the monsoon, generation exceeds domestic demand, producing a substantial seasonal surplus. This surplus is largely curtailed or exported at low marginal value. Meanwhile, the nation remains dependent on imported petroleum and fertilizer, placing sustained pressure on foreign reserves. Nepal's cement industry is also expanding, supported by an estimated 1.25 billion tonnes of cement-grade limestone available in the country. This sector represents a significant and concentrated source of carbon dioxide (CO2) emissions. This study integrates these two issues into a single strategy. It proposes the use of low-cost surplus electricity (≈US$0.04/kWh, compared with ≈US$0.40 in the UK and ≈US$0.08 in China) to electrochemically convert cement-derived CO_2 into green fuels and chemicals. Such products constitute storable, tradable, and high-value energy carriers.

The principal scientific challenge is product selectivity. The CO_2 reduction reaction must be directed toward a single high-value C_{2+} product through efficient C–C coupling. This work addresses the challenge by developing and screening catalysts for enhanced selectivity, and by advancing from laboratory-scale H-cell electrolysis toward industrially relevant reactor designs. Experiments are conducted in a potassium bicarbonate electrolyte, with product distributions quantified by gas chromatography and current output. The proposed pathway advances global decarbonization while strengthening Nepal's economy through import substitution and domestic high-value manufacturing.

Keywords

CO_2 electroreduction, green fuels, surplus hydropower; catalyst selectivity, C–C coupling, cement decarbonization.

Green Fuels from Nepal's Surplus Electricity: A Pathway to Global Decarbonization & National Economic Growth

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1. Nepal's surplus electricity

- Nepal has a strong **seasonal electricity surplus**: during the monsoon
- Surplus is largely **spilled or exported at low marginal prices**

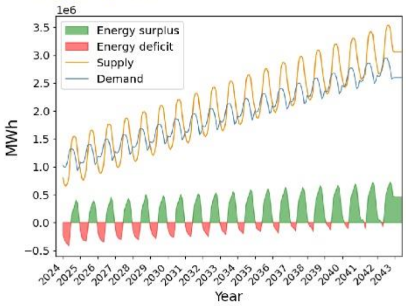

Figure 1: Hydropower generation, supply and demand predicted from 2024 to 2043 with SARIMA model

2. Nepal's growing cement industries

- Nepal has **1.25 billion metric tons** of cement grade limestone deposits.
- Production of cement releases significant amount of CO_2 gas.

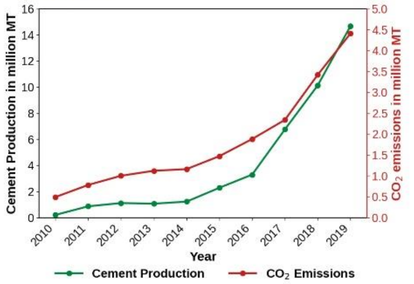

Figure 2: Increase in cement production and hence CO_2 emission

3. Opportunity for Nepal

- Converting CO_2 exhaust from cement industry in Nepal with its surplus electricity into green fuels turns an intermittent, hard-to-store asset into a **storable, tradable, high-value carrier**.
- Electricity price : **Nepal ($0.04/kWh) / UK ($0.40/kWh) / China ($0.08)**

4. Aim

- To improve existing catalysts to obtain **higher selectivity towards desired product**
- Develop **lab-scale to industrial relevant reactor design**.

5. Electrochemical conversion of CO_2

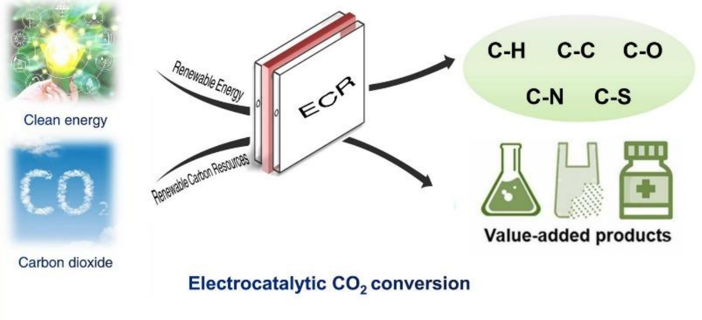

Figure 3: Schematic of eCO_2R

6. Market value

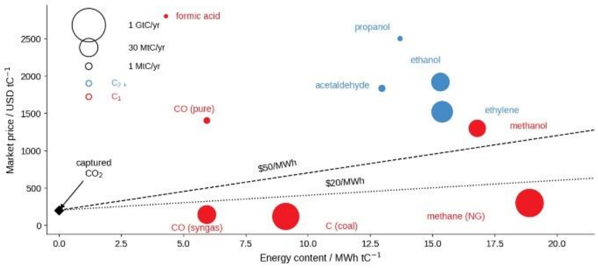

Figure 4: Market value for different product Nepal could domestically produce

7. Experimental overview

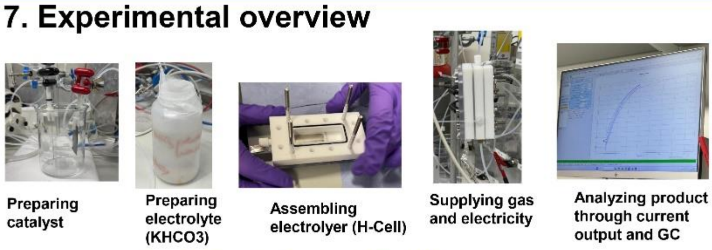

Figure 5 : Schematic of experiments: CO_2 electrolysis

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- **Supervisors: Dr. Anna Hankin, Prof. Ifan Stephens**

LinkedIn

Policy Design for River-sourced Sustainable Management of Construction Materials: Sand and Gravel Mining

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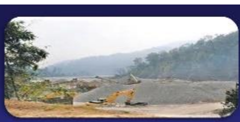
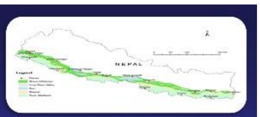
Abstract

The demand for critical construction materials like sand and gravel is skyrocketing due to the booming of construction industry and infrastructure development in Nepal. Current practices of sand/gravel mining to satisfy the demand and illegal trade of sand caused severe environmental and social impacts. The study aimed to design a sustainable sand/gravel mining policy to mitigate the issues and maintain the supply of the critical materials by adopting sustainable mining practices in Nepal.

The study employs an empirical methodology with a questionnaire survey amongst key stakeholder to explore the environmental impact, perceptions and challenges from river sand/gravel mining. The quantitative data were analysed using SPSS to identify patterns and statistical relationships. Findings suggest significant environmental and social impacts from current mining practices. Stakeholders reported that river degradation, infrastructure damage, and reduced community well-being due to excessive extraction and weak enforcement of regulations. Local communities were especially concerned about environmental degradation, scarcity of water sources for drinking and irrigation, and many respondents strongly supported for effective regulatory measures. The discussion emphasizes that inadequate policy enforcement is worsening the environmental harm and social tensions.
The study has several recommendations that include scientific zoning for mining, stricter regulations, low-impact extraction, restoration and replanting, use of recycled sand/gravel, and local stakeholder engagement to ensure sustainable resource management and infrastructure developments in Nepal. Successful implementation of these recommendations will require strong political will, inclusive legal reforms, capacity-building in regulatory agencies, and persistent monitoring to meet the sustainable management of critical construction materials.

Keywords
Sustainable, Construction materials, River, Sand/gravel Policy design, Impact, Environmental, Social and Economic, Mitigations.





Policy Design for River-sourced Sustainable Management of Construction Materials: Sand and Gravel Mining

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Abstract: The study aimed to design sustainable policy by exploring the environmental, social, and economic impacts from riverbed sand and gravel mining practices in Nepal. The review of past studies and stakeholder surveys in Chure areas discovered that there are significant social and environmental impact on local community around mining sites that includes riverbed degradation, infrastructure damage, loss of farmland, flooding, air pollution and community well-being concerns. The study has several recommendations that includes scientific zoning for mining, stricter regulations, low impact extraction, restoration and replanting, use of recycle sand/gravel, and local stakeholder engagement to ensure sustainable resource management and infrastructure developments in Nepal. Successful implementation of these recommendations will require the big political will, inclusive legal reforms, capacity-building in regulatory agencies, and persistent monitoring to meet the sustainable management of critical construction materials.

Background/Rationale: Sand and gravel from Nepal's riverbeds are essential for national construction, but unregulated extraction has led to severe environmental and social impacts—including erosion, water quantity and quality decline, and increased conflicts in local sites. Governance gaps and weak enforcement have enabled illegal mining, especially in sensitive areas like **Chure hills.** There is an urgent need to balance the economic benefits of these materials with environmental protection and community welfare. This study focus on assessing stakeholder perceptions and offering policy recommendations for sustainable sand and gravel management in Nepal.

Figure (1): Workshop with Key Stakeholders at IOE, Lalitpur Nepal

Figure (2): Existing practices of Local river sand/gravel extraction/ mining

Figure (3): Resident interaction at Ratto River, Bardibas, Nepal

Methodology: A descriptive, mixed-method approach was used. Around 90 key stakeholders (local residents, contractors/subcontractors, suppliers, state and local government officials) from Mahottari and Dhanusha districts were surveyed using structured questionnaires (Likert-scale). Data were analysed in SPSS for descriptive statistics and non-parametric tests (Kruskal-Wallis), supported by qualitative analysis of existing policy report and review policy in other countries and around the world.

Results and Discussions:

1. **Environmental Impacts:** The study shows equally **impact on alteration of river flow and reduced groundwater** recharge followed by deterioration in water quality, soil erosion, and ecosystem with wildlife disruption. The study reveals that unmanaged extraction had **shifted river channels**, **dried river sections** in the dry season, and **increased sediment and turbidity**, making **water less fit for drinking and irrigation**. Soil erosion and the loss of riverbank vegetation have caused loss of fertile land, biodiversity and infrastructure. Groundwater decline, are less readily perceived by local communities but they agreed the subsurface water resources are also at risk.
2. **Economic Impacts:** Contribute to **higher income for contractors and employment opportunities for some locals**. Incomes from sand mining often match or exceed alternatives like **day labour or agriculture**, and steady employment can **reduce out-migration**. However, the distribution of economic gains is uneven, **most profits accrue to a few operators**, while broader community members face higher living costs, damaged infrastructure, and loss of farmland or tourism revenue. Stakeholders noted the financial burden on local governments for repairing roads and bridges damaged by heavy transport vehicles, with minimal tax or royalty returns from the industry.
3. **Social Impacts:** Found moderate benefits in employment but greater concern about diminished **quality of life, health issues** (especially respiratory illness due to dust and waterborne disease from polluted rivers), and increased risks to safety. Some respondents described **social conflicts and displacement of households** following riverbank erosion or environmental decline. Concerns about **worker safety** were widely shared, highlighting **lack of regulation**, training, and equipment, including hazardous road conditions due to overloaded trucks.
4. **Stakeholder Perceptions:** Most stakeholders expressed **dissatisfaction with current policies**, describing the existing regime as **poorly enforced and dominated by powerful** operators. There is limited awareness about sand mining regulations, and a clear desire for more transparent, inclusive governance. Notably, respondents supported **improved site selection, stricter enforcement**, modernization of extraction techniques, **site rehabilitation, and benefit-sharing** with affected communities.

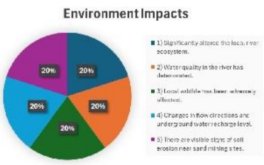

Figure (4): Environmental Impacts

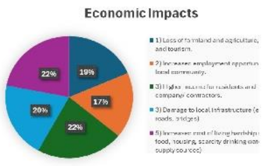

Figure (5): Economic Impacts

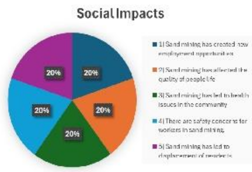

Figure (6): Social Impacts

Figure (7): Policy Mitigation measures

Conclusions: Sand and gravel mining in Nepal is at a crossroads. It is essential for infrastructure development and provide income for some community members, but these have costs including environmental degradation, increased health and safety risks, and social tensions, are high in local communities. Stakeholder strongly support shift to a more regulated, transparent, and sustainable approach. This means prioritizing scientific zoning, strict enforcement, environmentally responsible techniques, site rehabilitation, and active community engagement. Successful implementation of these measures will require political will, legal reforms, capacity-building in regulatory agencies, and persistent monitoring. The **path forward is challenging but necessary if Nepal is to safeguard both its rivers and its future generation and development prospects**. The study is limited to Rato River sand mining sites in Mahottari and Dhanusha. Future study need to cover all Chure areas.

Recommendations:

1. Delineate **sustainable mining zones** based on scientific assessment, restricting extraction from sensitive river sections and confining activities to dry seasons.
2. Strengthen **regulatory enforcement and monitoring** by setting dedicated monitoring units, using modern technologies, and involving community-based oversight.
3. Promote environmentally friendly practices such as **low-impact extraction**, dust and noise control, and strict limits on extraction depth and volume.
4. Command rehabilitation of extraction sites **through restoration and replanting**, financed by levies or bonds from mining operators.
5. Enhance **community engagement** via participatory governance forums and awareness campaigns and ensure fair benefit-sharing with affected communities.
6. Support alternatives to river sand by incentivizing **use of manufactured sand and recycled** aggregates.
7. Update **legal frameworks and clarify institutional roles** to ensure accountability, effective oversight, and coordination across government levels.

Sustainable Cities in Nepal: Concepts, Opportunities and Challenges

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Abstract

Rapid urbanisation in Nepal, particularly within the Kathmandu Valley, has placed considerable pressure on urban infrastructure, transport systems, environmental quality, and public service delivery. As the country continues its urban transition, achieving sustainable urban development has become an increasingly significant planning priority. This paper presents a comprehensive review of the concepts of sustainable and smart cities and examines their applicability within the Nepalese urban context. The study is based on a systematic review of published literature, government reports, policy documents, and selected international case studies to identify the principal opportunities and challenges associated with sustainable urban development in Nepal. The review identifies substantial shortcomings in urban infrastructure, including transport, environmental management, and land-use planning, together with challenges related to rapid urbanisation, traffic congestion, air pollution, and institutional governance.

It further highlights the potential of green infrastructure, renewable energy, rainwater harvesting, digital governance, enhanced public transport, and context-appropriate smart technologies to improve urban sustainability. The findings suggest that strengthening urban planning, institutional capacity, governance frameworks, and infrastructure investment is essential to enhance urban resilience, environmental quality, and the overall liveability of Nepalese cities. The study emphasises the need for integrated planning strategies and coordinated policy interventions to support sustainable, resilient, and inclusive urban development while contributing to the achievement of Sustainable Development Goal 11.

Keywords
Urban sustainability; smart cities; urbanisation; urban infrastructure; sustainable urban development; Nepal.

Sustainable Cities in Nepal: Concepts, Opportunities and Challenges

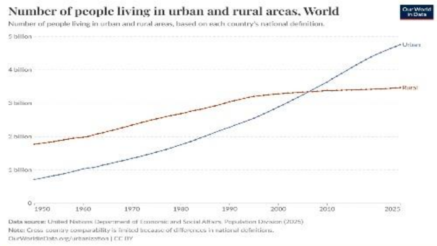
MANOJ KAPRI
Project Planner, MAPM, M.Sc

Objective

- ❑ Global urbanisation a Review
- ❑ Urban development in Nepal
- ❑ Smart cities meaning and approaches
- ❑ Opportunities and challenges
- ❑ Prognosis and Recommendations

World Population Data

- ❑ Population = 8.3 billion (2025 Nov. -UN projects)
- ❑ Pop Growth rate = 0.84% (2025, WB)
- ❑ Annual pop growth = approx. 75 million (Equivalent to UK's Population)
- ❑ Daily pop growth = 187,000 (Approximately)
- ❑ 1.5 million people globally move to cities every week : Annual urban population growth = 2%
- ❑ 92% of the growth is in developing countries; major planning need.



Pollution in Ktm Valley


Source : Kathmandu Post

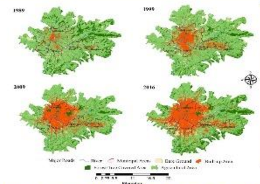
- ❑ WHO Guidelines for Fine particulate matter (PM2.5) :
  10 ug/m3 - annual mean
  25 ug/m3 - 24-hour mean
- ❑ Nepal Government's Standards:
  40 ug/m3 - 24-hour mean
- ❑ On April 23, 2026, the 24-hour average level of PM2.5, was 247 ug/m3 in parts of Kathmandu, Department of Environment data showed. (Various news sources)

Open Space provisions

- ❑ Well-distributed open spaces to help during disaster.
- ❑ Measure use in real-time.UK: 320-380 sft./person, South Asia: 50-60 sft./person. (increase to 100)
- ❑ A min. 0.2 Ha. open space available for all residents within a 5-minute walk.
- ❑ Can be used for staging medical and emergency services.
- ❑ Promote urban gardening for food security. Therapeutic gardens.
- ❑ Real-time use data, and public info on underutilised spaces.


Therapeutic park in the UK

Kathmandu Growth Density, and infrastructure



- ❑ Valley Pop. 2.99m (2021 census), approx. 3.2–3.5 (est.)with floating population.
- ❑ Average population growth rate between 2011 and 2021 census: 45000-55,000/ yr
- ❑ Geographical area = 350 sq. mi.

Source :Ishtiaque, A.; Shrestha, M.; Chhetri, N. Rapid Urban Growth in the Ktm Valley, Nepal

- ❑ Benefits of Density: compactness, arresting sprawl, saving prime agricultural land, efficient infrastructure.
- ❑ Infrastructure is inadequate, and pollution levels high.

UN SDG11 :Make cities and human settlements inclusive, safe, resilient and sustainable

"SDG 11 aims to renew and plan cities and other human settlements in a way that offers opportunities for all, with access to basic services, energy, housing, transportation and green public spaces, while reducing resource use and environmental impact."

Source : ec.europa.eu

Utilities and Infrastructure

- ❑ Passive water for landscape.
- ❑ On-site water harvesting. (55" rain in Ktm./yr.)
- ❑ Low impact drainage, bio swales, rain garden.
- ❑ Solar PV installations.
- ❑ Passive solar deployment.
- ❑ Increased broadband speed, fibre optics lines


Source : Setopati Media

Transportation and connectivity

- ❑ Use of single occupancy vehicles must be minimized.
- ❑ Public transit is important, with sanitization protocol.
- ❑ Hybrid remote working will help relieve congestion, pollution.
- ❑ Plan for a 15/20-Minute City (Paris, Melbourne)
- ❑ On-line shopping: parking for delivery vehicles.
  Transit stop design for public health. Promote walkability (e.g., detached & shaded sidewalks).

What makes a city Liveable, Sustainable and Smart?

What is A Sustainable City ?

"A sustainable city infuses information into its physical infrastructure to improve conveniences, facilitate mobility, add efficiencies, conserve energy, improve the quality of air and water, identify problems and fix them quickly, recover rapidly from disasters, collect data to make better decisions, deploy resources effectively".

Smart Infrastructure

Passive	Active
❑ Shade	❑ Sensor driven utilities follow
❑ Solar control	❑ Smar grid for electricity
❑ Walkable	❑ Distributed Solar Pv energy generation
❑ Green infra (LID)	❑ Smart streetlight sensors
❑ Water harvesting	❑ Smart air quality sensors

International Experience on Sustainable city is mixed

- ❑ Smart City is an evolving concept, which is gaining popularity, although some controversies linger.
- ❑ Toronto water-front sidewalk smart program was cancelled in 2019 for privacy concerns.
- ❑ Masdar City, UAE failed in access and mobility concerns.
- ❑ Santa Maria was planned as Mexico's smart city. Residents opposed it to save traditions.
- ❑ Successes: Efficiency, real time data e.g., congestion pricing to affect driver behaviour.(Singapore, Seoul)
- ❑ Challenges: Technology limits, concerns for privacy, data-driven systems vs desire for a simple-state.

How Does Sustainable city work?

Prognosis for Nepal

- ❑ Nepal is newly urbanising and thus can learn from other's mistakes.
- ❑ The hill situation can help in drainage, water supply and wastewater flows.
- ❑ Has a rich history of good traditional planning and design.
- ❑ Traditionally mixed use, narrow streets, open plazas, cultural resources, tacit guidelines.
- ❑ Nepal has done well to quickly improve social and educational indicators e.g., for SDG. Can a similar approach be advantageously used in urban development arena?

Some Recommendations

- ❑ Improve basic urban infrastructure
- ❑ Start with passive smart elements. E.g., urban forestry, permeable paving, solar PV, rainwater harvesting, using daylight & solar controls.
- ❑ Utilize smart technologies (transit apps, and real time AI) in traffic and transportation management.
- ❑ Utilise smart systems (including apps) in parking.
- ❑ Implement transit projects and electrical vehicles.
- ❑ Make pollution measurement and early waning system ubiquitous.
- ❑ Enhance and popularise planning and e-governance.

Summary

- ❑ Urbanization is important in human history.
- ❑ Nepal is experiencing a rapid urban development that includes several challenges.
- ❑ A sustainable and liveable city depends on effective management of urban components
- ❑ Some smart city elements are viable in Nepal & may help improve urban function & quality of life.
- ❑ As a newly urbanising country, Nepal can learn from others and create a compelling urban future.

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MARVEL-RAG: Product-Grounded Multimodal Retrieval-Augmented Generation for Automated Social Media Marketing Content in E-Commerce

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Abstract

The rapid expansion of e-commerce has created an increasing demand for high-quality multimodal marketing materials, including product descriptions, promotional captions, social media posts, images, and short-form videos. Producing this content manually for large and continuously evolving product catalogues is costly and time-consuming, whereas conventional large language model (LLM)-based generation often suffers from factual inaccuracies, unsupported product claims, and inconsistent brand representation. This paper introduces MARVEL-RAG (Marketing Automation with Retrieval-Enhanced Language-guided Generation), a retrieval-augmented framework designed to generate reliable and brand-aligned multimodal marketing content. The proposed approach combines structured product information, product imagery, and a curated knowledge repository containing brand guidelines, previous marketing campaigns, customer reviews, and emerging social media trends. Retrieved contextual knowledge is incorporated into task-specific prompts that guide generative models to produce a variety of marketing assets, including product descriptions, captions, hashtags, promotional images, and video scripts, while preserving factual correctness and brand identity. The framework is evaluated against a conventional LLM-only pipeline using multiple content quality measures. Experimental results indicate that MARVEL-RAG improves overall content quality by 9.3%, delivering notable enhancements in factual grounding and brand consistency without compromising generation efficiency. These findings highlight the value of retrieval-augmented generative AI as a practical solution for scalable, trustworthy, and multimodal marketing automation in modern e-commerce environments.

Keywords
Retrieval-Augmented Generation (RAG), Multimodal Content Generation, Digital Marketing, E-Commerce, Large Language Models, Brand Consistency, Hallucination Reduction.

Est. 1841 YORK ST JOHN UNIVERSITY LONDON

MARVEL-RAG: Product-Grounded Multimodal Retrieval-Augmented Generation

For Automated Social Media Marketing Content in E-Commerce

SANGITA POKHREL
YORK ST JOHN UNIVERSITY

1. INTRODUCTION

Digital marketing increasingly relies on Generative AI to create personalized content across multiple channels. However standalone Large Language Models (LLMs) often suffer from hallucinated information, inconsistent brand messaging, lack of access to current business knowledge and so on.

Multimodal Retrieval-Augmented Generation (RAG) addresses these limitations by integrating organisational knowledge and multimedia content into the generation process.

Research Question

How can Multimodal RAG improve the quality, consistency, and relevance of AI-generated marketing content?

2. AIM & OBJECTIVES

AIM

To design a Multimodal RAG framework capable of generating brand-aligned marketing assets using textual and visual knowledge sources.

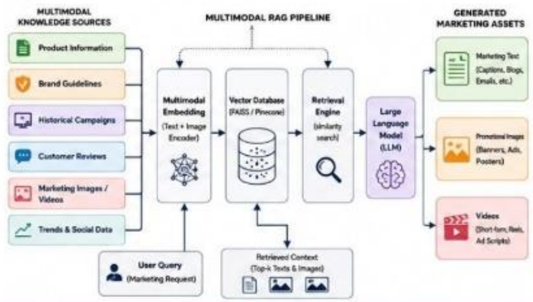
OBJECTIVES

- Design a multimodal knowledge repository
- Integrate text and image retrieval mechanisms
- Generate marketing content across modalities
- Compare performance against standard LLM approaches

3. DATA SOURCES (KNOWLEDGE BASE)

Data Types	Description
Product Information	Specifications, features, benefits
Brand Guidelines	Tone, style, colors, branding rules
Customer Reviews	User feedback and ratings
FAQs & Knowledge Base	Common questions & answers
Campaign History	Past campaigns, performance data

4. PROPOSED MULTIMODAL RAG ARCHITECTURE



5. METHODOLOGY & SYSTEM COMPONENTS

Component	Technology / Tool
Large Language Model (LLM)	GPT-4 / GPT-4o
Image Generation	Stable Diffusion
Embedding Model	CLIP
Vector Database	FAISS / Pinecone
Evaluation	RAG, LLM Evaluator

6. EXAMPLE RETRIEVAL PROCESS

1. USER QUERY

'Create an Instagram campaign for an eco-friendly skincare product'

2. RETRIEVAL (TOP-K)

- Product Specifications
- Brand tone guidelines
- Product Image
- Price of the product

3. LLM GENERATION

LLM used retrieved context to generate brand-aligned marketing assets.

4. OUTPUT

- Marketing Content
- Promotional Image
- Short-form video
- Hashtags
- Social Media Ready designs

6. RESULTS & EVALUATION

Method	Quality Score	Improvement
LLM-only Automation	72.45 ± 1.23	--
MARVEL-RAG System	78.92 ± 1.45	+6.47 points (+9.3%)
Metric	LLM-only	RAG System
Generation Time	8.5 ± 0.5s	9.2 ± 0.4s
Token Usage	945 ± 45	912 ± 38

Metric	Weight	LLM-only	RAG System
Brand Consistency	40%	70.1	79.3
Factual Accuracy	35%	73.4	82.5
Content Quality	25%	74	80.4
Overall Score	-	72.45	78.92

6. CONCLUSION

MARVEL-RAG demonstrates that grounding generative AI with retrieval and automated verification significantly improves the reliability, factual accuracy, and brand consistency of multimodal marketing content. The proposed framework offers a practical and scalable solution for AI-assisted digital marketing while laying the foundation for future multimodal, personalised, and human-centred content generation.

Future work will incorporate larger real-world datasets, human expert evaluation, and fully multimodal retrieval across text, image, and video.

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From Regulatory Challenge to Client-Informed MVP

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Abstract

RentNotice is a compliance-first SaaS platform designed to support UK landlords and estate agents in managing rental property operations, compliance tasks, stakeholder communication, and audit-ready records. The presentation demonstrates how a real-world regulatory and operational challenge can be translated into a working digital product using a structured Software Development Life Cycle approach.

The private rented sector represented 19% of all UK households in the year ending March 2024 [1]. In England, the private rented sector accounted for around 4.7 million households, or 19% of households, in 2024–25 [2]. The Renters' Rights Act received Royal Assent on 27 October 2025 [3]. Government guidance states that the Renters' Rights Act changes for private landlords came into effect on 1 May 2026 [4].

The presentation covers the journey from problem identification, requirements analysis, system design, and implementation to MVP development, early client feedback, and ongoing iteration. The platform brings together property records, tenancy information, documents, compliance tracking, notifications, audit logging, and an AI Compliance Assistant for risk detection, smart alerts, and operational recommendations. Attendees will gain practical insight into how software projects move from idea to MVP through structured, user-centred, and iterative development. Using RentNotice as a case study, the session highlights that successful software engineering is not only about coding, but also about understanding domain problems, mapping stakeholder workflows, designing scalable architecture, testing assumptions, and improving the product through client feedback.

- Understanding how a regulatory challenge can become a practical SaaS product opportunity and how SDLC stages can be applied from problem identification to MVP iteration.
- Seeing how landlords, agents, tenants, contractors, and administrators can be connected through a shared compliance workflow.
- Exploring how AI can support risk detection, smart alerts, and operational recommendations.
- Recognizing the importance of human review, legal caution, audit trails, and responsible product design.

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RentNotice
Compliance-first property operations. Powered by AI.
DESIGN AND DEVELOPMENT OF A SAAS-BASED RENTAL PROPERTY MANAGEMENT & COMPLIANCE PLATFORM
From Regulatory Challenge to Client-Informed MVP Iteration
RC Adhikari | Sr. Software Engineer, Investment Bank, Consulting & Agency
1 PROBLEM & MOTIVATION
UK rental compliance is complex and time-sensitive.
Tools from landlords and agents are fragmented.
Manual tracking leads to missed deadlines and inconsistent communication.
Multiple stakeholders need timely, role-based updates.
A compliance-first digital platform is needed.
2 AIM & OBJECTIVES
Build a SaaS tool for landlords and estate agents.
Manage properties, listings, tenancies and documents.
Track compliance tasks linked to Renters' Rights reforms 2025/2026.
Notify landlords, agents, tenants and contractors.
Deliver and iterate an MVP based on early client feedback.
3 SDLC & METHODOLOGY
Idea & Feasibility
Requirements Gathering
System Design
Implementation
Testing
MVP Iteration & Feedback
Iterative development
User-centred design
Modular architecture
Continuous improvement
4 SYSTEM ARCHITECTURE
Users
Landlord
Estate Agent
Tenant
Contractor
Admin
Web Portal / SaaS Interface
Authentication & RBAC
Core Services
Property Management
Tenancy Management
Compliance Tracker
Document Repository
Notice & Reminder Engine
Maintenance & Contractor Workflow
Database & Audit Log
Notification Service
AI Compliance Assistant
AI Insight & Compliance Engine
Risk detection • Smart alerts • Recommendations
Key Technologies
Laravel
Livewire
Alpine.js
Tailwind CSS
MySQL
Vite
Role-Based Access Control
Audit Logging
AI/ML Services
Email Alerts
Dashboard Notifications
Future SMS / WhatsApp (Planned)
5 FROM PROBLEM TO CLIENT-INFORMED MVP
1 Identify regulatory problem
2 Define users & requirements
3 Design data model & UX flow
4 Build MVP modules
5 Client walkthrough & feedback
6 Iterate & refine roadmap
6 CORE MODULES
Property & Portfolio Records
Landlord / Agency Management
Tenant & Tenancy Lifecycle
Compliance Calendar
Document Repository
Maintenance & Contractors
Notices & Communication
Audit Trail & Reports
7 STAKEHOLDER NOTIFICATION FLOW
Trigger Event
(certificate expiry, tenancy change, repair request, notice deadline)
AI analyses risk & checks compliance
Create task & reminder
Notify relevant stakeholder
Action completed & logged
8 MVP ITERATION SCOPE
Register properties and units
Create landlords, tenants and contractors
Record tenancy details
Upload compliance documents
Track statuses and due dates
AI-driven risk alerts & suggestions
View dashboard alerts and insights
Refine workflows using early client feedback
9 OUTCOMES & VALUE
Centralised records
Better visibility of obligations
Reduced manual follow-up
Clear audit-ready history
Improved collaboration across parties
Foundation for SaaS productisation
10 SOFTWARE ENGINEERING ANALYSIS
Problem-to-solution mapping is explicit.
Modular design supports future scaling.
Role-based workflows reflect real user needs.
MVP iteration reduces delivery risk.
Compliance logic is separated from UI concerns.
AI augments accuracy and timeliness of compliance operations.
11 LIMITATIONS
Legal rules evolve and need regular updates.
MVP version does not cover every edge case.
External integrations are limited.
Broader user testing is still needed.
The tool supports compliance tracking and is not legal advice.
12 FUTURE WORK
Beta testing with landlords and estate agents
Automated rule updates using AI
AI analytics and reporting dashboard
Mobile-friendly experience
Contractor self-service portal
AI-assisted compliance checks
13 CONCLUSION
RentNotice demonstrates how SDLC can convert a regulatory challenge into a client-informed, AI-enabled SaaS MVP.
A compliance-first platform can help UK landlords and estate agents manage listings, obligations and communications more effectively.
Knowledge-transfer poster | Client-informed MVP iteration | No confidential client or tenant data disclosed
AI-assisted outputs require human review | Supports compliance tracking; not legal advice.

Integration of Electromechanical Actuators (EMA) Governed by Fly-By-Wire System to Control Main Rotors of Robinson R22 Helicopter to Mitigate Mast Bumping

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Abstract

Mast bumping remains a persistent and life-threatening hazard in the Robinson R22 helicopter, a widely used training and utility aircraft with a semi-rigid teetering rotor system. Despite numerous mechanical interventions by Robinson—including teeter stops, friction spring assemblies, and shim stacks—accident data from NTSB, ATSB, and TAIC (1996–2023) reveal that loss-of-control events linked to low-G manoeuvres and excessive cyclic inputs continue to occur, with a 2022 fatal crash in Western Australia citing a damaged teeter stop as a contributing factor. This research proposes a novel safety architecture that replaces the conventional mechanical flight control linkage with three Electromechanical Actuators (EMAs) governed by a closed-loop Fly-By-Wire (FBW) system. The FBW flight-envelope protection software actively blocks cyclic commands that would induce mast bumping, while the system operates in tandem with the existing mechanical linkage—incorporating a shear-pin fail-safe that reverts control to manual operation if an EMA fails, and a guarded isolation switch that allows the pilot to disengage the system at any time.

A mixed-methods approach combined a qualitative literature review of peer-reviewed journals and regulatory reports with a quantitative survey of 50 aviation professionals, including 39 aircraft technicians, 7 engineers, and 4 pilots. Survey findings indicate that 68% of respondents view FBW as safer than purely mechanical systems, 72% believe it provides superior handling characteristics, and 60% consider it more fault tolerant, though mechanical systems were still rated as easier to troubleshoot and repair. The study concludes that a partial-authority FBW system with EMAs, operating in parallel with existing mechanical controls, offers strong potential to significantly reduce mast-bumping risk in the R22. However, full-scale implementation would necessitate comprehensive dynamic modelling, prototyping, cost-benefit analysis, and certification-level testing to validate system performance, reliability, and regulatory compliance for lightweight helicopter applications.

Keywords
Mast bumping, Robinson R22, fly-by-wire, electromechanical actuators, flight envelope protection, helicopter safety, low-G manoeuvres, fail-safe design, flight control systems

STAFFORDSHIRE UNIVERSITY

INTEGRATION OF ELECTROMECHANICAL ACTUATORS (EMA) GOVERNED BY FLY-BY-WIRE SYSTEM TO CONTROL MAIN ROTORS OF ROBINSON R22 HELICOPTER TO MITIGATE MAST BUMPING

Krishna B. Gurung | B Eng Aeronautical System Engineering

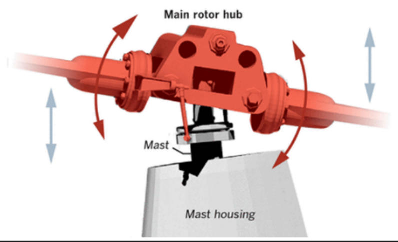
1 PROBLEM & MOTIVATION

Mast bumping is a critical safety issue in the Robinson R22 helicopter, often leading to the loss of control and causing fatal accidents. According to Civil Aviation Authority of New Zealand, there were 11 mast bumping in R22, between 1991 to 2015, that caused 14 fatalities.

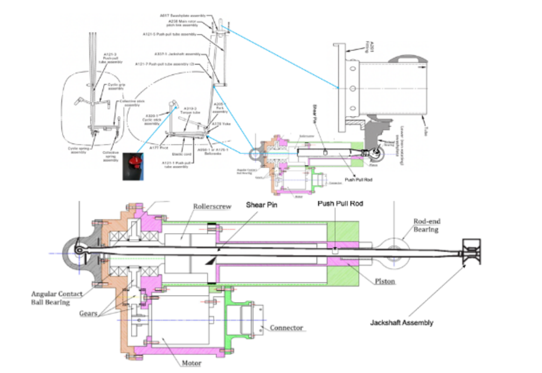
The current designs based on mechanical linkage system principle, employed in R22 helicopter, does not fully eradicate the risk of mast bumping. The proposed EMA governed by FBW, offers enhanced control, superior handling, better maintainability, reliability, and safety by preventing the pilot's inadvertent excessive cyclic inputs during low-G conditions. Implementation of EMA controlled by FBW system helicopter can prevent mast bumping therefore improving overall flight safety.

2 AIM & OBJECTIVES

- ❖ Identify the root cause of the mast bumping problem in the Robinson R22 helicopter by analysing data published by the Australian and US Transport Safety Board from 1996 to 2023.
- ❖ Evaluate the limitation of mechanical linkage system principle-based design applied by Robinson Helicopter company to date.
- ❖ Explore the potential of Fly by Wire principle-based design to tackle mast bumping in the Robinson R22 helicopter in the future.



3 SYSTEM ARCHITECTURE



4 FUTURE WORKS

- ❖ Implementation of FBW system in lightweight helicopter.
- ❖ Further research with FBW system and cost analysis to be carried out.
- ❖ Collaboration with technicians, engineers, pilots, and industrialist.

5 CONCLUSION

- ❖ Root cause of mast bumping is abrupt pilot cyclic inputs and teeter-hinge design flaws.
- ❖ Existing R22 mechanical linkages fail to eliminate the issue.
- ❖ Solution: FBW governed by FBW; proven as the safest, most reliable, and fault-tolerant flight system.
- ❖ Three EMAs power and control the main rotors with closed loop system that **u**ses flight protection software to block excessive cyclic inputs.
- ❖ Actively negates pilot errors that cause mast bumping and delivers superior handling, safety, and system reliability.

Implementation of Movie Recommendation Using Machine Learning and Deep Learning

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Abstract

Recommendation systems have become increasingly important for platforms such as streaming services due to the growing demand for personalized content delivery. Although traditional recommendation techniques are effective, they often struggle to balance prediction accuracy and computational efficiency. This study investigates and compares the performance of various Machine Learning (ML) and Deep Learning (DL) algorithms for movie recommendation to address these challenges. Traditional ML models, including KNNWithMeans, Singular Value Decomposition (SVD), SVD++, Non-Negative Matrix Factorization (NMF), and BaselineOnly, are evaluated alongside advanced DL models such as Neural Collaborative Filtering (NCF), Wide & Deep, and Transformer-based architectures. The MovieLens dataset was used for experimentation, with an 80:20 train-test split, and genre information was one-hot encoded to improve model compatibility. Model performance was evaluated using Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and training time. The results indicate that while deep learning models generally provide high predictive accuracy, they require greater computational resources. The Transformer model achieved an RMSE of 0.870 in 92.7 seconds, whereas SVD++ achieved the best RMSE of 0.864 in 83.13 seconds. BaselineOnly demonstrated the best balance between accuracy and efficiency, achieving an RMSE of 0.870 with a training time of only 0.11 seconds. In contrast, Neural Collaborative Filtering required significantly more computational resources despite achieving competitive performance.

These findings highlight the trade-off between recommendation accuracy and computational efficiency. While deep learning approaches offer strong predictive capabilities, traditional machine learning methods such as SVD++ and BaselineOnly remain highly competitive, particularly in resource-constrained environments. Future research should focus on incorporating contextual user information and improving the efficiency of deep learning models for recommendation systems.

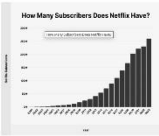
Keywords
Recommendation Systems, Machine Learning, Deep Learning, Movie Recommendation, Computational Efficiency, Transformer, Wide & Deep, Neural Collaborative Filtering.

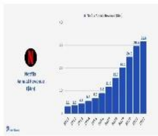
Implementation Of Movie Recommendation Using Machine Learning And Deep Learning

Er. Suraj Ale Magar | MSc Data Science (Kingston University London)

1. INTRODUCTION

- Streaming platforms like Netflix, Amazon Prime, and YouTube have millions of users worldwide
- Netflix has over 250 million subscribers globally
- In 2022, Netflix generated around 31.6 billion USD in revenue
- Many Users face difficulty in choosing movies due to too many available options





2. PROBLEM STATEMENT AND OBJECTIVES

Problem Statement

- Personal experience : Often faced difficulty and spent too much time deciding what movie
- Content Overload: Large number of choices makes it difficult for users to find relevant movies
- Recommendation Challenges: Cold start issues and scalability problems affect recommendation performance

Objectives

- To create advanced movie recommendation model
- To assess and compare performances of different ML and DL Algorithms
- To increase accuracy and relevancy of recommendations

4. METHODOLOGY

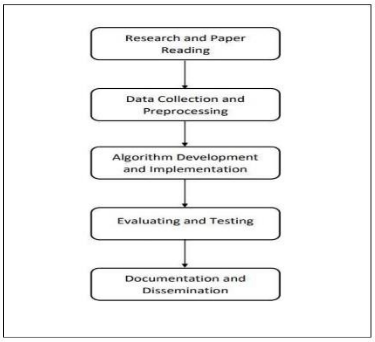


Fig : Research Method

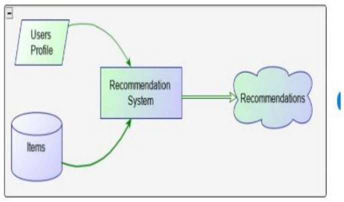


Fig : Movie Recommendation Process

5. IMPLEMENTATION DETAILS

Algorithms Used

- Machine Learning Algorithms : KNN With Means, SVD, SVD ++, Non-Negative Matrix Factorization, Baseline Only
- Deep Learning Algorithms : Neural Collaborative Filtering, Wide And Deep Model, Transformer Model

Evaluation Metrics

- Mean Absolute Error (MAE) (Model Predicted Rating on Movie - Actual user Rating On Movie)
- Mean Squared Error (MSE)
- Root Mean Squared Error (RMSE)
- Training Time

6. TOOLS AND SOFTWARE USED

Tools Used

- Development Environment : Google Colab, Jupyter Notebook
- Programming Language : Python
- Libraries : Numpy, Pandas, Matplotlib, Scikit-Learn, Tensorflow, Keras

Data Used

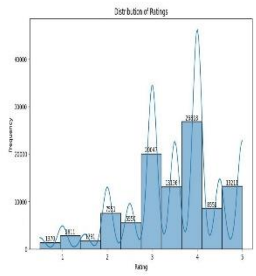
- MovieLens Dataset With 100,836 Ratings For 9742 Movies
- 610 Users With at least 20 ratings each
- Data Files : Movies.csv, ratings.csv, links.csv, tags.csv
- Key Features : movieid, title, genres, ratings, tag, timestamp

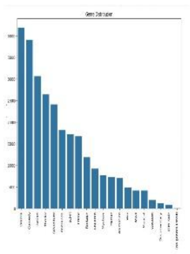
Source : GroupLens Research (2018). MovieLens dataset. Available at: https://grouplens.org/datasets/movielens/latest/

3. LITERATURE REVIEW

Author	Year	Methods	Drawbacks
Zhang et al.	2020	Traditional ML (Collaborative Filtering) + Neural Networks	- Cold-start issues
			- Sensitive to noisy data
Liu et al.	2021	Content-Based Filtering with Natural Language Processing (NLP)	- Limited to similar items
			- May overlook broader preferences
Kumar & Kumar	2022	Hybrid model (CF + Content-Based + Knowledge-Based)	- Complex tuning required
			- Higher computational costs
Bharadwaj et al.	2023	Ensemble methods (Traditional ML)	- Needs substantial training data
			- Risk of overfitting
Zhao et al.	2023	Deep Learning (Deep Reinforcement Learning)	- High resource requirements
			- Hard to interpret model decisions

7. EXPLORATORY DATA ANALYSIS





8. RESULTS

S.N	Model	MSE	RMSE	MAE	Training Time (Seconds)
1	KNNWithMeans(ML)	0.819	0.905	0.692	0.42
2	SVD(ML)	0.768	0.876	0.673	1.62
3	SVD++(ML)	0.746	0.864	0.662	83.13
4	NMF(ML)	0.851	0.922	0.708	2.54
5	BaselineOnly(ML)	0.757	0.870	0.670	0.11
6	Neural Collaborative Filtering(DL)	0.840	0.916	0.697	32.01
7	Wide and Deep Model(DL)	0.889	0.943	0.731	63.08
8	Transformer Model (DL)	0.767	0.87	0.665	92.70

Machine Learning (ML) : Fast Training, Good for simple Data
Deep Learning (DL) : Higher Accuracy, Needs More Resources

9. CHALLENGES AND SOLUTIONS

Challenge 1 : Limited Computational power on local machine
Solution : Used Google Colab online GPU/TPU For Model Training

Challenge 2: Ensuring Fair Comparison across models
Solution : Used Consistent Evaluation Metrics for all models

10. CONCLUSION

- Developed and evaluated ML and DL Movie recommendation models
- Made movie selection easier by suggesting movies based on user preferences.
- Compared models using MAE, MSE, RMSE, and training time
- ML is faster with less data, DL is more accurate but resource-heavy

11. FUTURE WORK

- Utilize user demographic and real-time information
- Use external datasets and more computational power
- Scope: can be used in platforms like Netflix (movies), YouTube (videos), Amazon (shopping), and Spotify (music) for recommendations

From Bridge Construction to Digital Twins

Integrating Site Experience, Structural Design and Structural Health Monitoring for Smart Infrastructure

Binod Shrestha | MSc Structural Engineering with Placement | University of Surrey |
Email: shts.binod@gmail.com

1 INTRODUCTION

Location : Marpha Khola, Mustang, Nepal
Project : Kaligandaki Corridor, Beni-Jomsom-Korala Highway
Status : National Pride Project of Nepal
Client : Department of Roads, Government of Nepal
Contractor : Himdhung & Thokar / Immortal Construction
Value : £1.18 million

2 Cold Weather Concreting & Construction Challenges in Mountainous terrain

- Site Temperature dropped below freezing -10°C
- Mixing water heated to 25 - 32°C
- Concrete placement temperature -5°C on site.
- Curing delayed to provide enough hydration.
- Reduced Slump and caused pump choking.
- Delayed concrete strength gain.
- Risk of Freezing and Thawing
- Reduced Equipment and worker efficiency.

3 BRIDGE CONSTRUCTION EXPERIENCE


Google Earth Aerial View of the Project After


Heating water using woods to increase the concrete


Flood risk - debris flow with boulders obstructing


Falsework and staging preparation after Flood debris


Reinforcement detailing and profiling of the


Fully prestressed Bridge after formwork and


Completion of 120 m longest Prestressed Bridge of Mustang

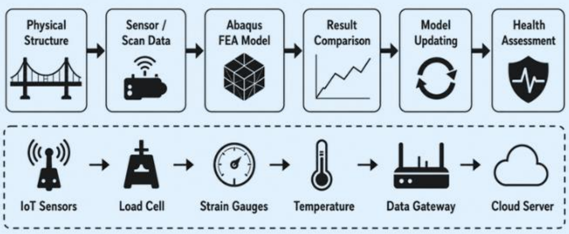
4 AIM AND OBJECTIVES

- Integrate site construction experience with analytical modelling and SHM.
- Develop a prototype Digital Twin linking field data, FEA and decision support.
- Improve understanding of load paths, moving-load effects and failure mechanisms.
- Enable early identification of risks and support maintenance planning.

5 STRUCTURAL DESIGN AND ANALYTICAL MODELLING

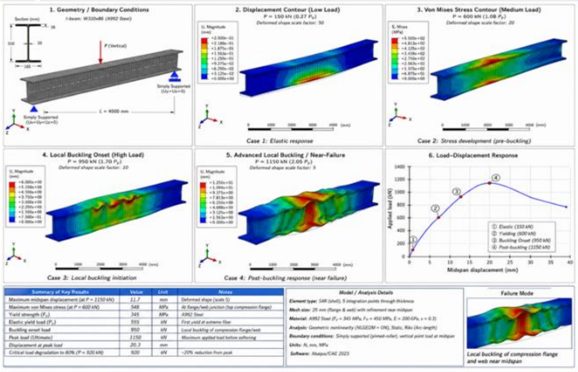
- Evaluated structural behavior through load path, bending moment, shear force and serviceability checks.
- Applied moving-load analysis for prestressed concrete bridge response under traffic loading.
- Interpreted Abaqus FEA outputs including deformation, stress distribution, strain and local buckling risk.
- Connected design calculations with site constructability, durability and maintenance planning.

6 METHODS: PROTOTYPE DIGITAL TWIN AND SHM FRAMEWORK



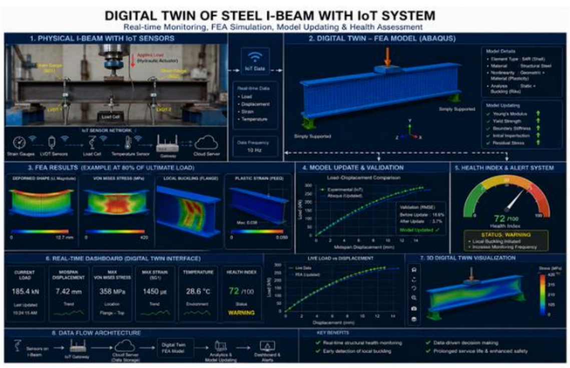
A proposed closed-loop workflow linking field data, FEA and decision support.

7 DIGITAL TWIN OUTPUTS AND FEA DEMONSTRATION



FEA outputs demonstrate deformation, stress distribution, local buckling onset and post-buckling response under increasing load.

8 IOT-ENABLED DIGITAL TWIN ARCHITECTURE



Concept architecture linking field data, FEA updating and structural health assessment.

9 KEY RESULTS / PROFESSIONAL HIGHLIGHTS

- 120 m prestressed bridge; QA/QC, reinforcement checks and 267.73 m³ cold-weather concreting.
- Load-path analysis, moving-load assessment, serviceability checks and Abaqus FEA interpretation.
- Digital Twin and SHM for early risk detection, predictive maintenance and low

10 CONCLUSIONS

This poster reflects my progression from hands-on bridge construction to structural analysis and my future interest in applying **Digital Twin and SHM technologies** for safer, smarter and more sustainable bridge infrastructure.

11 REFERENCES & ACKNOWLEDGEMENT

- Eurocode 3 - EN 1993: Design of Steel Structures
- ISO 19650-1:2018
- Abaqus Analysis User's Guide.
- NIST Digital Twin Concepts.

Acknowledgement
I acknowledge the **University of Surrey** and bridge project teams in Nepal for their support and valuable field experience.

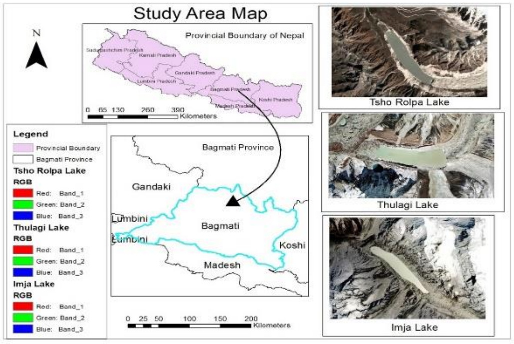
Building Bridges. Connecting Data. Enabling Smart Infrastructure.

Glacier Lake Outburst Flood Hazard Assessment of Major Glacial Lakes in Nepal

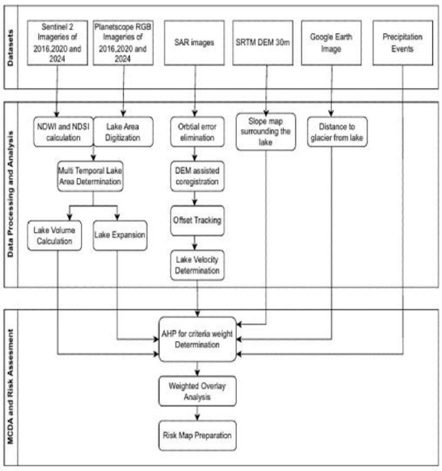
-Sujan Sapkota (sujansapkota27@gmail.com)
Lead GIS Analyst (Northern Ireland Housing Executive)

Introduction

•Nepal is home to over 1,466 glacial lakes (Khadka et al., 2019).
•For this study, the extent of risk in three of the largest glacial lakes in Nepal: TshoRolpa, ImjaTsho and Thulagi lake have been studied.
•Remote sensing offers a useful tool for monitoring these lakes (Bolch et al., 2021).



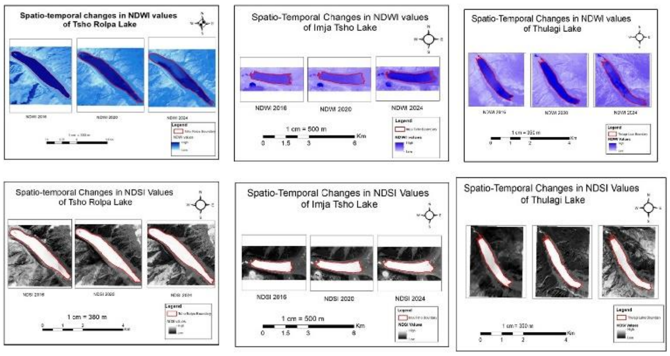
Methodology Used



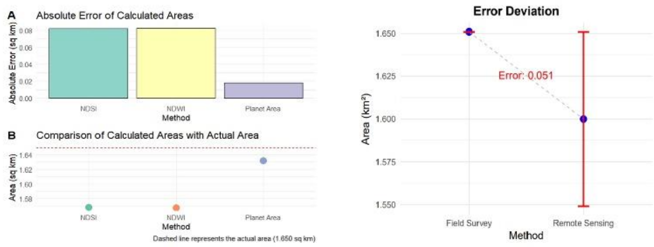
Datasets Used

Datasets	Source	Resolution/Scale	Date
Harmonized Sentinel-2	Copernicus Open Access Hub	10 meters	2016-2024
PlanetScope images	Planet Labs	3 meters	2016 2024
Precipitation Events	Department of Hydrology and Meteorology		2016-2024
Digital Elevation Model (DEM)	Satellite Radar Topography Mission (SRTM)	30 meters	2024
Synthetic Aperture Radar (SAR) Images	Sentinel 1C	30 meters	2023 & 2024
High Resolution Imagery	Google Earth	Varying Resolution	Different Dates

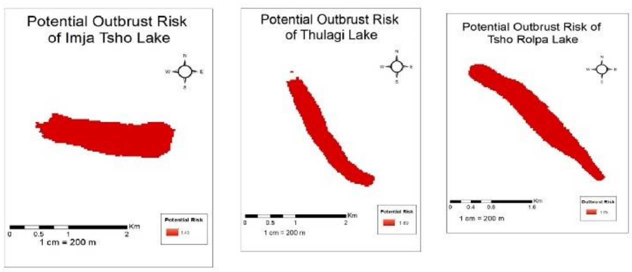
Results



Validation



Risk Assessment Results



Lake Name	Risk Value	Normalized Risk	Risk Class
Tsho Rolpa	1.75	0.875	High Risk
Thulagi	1.69	0.845	High Risk
Imja Tsho	1.43	0.715	High Risk

Conclusion

•The percentage of increase in area of TshoRolpa, ImjaTsho, and Thulagilake from 2016 to 2024, was observed to be 3.36%, 10.15%, and 5.221% respectively, over each 4-year interval.
•The lake surface velocity was 0.816 m/day, 0.012 m/day and 0.345 m/day for TshoRolpa, ImjaTsho and Thulagirespectively.
•The resulting normalized risk were found out to be 0.875, 0.845 and 0.715 for Tsho Rolpa, ImjaTsho and Thulagi respectively.

HS2: On-site material production

Key words
Material production, material class, methodology, application, de-carbonization

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Aim

Examine sustainability practice at HS2 on-site material production

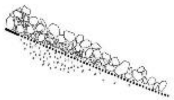
Literature review

Importance	Literature concept
Engineering specification	Produced quantity of materials Meet quality & SCEW standards
Carbon reduction	Avoid query extraction Avoid distance HGV vehicle movement
Minimize waste	Convert waste into product Re-use and Re-cycle of materials
Circular economy	Borrow and return concept Continuous re-generating material

Methodology


Primary crushing


Secondary crushing


Screening and sieving

Material types


1A1


2C1


6C1


6F8


6F15


6N5

Abstract

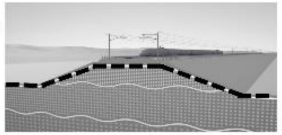
On-site material production is essential to the HS2 project, ensuring the supply of high-quality materials that meet engineering standards and project demands. It reduces reliance on external suppliers, improves supply chain efficiency, and supports sustainability by lowering carbon emissions and promoting circular economy practices through material reuse and recycling.

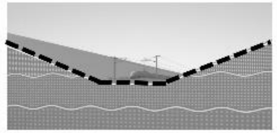
Cut

Excavate material to required formation level
Trim side slopes and battens to safe angle

Fill

Backfill right material in right place
Conduct material test & quality assurance


Embankment filling


Deep cutting

Material test and Quality assurance


NDG test on 1A1


6F8 test on 6F8

LWD test on 6P3


Geo-scan on ground level

Application of materials in HS2


1A1 for mainline train track


9J1 for UEF embankment


6F8 for sub-grade filling

Key Finding

Borrow pit	Cut & Fill	Crushing & screening
No dependent on commercial No query extraction Minimized landfill waste	No destruction to environment Reduced HGV movement & carbon 90% local material re-used	Self-produced as per design Supported circular economy Utilized waste into product

Conclusion

Self-sustained circular factory with 90% material produced and re-used within HS2 in earthwork construction

COST OF POOR QUALITY (COPQ) IN CONSTRUCTION

BUILD IT RIGHT FIRST TIME- QUALITY SAVES COST

SUDIB KC | QUALITY MANAGER

Sudib KC, is Quality Management professional with over 30 years of experience driving excellence in construction and consulting industries, across various infrastructure development projects in Nepal and the UK. He also worked for the United Nations Development Programme (UNDP) in Nepal in the capacity of National Project Development Expert. Currently, he is serving as a Quality and Completions Manager on the UK's prestigious High Speed 2 (HS2) project.

- Bachelor of Civil Engineering, BE (Hons)
- MSc in Urban Planning
- Chartered Quality Professional, CQP MCQI
- ISO9001 Quality Management Lead Auditor

DEFINATION

The cost of Poor Quality (COPQ) in Construction refers to the Total cost incurred because work is not done correctly the first time. It represents the financial impacts of defects, error, rework, inefficiencies, and failures across the project lifecycle.

- Costs to fix mistakes
- Costs arising from failures to meet requirements
- Costs due to inefficient processes and poor management
- Some costs are visible, the majority remain hidden and have a significant impact on project performance and profitability

MAIN DRIVERS OF POOR QUALITY

- The cost of Poor Quality (COPQ) in Poor communication and coordination
- Design changes and information gaps
- Supply chain fragmentation
- Inadequate quality assurance
- Weak planning and project management
- Poor Quality Control and lack of construction Progressive assurance
- Direct and indirect quality failure

COMPARISION-COST OF POOR QUALITY – NEPAL VS UK VS GLOBAL

COST OF POOR QUALITY IN NEPAL

- Cost overruns: 18% to 41% in case studies of building projects *[unitedtechege.edu.np]*, Often exceed 30% in many construction projects nationally *[academia.edu]*
- Time overruns (linked to quality failures): Almost all projects experience delays, with 28% to 150% time overrun *[unitedtechege.edu.np]*

COST OF POOR QUALITY IN GLOBAL

- 5% – 10% of total project cost = typical rework cost *[planradar.com]*
- 5%–20% range *[planradar.com]*
- 20%–45% overruns *[link.springer.com]*

COST OF POOR QUALITY IN UK

- 5% to 12% of project value is commonly attributed directly to poor quality (defects, errors, rework). *[bourton.co.uk]*
- 11%–12% of project cost *[premiercon...onnews.com]*, *[visibuild.com]*
- 20%+ typical delays *[linkedin]*

FACTORS	NEPAL	UK	GLOBAL
COST OVERRUN	18%-41%	5%-12%	5%-10%
COPQ	30%	11%-12%	5% -20%
TIME OVERRUN	28%-150%	20%+	20% -45%

COUNTRIES	COST OF POOR-QUALITY LEVEL
NEPAL	MUCH HIGHER AND VARIABLE (RISK ZONE)
UK	CONTROLLED BUT STILL SIGNIFICANT
GLOBAL	CONSISTENT BASELINE PROBLEM

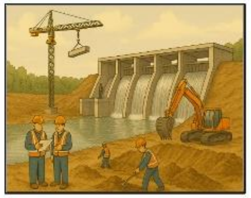
PREVENTION

- Training and Competency
- Proper Planning and Clear method statements
- Design reviews and constructability reviewed
- Follow drawings and specifications
- Check work before moving on
- Report issues early
- Used approved materials
- Take ownership of quality
- Approved Supplier and subcontractor qualification
- Risk assessments and Controls
- Digital tools (BIM, QA tracking System, AI
- Quality management System (QMS)
- Right first-time culture

KEY MESSAGE

- Quality in not a cost-Poor quality is the real cost
- Preventing defects is much cheaper than fixing them
- 1% improvement in quality=billion saved globally

"QUALITY IS DOING THE RIGHT THING WHEN NO ONE IS WATCHING"-HENRY FORD



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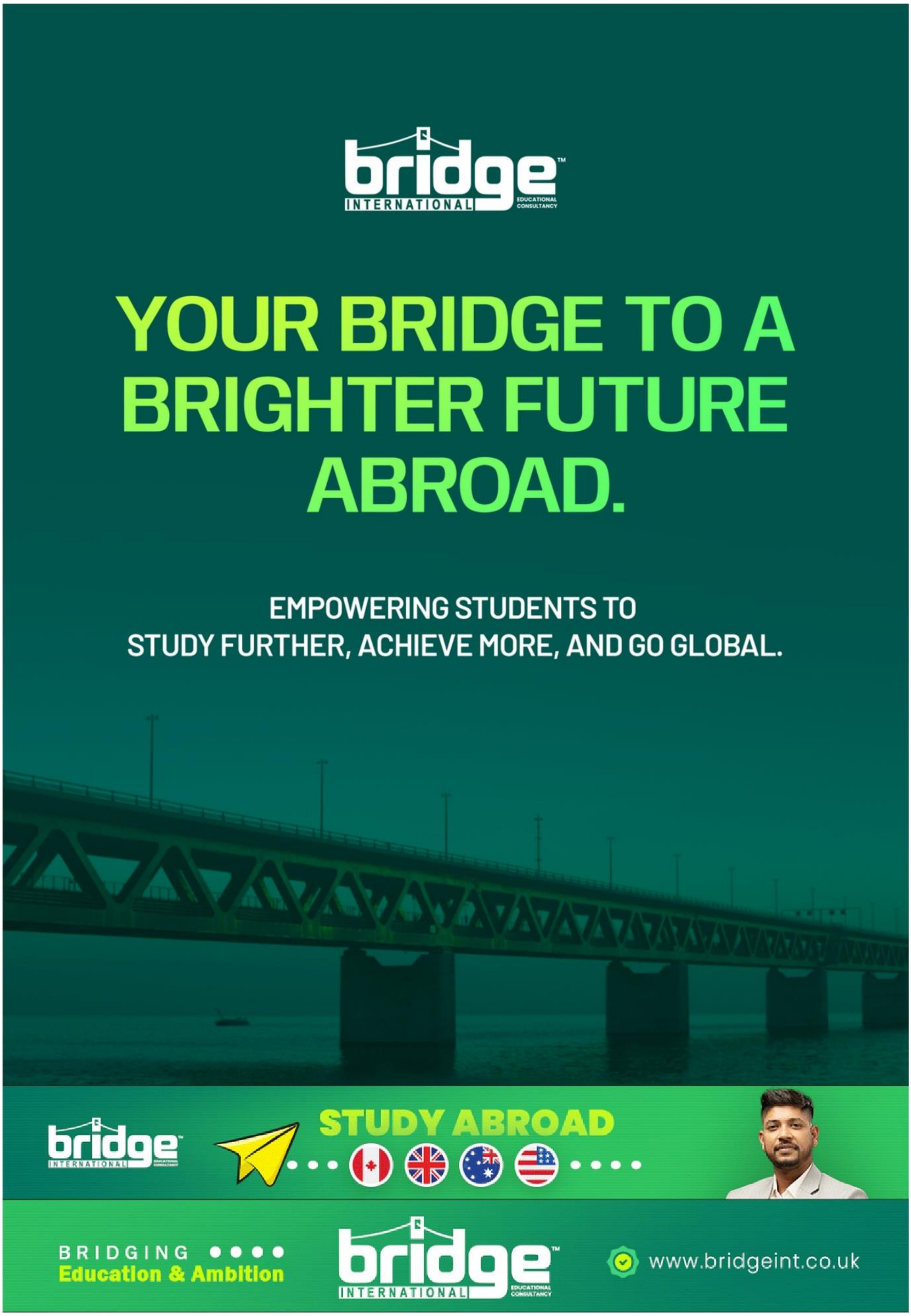
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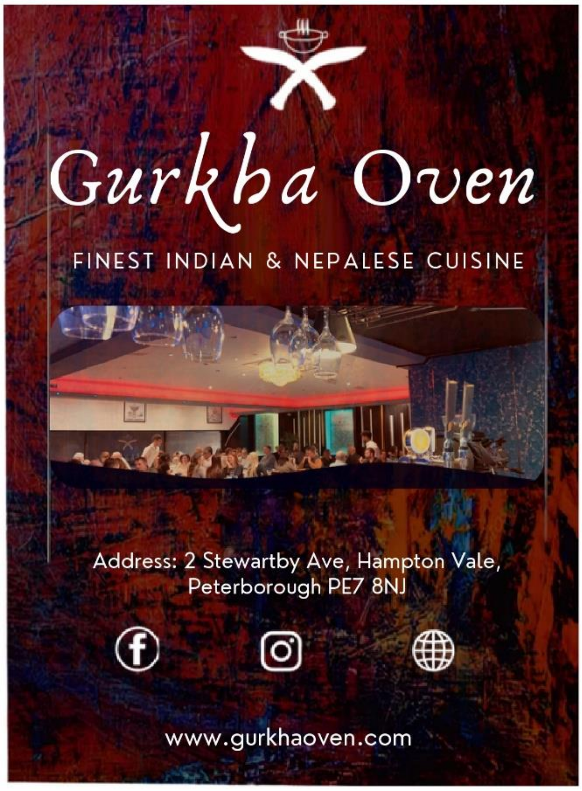

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We would also like to take this opportunity to acknowledge and thank all the organizations, partners, and well-wishers who engaged with us during the planning stages. We truly appreciate your time, the constructive conversations, and your ongoing interest in SONEUK's mission. We highly value these relationships and look forward to staying in touch and exploring collaborative opportunities in our future initiatives.

Thank you all for being a part of the SONEUK journey and for supporting the engineering community.

Past Conferences

11th SONEUK Conference

"Uniting Engineers for Change"