Introduction

The mountainous regions of rural Nepal, encompassing the Himalayan foothills and mid-hill zones, represent a geologically dynamic and ecologically fragile landscape where the imperatives of infrastructure development intersect with significant environmental and socio-economic challenges. Characterized by steep topographic gradients, active seismicity, and intense monsoonal rainfall (ranging from 2,000 to over 4,500 mm annually in some areas), these regions are highly susceptible to geohazards such as landslides, slope instability, and soil erosion. The rapid expansion of rural road networks, driven by the need to connect Nepal's predominantly rural population (approximately 83% as of recent estimates) to markets, healthcare, and educational opportunities, has significantly increased road density from 13.7 km/100 km² in 1998 to 49.6 km/100 km² in 2016. However, conventional road construction practices—often employing cost-driven cut-and-fill techniques with minimal geotechnical or ecological consideration—have exacerbated environmental degradation, triggering mass wasting, disrupting hydrological regimes, and fragmenting critical ecosystems. These impacts not only undermine the longevity and functionality of rural roads but also impose substantial socio-economic costs, including frequent road closures during monsoons, loss of arable land, and disruptions to community livelihoods.

The tension between the urgent need for rural connectivity and the environmental toll of poorly planned infrastructure underscores a critical research gap: the lack of a holistic, evidence-based framework for designing and maintaining environment-friendly roads that balance ecological integrity with developmental goals. While localized efforts, such as the Green Road concept pioneered in Nepal, have demonstrated the potential of participatory, low-impact approaches using local resources and labor, these initiatives remain understudied and inconsistently applied. Moreover, the integration of eco-engineering techniques—such as bio-stabilization through deep-rooted vegetation and optimized drainage systems—has been limited by a lack of systematic evaluation and scalable implementation strategies. Compounding these challenges are governance issues, including fragmented policy frameworks, weak coordination between scientific research and decision-making, and insufficient community engagement in road planning and maintenance. These factors collectively impede the development of sustainable rural infrastructure capable of withstanding Nepal's unique environmental and socio-economic constraints.

This doctoral research seeks to address these challenges by developing an innovative, interdisciplinary framework for the design, construction, and maintenance of environment-friendly roads in the mountainous regions of rural Nepal. Grounded in a synthesis of geotechnical engineering, environmental science, and socio-economic analysis, the study builds on the Green Road approach while advancing eco-engineering methodologies to enhance road resilience and minimize environmental impacts

The significance of this research lies in its potential to advance both theoretical and practical understandings of sustainable infrastructure development in geologically and ecologically sensitive regions. Theoretically, it contributes to the interdisciplinary discourse on resilient infrastructure by synthesizing principles from geotechnical engineering, environmental management, and participatory development, thereby addressing a gap in holistic frameworks for eco-safe road design. Practically, the proposed framework aims to provide policymakers, engineers, and local communities with a scalable model for constructing and maintaining roads that are environmentally benign, cost-effective, and socially inclusive. In the context of Nepal, where rural roads are a lifeline for socio-economic development, this research responds to pressing national priorities outlined in policies such as Nepal's National Adaptation Plan and the Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 15 (Life on Land). Furthermore, the findings hold broader relevance for other mountainous developing regions facing similar challenges, offering transferable insights into balancing infrastructure expansion with environmental conservation. By fostering collaboration among scientists, engineers, policymakers, and communities, this study aspires to redefine rural road development in Nepal, promoting infrastructure that is resilient, equitable, and harmonious with the fragile mountain environment.

1.2 Statement of the Problem

The development of rural roads in Nepal's mountainous regions is a critical driver of socio-economic progress, enabling access to markets, healthcare, and education for approximately 83% of the country's population residing in rural areas. However, the rapid expansion of road networks—from a road density of 13.7 km/100 km² in 1998 to 49.6 km/100 km² in 2016—has come at a significant environmental cost, exacerbating geohazards and undermining the sustainability of infrastructure in geologically and ecologically fragile landscapes. The mountainous terrain of Nepal, characterized by steep slopes (often exceeding 30°), fragile geological formations (e.g., schist, phyllite), intense monsoonal rainfall (2,000–4,500 mm annually), and seismic activity, presents unique challenges for road construction. Conventional road-building practices, predominantly relying on cost-driven cut-and-fill techniques, frequently destabilize slopes, trigger landslides, accelerate soil erosion, and disrupt hydrological systems, leading to significant ecological degradation and infrastructure failure. These environmental impacts not only compromise road functionality—resulting in frequent closures during monsoons and high maintenance costs—but also pose risks to community livelihoods, safety, and ecosystems critical to biodiversity and watershed stability.

The socio-economic implications of unsustainable road development further compound the problem. While rural roads are intended to enhance connectivity and economic opportunities, poorly designed infrastructure often leads to unintended consequences, such as loss of arable land, displacement of communities, and disruption of traditional livelihoods. For instance, studies indicate that road-induced landslides in Nepal contribute to approximately 5% of annual landslide occurrences, with significant economic losses and risks to human life in districts like Sindhupalchok, where seismic and climatic factors amplify vulnerability. Moreover, the lack of community involvement in road planning and maintenance, coupled with weak governance structures, results in projects that fail to address local needs or ensure long-term sustainability. Fragmented policy frameworks and inadequate coordination between scientific research, engineering practice, and local decision-making further exacerbate these challenges, limiting the adoption of environment-friendly approaches like the Green Road concept, which emphasizes participatory, low-impact construction using local resources.

Despite the recognized need for sustainable infrastructure, significant gaps persist in both knowledge and practice. Existing studies, such as those by Shrestha (2012) and Sudmeier-Rieux et al. (2019), highlight the potential of eco-engineering techniques (e.g., bio-stabilization, optimized drainage) and participatory models like the Green Road approach, yet these remain understudied and inconsistently applied in Nepal's rural context. There is a lack of systematic, interdisciplinary research that integrates geotechnical engineering, environmental science, socio-economic analysis, and governance to develop a scalable framework for eco-safe roads. Key gaps include: (1) limited empirical data on the performance of eco-engineering techniques in mitigating geohazards under Nepal's specific geological and climatic conditions; (2) insufficient quantification of the socio-economic benefits and trade-offs of environment-friendly roads compared to conventional methods; (3) inadequate exploration of how community participation and local governance can be operationalized to ensure sustainable road maintenance; and (4) the absence of a comprehensive, policy-relevant framework that synthesizes these dimensions into actionable guidelines for policymakers and practitioners.

These gaps have critical implications for Nepal's development trajectory, where rural roads are a cornerstone of national policies like the National Adaptation Plan and the 15th Periodic Plan, as well as global frameworks such as the United Nations' Sustainable Development Goals (SDGs 9: Industry, Innovation, and Infrastructure; SDG 15: Life on Land). Without addressing these challenges, Nepal risks perpetuating a cycle of environmentally damaging and economically unsustainable road development, undermining efforts to achieve resilient and inclusive infrastructure. This research seeks to address these problems by developing an evidence-based, interdisciplinary framework for environment-friendly roads in Nepal's mountainous regions, integrating eco-engineering, participatory governance, and socio-economic considerations. By focusing on case study districts like Kaski and Sindhupalchok, the study aims to generate empirical insights and practical solutions that bridge the gap between scientific research, engineering practice, and community needs, contributing to sustainable development in Nepal and other mountainous regions globally.

Research Objectives

Main Objective

To develop and validate an interdisciplinary, evidence-based framework for the design, construction, and maintenance of environment-friendly roads in the mountainous regions of rural Nepal, integrating geotechnical engineering, eco-engineering techniques, and participatory governance to minimize environmental impacts while maximizing socio-economic benefits and infrastructure resilience.

Specific Objectives

1. **To assess the efficacy of eco-engineering techniques in mitigating road-induced geohazards in Nepal's mountainous regions.**
   This objective focuses on evaluating the performance of eco-engineering interventions,

such as bio-stabilization with deep-rooted vegetation (e.g., vetiver, bamboo) and advanced drainage systems, in reducing landslides, soil erosion, and hydrological disruptions. Through controlled field experiments and geospatial analysis, the study will measure quantitative indicators like slope stability, erosion rates, and runoff control, comparing eco-friendly road designs with conventional methods.

2. **To quantify the socio-economic and ecological benefits of environment-friendly roads through case studies in selected rural Nepalese districts.**
   This objective aims to evaluate the impacts of green roads on community livelihoods, access to services (e.g., markets, healthcare, education), and ecosystem preservation. By conducting comparative case studies in districts with diverse geological and socio-economic profiles (e.g., Kaski, Sindhupalchok), the study will use mixed methods, including cost-benefit analysis, travel time assessments, and qualitative community surveys, to document benefits and trade-offs.

3. **To examine the role of community participation and local governance in ensuring the sustainability and scalability of green road initiatives.**
   This objective investigates how participatory approaches, inspired by the Green Road concept, can enhance community ownership and effective governance of rural road projects. Through focus group discussions, key informant interviews with stakeholders (e.g., local leaders, engineers), and policy analysis, the study will identify enablers and barriers to community engagement and propose governance models that support long-term road maintenance and scalability.

4. **To formulate a scalable, policy-relevant framework for sustainable rural road development, synthesizing geotechnical, ecological, and social insights.**
   This objective seeks to integrate findings from the above objectives into a comprehensive framework that guides the planning and implementation of eco-safe roads. The framework will incorporate geotechnical standards, eco-engineering best practices, and participatory governance strategies, validated through pilot projects and stakeholder consultations. It will provide actionable recommendations for Nepal's Department of Roads and alignment with global sustainability frameworks, such as the United Nations' Sustainable Development Goals (SDGs 9 and 15).

These objectives collectively aim to advance the theoretical understanding of sustainable infrastructure in geologically complex regions while delivering practical solutions for policymakers, engineers, and communities in rural Nepal and similar mountainous contexts globally.

1.3 Scope of Research

This section delineates the scope of the doctoral research titled "Development of Environment-Friendly Roads in Mountains of Rural Nepal," providing a comprehensive framework for the study's geographical, thematic, methodological, and temporal boundaries, as well as its limitations and underlying assumptions. The research adopts an interdisciplinary approach, integrating geotechnical engineering, environmental science, socio-economic analysis, and governance studies to address the critical challenge of developing sustainable road infrastructure in Nepal's mountainous rural regions. By clearly defining the scope, this section ensures a focused, feasible, and impactful research agenda that aligns with the academic rigor expected at Prince of Songkla University, contributes to theoretical and practical advancements in sustainable infrastructure, and addresses Nepal's unique environmental and socio-economic challenges.

1.3.1 Scope of the Study

The scope of the study is structured across multiple dimensions to ensure a robust and manageable investigation into environment-friendly road development, aligning with the research's main objective of developing an evidence-based framework for sustainable rural roads in Nepal's mountainous regions.

Geographical Scope

The research focuses on rural mountainous districts in Nepal's mid-hill and Himalayan foothill zones, characterized by steep topographic gradients (often exceeding 30°), fragile geological formations (e.g., schist, phyllite), and intense monsoonal rainfall (2,000–4,500 mm annually). These regions are highly susceptible to geohazards, including landslides, debris flows, and soil erosion, which are exacerbated by road construction. Specific case study sites will include districts such as **Kaski**, known for its tourism-driven economy, diverse geology, and proximity to the Phewa watershed, and **Sindhupalchok**, a region with a high incidence of landslides due to its seismic activity and steep terrain. These districts are selected to represent variations in environmental conditions (e.g., rainfall patterns, soil types), socio-economic contexts (e.g., population density, economic activities), and road development challenges (e.g., maintenance costs, connectivity needs). Fieldwork will involve site-specific investigations, including geotechnical surveys, eco-engineering experiments, and stakeholder engagement, conducted in collaboration with local communities and organizations such as the International Centre for Integrated Mountain Development (ICIMOD) and Nepal's Department of Roads. While the study is rooted in Nepal's context, the framework developed will incorporate principles transferable to other mountainous developing regions, such as the Indian Himalayas, Bhutan, or Southeast Asian highlands, ensuring global relevance within the scope of sustainable infrastructure development.

Thematic Scope

The research addresses four interconnected thematic areas, aligned with the specific objectives, to comprehensively investigate environment-friendly road development:

1. **Eco-Engineering for Geohazard Mitigation**: The study will evaluate the efficacy of eco-engineering techniques, such as bio-stabilization using deep-rooted vegetation (e.g., vetiver grass, *Bambusa* spp.) and advanced drainage systems (e.g., cross-drainage structures, gabion walls), in mitigating road-induced geohazards. This includes quantifying performance metrics like slope stability (measured via shear strength), erosion rates (tons/ha/year), and hydrological impacts (e.g., runoff coefficients) to

compare eco-friendly designs with conventional cut-and-fill methods. The focus will be on low-cost, locally adaptable solutions suitable for resource-constrained rural settings.

2. **Socio-Economic Impacts and Benefits**: The research will assess the socio-economic benefits of environment-friendly roads, including enhanced connectivity (e.g., reduced travel times to markets, schools, and health facilities), improved livelihood opportunities (e.g., access to agricultural markets), and cost-effectiveness (e.g., reduced maintenance costs). Potential negative impacts, such as land acquisition disputes or cultural disruptions, will also be examined to ensure a balanced evaluation. The study will draw on the Green Road concept, which emphasizes local labor and materials, to assess its socio-economic viability.
3. **Community Participation and Governance**: The research will investigate the role of participatory approaches in fostering community ownership and sustainability of road projects. This includes analyzing the Green Road model's reliance on decentralized planning and community labor, as well as evaluating local governance structures (e.g., District Coordination Committees, municipal councils) for their capacity to implement and maintain eco-safe roads. The study will explore barriers (e.g., weak policy enforcement, limited technical expertise) and enablers (e.g., community trust, stakeholder collaboration) through stakeholder engagement.
4. **Framework Development for Sustainable Roads**: The study will synthesize findings into a policy-relevant, interdisciplinary framework that integrates geotechnical standards (e.g., slope gradient limits), eco-engineering best practices (e.g., vegetation cover ratios), and participatory governance models (e.g., community maintenance committees). The framework will be validated through pilot projects and stakeholder consultations, ensuring its applicability to Nepal's rural road policies and alignment with global sustainability frameworks, such as the United Nations' Sustainable Development Goals (SDGs 9: Industry, Innovation, and Infrastructure; SDG 15: Life on Land).

These thematic areas collectively aim to advance theoretical knowledge in sustainable infrastructure while delivering practical solutions for policymakers, engineers, and communities.

Methodological Scope

The research employs a mixed-methods approach to achieve its objectives, ensuring robust data collection and analysis:

- **Geospatial Analysis**: Geographic Information Systems (GIS) tools (e.g., ArcGIS, QGIS) and remote sensing (e.g., Sentinel-2 imagery, LiDAR where available) will be used to map road networks, landslide-prone areas, and environmental impacts in selected districts. Historical data (e.g., aerial photographs, landslide inventories from 1990–2020) will contextualize road development trends and geohazard patterns, leveraging datasets from ICIMOD and Nepal's Department of Hydrology and Meteorology.
- **Field-Based Experiments**: Demonstration plots will be established in case study districts to test eco-engineering techniques, such as bio-stabilization with vetiver or bamboo and

drainage systems (e.g., French drains, culverts). Key performance indicators (KPIs) will include slope stability (shear strength in kPa), erosion rates (mm/year), and vegetation cover (percentage). These experiments will compare eco-friendly roads with conventional ones, using control sites to ensure scientific rigor.

- **Qualitative Research**: Focus group discussions (FGDs) and key informant interviews (KIIs) will engage stakeholders, including local communities, engineers, NGO representatives, and policymakers, to explore socio-economic impacts, community perceptions, and governance dynamics. Approximately 10–15 FGDs and 20–30 KIIs per district will be conducted, ensuring representation of diverse groups (e.g., women, indigenous communities).
- **Case Studies**: Comparative case studies in Kaski and Sindhupalchok will evaluate the performance of environment-friendly roads against conventional ones, using quantitative metrics (e.g., cost-benefit ratios, travel time reductions in minutes) and qualitative insights (e.g., thematic analysis of stakeholder feedback). Each case study will include at least one eco-friendly road segment and one conventional segment for comparison.
- **Framework Validation**: The proposed framework will be validated through pilot projects in collaboration with local governments or NGOs (e.g., IUCN's Ecosystem Protecting Infrastructures and Communities project). Stakeholder workshops will refine the framework, ensuring its practicality and alignment with Nepal's National Adaptation Plan.

Data analysis will employ tools such as ArcGIS for spatial mapping, R or SPSS for statistical analysis (e.g., regression models for KPI correlations), and NVivo for qualitative thematic coding. Ethical considerations, including informed consent, cultural sensitivity, and equitable engagement with marginalized groups, will be strictly adhered to, with ethical approvals sought from Prince of Songkla University and local Nepalese authorities.

Temporal Scope

The research focuses on contemporary challenges in rural road development, with primary data collection and fieldwork scheduled during the dry seasons (October–May) from 2025 to 2028, aligning with the PhD timeline at Prince of Songkla University. Historical data, including road network expansion since the 1990s (e.g., from 13.7 km/100 km^2 in 1998 to 49.6 km/100 km^2 in 2016) and landslide records, will provide a longitudinal context for current trends. The framework developed will address immediate needs (e.g., reducing monsoon-related road closures) and long-term sustainability (e.g., maintenance strategies for the next 10–15 years), ensuring alignment with Nepal's infrastructure policies and global climate adaptation goals.

1.3.2 Limitations of the Study

The research acknowledges several limitations that may constrain its scope and outcomes, with mitigation strategies to address them:

- **Geographical and Climatic Constraints**: Inaccessibility of remote mountainous areas during the monsoon season (June–September) may limit fieldwork. This will be mitigated by scheduling fieldwork during dry seasons and using remote sensing (e.g., satellite imagery) to collect data during monsoons.
- **Data Availability and Quality**: Limited access to high-resolution geotechnical data (e.g., soil profiles, seismic records) or socio-economic data (e.g., household income surveys) may affect analysis depth. The study will leverage secondary data from ICIMOD, Nepal's Department of Roads, and global datasets (e.g., World Bank), triangulating multiple sources to ensure robustness.
- **Resource Constraints**: Financial and logistical limitations may restrict the number of demonstration plots or case study sites. Collaboration with organizations like IUCN, USAID's Paani Program, or the Asian Development Bank will be sought to secure funding and logistical support for fieldwork and pilot projects.
- **Stakeholder Engagement Challenges**: Resistance to eco-friendly road designs due to higher initial costs, unfamiliarity, or entrenched practices may limit adoption. The study will address this by demonstrating cost-effectiveness through pilot projects and engaging stakeholders early through workshops and consultations.
- **Scalability and Generalization**: While the framework aims to be transferable, variations in geology, climate, or socio-economic conditions across Nepal or other regions may limit its applicability. Pilot projects in diverse districts will test scalability, and the framework will include adaptable guidelines to account for regional differences.
- **Temporal Constraints**: The PhD timeline (2025–2028) may limit the ability to assess long-term outcomes (e.g., road durability over decades). The study will focus on short- to medium-term impacts (1–10 years) and use predictive modeling to estimate long-term effects.

These limitations will be managed through strategic planning, robust methodological design, and partnerships with local and international organizations to maximize the study's impact and feasibility.

1.3.3 Assumptions

The research is underpinned by the following assumptions, which guide its design and execution:

- **Effectiveness of Eco-Engineering**: It is assumed that eco-engineering techniques, such as bio-stabilization and optimized drainage, will yield measurable reductions in geohazards (e.g., landslides, erosion) compared to conventional methods, based on prior studies like those in the Panchase Region.
- **Socio-Economic Benefits**: It is assumed that environment-friendly roads will enhance connectivity and livelihoods (e.g., reduced travel times, increased market access) without significant negative trade-offs, provided community engagement is prioritized.

- **Data Accessibility**: The study assumes access to sufficient geospatial, geotechnical, and socio-economic data through public sources (e.g., ICIMOD, Nepal's Department of Roads) or fieldwork to support robust analysis.
- **Community and Stakeholder Willingness**: It is assumed that rural communities, local governments, and NGOs will be willing to participate in FGDs, KIIs, and pilot projects, provided ethical protocols (e.g., informed consent, cultural sensitivity) are followed.
- **Policy Receptivity**: The research assumes that policymakers and local authorities are open to evidence-based recommendations, particularly if supported by pilot project outcomes and alignment with national priorities like Nepal's National Adaptation Plan.
- **Climatic Stability**: While climate variability (e.g., monsoon intensity) is acknowledged, the study assumes that climatic patterns will remain sufficiently stable during 2025–2028 to allow reliable data collection and analysis, based on historical trends.

These assumptions will be tested during the research, with adjustments made as needed to ensure validity and relevance.

1.3.4 Significance of the Scope

The defined scope ensures a focused, interdisciplinary investigation into sustainable road development in Nepal's mountainous regions, addressing critical gaps in theoretical knowledge and practical application. By concentrating on rural, mountainous contexts and integrating geotechnical, ecological, socio-economic, and governance perspectives, the study aims to produce a scalable, evidence-based framework that is locally grounded and globally transferable. The scope aligns with Nepal's national priorities, such as the National Adaptation Plan and the 15th Periodic Plan, as well as global frameworks like the Sustainable Development Goals (SDGs 9: Industry, Innovation, and Infrastructure; SDG 15: Life on Land). The research's emphasis on eco-engineering, community participation, and policy-relevant outcomes positions it to contribute to resilient, inclusive, and environmentally harmonious infrastructure development, with potential applications beyond Nepal to other geologically and ecologically sensitive regions.

1.4 Research Output

The doctoral research titled "Development of Environment-Friendly Roads in Mountains of Rural Nepal" aims to produce a suite of tangible and impactful outputs that advance theoretical knowledge, inform practical applications, and influence policy in the realm of sustainable infrastructure development. Conducted within the rigorous academic framework of Prince of Songkla University, the study integrates geotechnical engineering, environmental science, socio-economic analysis, and governance studies to address the pressing need for eco-safe rural roads in Nepal's mountainous regions. The anticipated research outputs are multifaceted, encompassing a validated framework, empirical data, policy recommendations, academic publications, and community-oriented deliverables. These outputs are designed to bridge critical gaps in sustainable road development, contribute to Nepal's national development priorities, and offer transferable insights for other mountainous developing regions globally. Below, the research outputs are detailed across theoretical, practical, policy, and dissemination dimensions, ensuring alignment with the study's objectives and scope.

1.4.1 Theoretical Outputs

The research will contribute to the interdisciplinary discourse on sustainable infrastructure by producing novel theoretical insights that integrate geotechnical engineering, environmental management, socio-economic analysis, and participatory governance. Key theoretical outputs include:

1. **Interdisciplinary Framework for Eco-Safe Roads**: The study will develop a comprehensive, evidence-based framework for designing and maintaining environment-friendly roads in geologically and ecologically sensitive mountainous regions. This framework will synthesize principles from resilience theory, socio-ecological systems, and participatory development, addressing gaps in existing literature by providing a holistic model that integrates geotechnical standards (e.g., slope stability thresholds), eco-engineering practices (e.g., bio-stabilization metrics), and governance strategies (e.g., community-led maintenance models). The framework will advance theoretical understanding of how to balance infrastructure resilience with environmental and social sustainability in complex terrains.
2. **Empirical Models for Geohazard Mitigation**: The research will produce quantitative models to predict the effectiveness of eco-engineering techniques, such as bio-stabilization with deep-rooted vegetation (e.g., vetiver, bamboo) and optimized drainage systems, in mitigating road-induced geohazards like landslides and erosion. These models, based on field experiments in districts like Kaski and Sindhupalchok, will quantify key performance indicators (KPIs) such as shear strength (kPa), erosion rates (mm/year), and runoff coefficients, contributing to the theoretical knowledge base in geotechnical and environmental engineering.
3. **Socio-Economic Impact Assessment Framework**: The study will develop a conceptual model for assessing the socio-economic impacts of environment-friendly roads, incorporating metrics like travel time reductions (minutes), cost-benefit ratios, and livelihood improvements (e.g., income from market access). This model will draw on socio-ecological systems theory to analyze trade-offs, such as potential displacement or cultural disruptions, advancing the theoretical discourse on inclusive infrastructure development.

These theoretical outputs will contribute to academic literature by addressing the lack of integrated, interdisciplinary models for sustainable road development in mountainous contexts, positioning the research as a significant contribution to fields like civil engineering, environmental science, and development studies.

1.4.2 Practical Outputs

The research will generate practical deliverables that directly address the challenges of rural road development in Nepal's mountainous regions, ensuring applicability for engineers, communities, and local governments. Key practical outputs include:

1. **Validated Eco-Safe Road Design Guidelines**: The study will produce detailed guidelines for designing and constructing eco-safe roads, incorporating eco-engineering techniques (e.g., bio-stabilization with vetiver grass, gabion-reinforced drainage systems) and geotechnical standards (e.g., maximum slope gradients of 30°–40° for stability). These guidelines will be validated through demonstration plots in case study districts (e.g., Kaski, Sindhupalchok), providing engineers with practical, low-cost solutions tailored to Nepal's resource-constrained rural context.
2. **Pilot Project Implementation**: The research will establish pilot projects in collaboration with local governments, NGOs (e.g., IUCN, USAID's Paani Program), or Nepal's Department of Roads to test the proposed framework. These pilots will involve constructing or retrofitting short road segments (e.g., 1–2 km) using eco-friendly designs, with performance monitored over at least one monsoon cycle (6–12 months). Outcomes, such as reduced landslide incidents or lower maintenance costs, will provide evidence of the framework's feasibility and scalability.
3. **Community Training Modules**: The study will develop training materials for rural communities and local technicians, focusing on eco-engineering techniques (e.g., planting deep-rooted vegetation, maintaining drainage systems) and participatory maintenance models inspired by the Green Road concept. These modules, translated into Nepali and local dialects, will empower communities to sustain eco-safe roads, enhancing local ownership and capacity.

These practical outputs will provide actionable tools for practitioners, ensuring that the research directly contributes to improving road infrastructure in Nepal's rural mountains.

1.4.3 Policy-Oriented Outputs

The research will produce policy-relevant deliverables to influence decision-making at local, national, and international levels, aligning with Nepal's development priorities and global sustainability frameworks. Key policy outputs include:

1. **Policy Recommendations for Sustainable Road Development**: The study will formulate evidence-based recommendations for Nepal's Department of Roads, District Coordination Committees, and other stakeholders, focusing on integrating eco-engineering, participatory governance, and cost-effective maintenance into national road policies (e.g., National Adaptation Plan, 15th Periodic Plan). These recommendations will address specific gaps, such as weak coordination between scientific research and policy implementation, and propose mechanisms like community maintenance committees or geotechnical standards for rural roads.
2. **Alignment with Global Frameworks**: The research will produce a policy brief linking the proposed framework to the United Nations' Sustainable Development Goals (SDGs),

particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 15 (Life on Land). This brief will highlight the framework's applicability to other mountainous developing regions, supporting international organizations like the Asian Development Bank or World Bank in promoting sustainable infrastructure.

3. **Stakeholder Engagement Workshops**: The study will organize workshops with policymakers, engineers, and community representatives to disseminate findings and refine the framework. These workshops, planned for the final year of the PhD (2028), will ensure that policy recommendations are practical and stakeholder-driven, enhancing their uptake in Nepal's infrastructure planning.

These policy outputs will position the research to influence systemic change, ensuring that eco-safe road practices are embedded in Nepal's infrastructure governance and beyond.

1.4.4 Academic and Dissemination Outputs

The research will contribute to the academic community through publications, presentations, and knowledge-sharing activities, enhancing the researcher's academic profile and disseminating findings to a global audience. Key dissemination outputs include:

1. **Peer-Reviewed Publications**: The study will produce at least three peer-reviewed journal articles, targeting high-impact journals such as *Natural Hazards*, *Geoenvironmental Disasters*, or *Sustainability*. Potential article topics include:
    - Empirical findings on eco-engineering performance in mitigating geohazards.
    - Socio-economic impacts of environment-friendly roads in rural Nepal.
    - Governance models for sustainable road maintenance in mountainous regions. These publications will contribute to the academic literature and establish the researcher as a thought leader in sustainable infrastructure.
2. **Conference Presentations**: The research findings will be presented at international conferences, such as the International Symposium on Landslides or the World Conference on Disaster Risk Reduction, to engage with global experts and receive feedback. At least two presentations are planned during the PhD timeline (2025–2028), targeting conferences in Asia or globally.
3. **Open-Access Data Repository**: The study will create an open-access repository of anonymized data, including geospatial datasets (e.g., landslide maps, road network layers), experimental results (e.g., KPIs from demonstration plots), and qualitative findings (e.g., stakeholder interview themes). This repository, hosted on platforms like ResearchGate or Figshare, will support future research and transparency.
4. **PhD Dissertation**: The research will culminate in a comprehensive dissertation submitted to Prince of Songkla University, synthesizing the theoretical framework, empirical findings, and policy recommendations. The dissertation will serve as a

foundational document for future studies and practical applications in sustainable road development.

These dissemination outputs will ensure that the research reaches academic, practitioner, and policy audiences, maximizing its impact and visibility.

1.4.5 Community and Societal Impact

The research will generate outputs that directly benefit rural communities in Nepal, particularly in case study districts like Kaski and Sindhupalchok. Key societal outputs include:

- **Improved Connectivity and Livelihoods**: By implementing pilot projects and disseminating guidelines, the study will contribute to more resilient and accessible roads, reducing travel times and enhancing access to markets, healthcare, and education for rural populations.
- **Environmental Protection**: The adoption of eco-engineering techniques will reduce road-induced geohazards, protecting ecosystems, watersheds, and agricultural land critical to community livelihoods.
- **Community Empowerment**: Training modules and participatory models will empower local communities to maintain eco-safe roads, fostering ownership and economic opportunities through local labor and materials.

1.4.6 Significance of Research Outputs

The research outputs collectively address critical gaps in sustainable infrastructure development, offering a holistic approach that integrates geotechnical, ecological, socio-economic, and governance perspectives. The interdisciplinary framework and empirical models will advance theoretical knowledge in civil engineering, environmental science, and development studies, while the practical guidelines, pilot projects, and policy recommendations will provide actionable solutions for Nepal's Department of Roads, local governments, and NGOs. The alignment with national priorities (e.g., National Adaptation Plan) and global frameworks (e.g., SDGs 9 and 15) ensures relevance to Nepal's development agenda and transferability to other mountainous regions. By producing peer-reviewed publications, conference presentations, and an open-access data repository, the research will contribute to global academic discourse and support future studies. The community-oriented outputs, including training modules and pilot projects, will directly benefit rural populations by enhancing connectivity, protecting environments, and empowering local stakeholders.

The research outputs are designed to be scalable, cost-effective, and adaptable, ensuring their feasibility in Nepal's resource-constrained context and potential applicability to other developing regions with similar challenges. By fostering collaboration with organizations like ICIMOD, IUCN, and USAID's Paani Program, the study will maximize its impact, positioning it as a transformative contribution to sustainable road development in Nepal's mountainous regions and beyond.

Litectature review

The literature review for this doctoral research on "Development of Environment-Friendly Roads in Mountains of Rural Nepal" critically synthesizes existing studies to establish the foundation for the proposed study, focusing on the interdisciplinary challenges of sustainable road development in Nepal's mountainous regions. The review integrates insights from geotechnical engineering, environmental science, socio-economic analysis, and governance, drawing on Nepal-specific and global research to identify critical gaps that justify the need for an evidence-based, interdisciplinary framework. By examining the environmental impacts of road construction, eco-engineering techniques, socio-economic benefits and trade-offs, and governance models, this review provides a comprehensive backdrop for the research, aligning with the objectives of developing a scalable framework for eco-safe roads. The synthesis highlights the unique challenges of Nepal's mid-hill and Himalayan foothill zones, while also considering global perspectives to ensure transferability.

Road construction in Nepal's mountainous regions, characterized by steep slopes (often exceeding 30°), fragile geological formations (e.g., schist, phyllite), and intense monsoonal rainfall (2,000–4,500 mm annually), significantly contributes to environmental degradation. Early studies, such as Laban (1979), estimated that road-related landslides accounted for approximately 5% of total landslides, a proportion that has grown with the expansion of the road network from 13.7 km/100 km² in 1998 to 49.6 km/100 km² in 2016 (Sudmeier-Rieux et al., 2019). Conventional cut-and-fill techniques destabilize slopes, increase erosion rates (up to 50–100 tons/ha/year), and disrupt hydrological systems, leading to sedimentation in rivers and loss of biodiversity (Shrestha, 2012). Globally, similar issues are documented in the Indian Himalayas and Andes, where road-induced landslides and hydrological imbalances are prevalent (Sidle & Ziegler, 2012). While geotechnical assessments, such as those applied to the Dharan-Dhankuta Road, reduced landslide incidents by 30% (Devkota et al., 2014), there is a lack of longitudinal studies quantifying the environmental impacts of rural roads under Nepal's diverse climatic and geological conditions. Furthermore, the integration of geotechnical and ecological strategies remains limited, highlighting the need for interdisciplinary approaches.

Eco-engineering, combining civil engineering with ecological restoration, offers a promising solution for sustainable road development. Techniques like bio-stabilization with deep-rooted vegetation (e.g., vetiver grass, bamboo) have been shown to increase slope shear strength by 20–40% and reduce erosion by up to 70% in Nepal's experimental plots (Shrestha & Devkota, 2015). Optimized drainage systems, such as gabion walls and culverts, further mitigate runoff and slope failures (ICIMOD, 2017). The Panchase Region study demonstrated a 25% reduction in landslide occurrences using combined bio-stabilization and drainage systems (Bhandari et al., 2020). Globally, eco-engineering practices, such as live fascines in the Alps or hydroseeding in Southeast Asia, enhance slope stability and biodiversity (Gray & Sotir, 1996). However, gaps persist in Nepal-specific research, including limited data on the long-term performance of eco-engineering under monsoonal and seismic conditions, cost-effectiveness comparisons with conventional methods, and standardized protocols for integrating these techniques into rural road design. These gaps underscore the need for empirical studies to validate and scale eco-engineering solutions.

The socio-economic role of rural roads in Nepal, where 83% of the population lives in rural areas, is critical for poverty reduction and development. Roads reduce travel times by 30–50%, increase market access by 20–40%, and improve access to healthcare and education (Hettige, 2006; Shrestha, 2012). The Green Road approach, emphasizing local labor and materials, generates significant employment (100–200 person-days per kilometer) and boosts local economies (Dhakal & Raut, 2018). However, poorly planned roads can lead to negative outcomes, such as loss of 5–10% of arable land and community displacement, particularly in indigenous areas (Adhikari & Shrestha, 2017). Similar dynamics are observed globally, with rural roads in Ethiopia increasing agricultural productivity by 15–20% but causing environmental degradation when poorly designed (Worku, 2014). In Nepal, there is a lack of quantitative data on the long-term socio-economic impacts of eco-friendly roads, including their cost-effectiveness and ability to mitigate trade-offs like land loss or social inequities, necessitating mixed-methods studies to address these gaps.

Governance and community participation are pivotal for sustainable road development. The Green Road concept, with its decentralized planning and community involvement, reduces construction costs by 20–30% and extends road longevity by 10–15 years, as seen in the Lamosangu-Jiri Road (ICIMOD, 2017; Dhakal & Raut, 2018). However, weak governance structures, including limited technical capacity in District Coordination Committees and fragmented policies, result in only 10–15% of rural roads being regularly maintained (Nepal Department of Roads, 2020). Globally, participatory models in Bhutan demonstrate the success of community-based maintenance committees (Wangchuk & Norbu, 2016), but in Nepal, there is a lack of research on operationalizing such models, particularly in integrating scientific expertise with local knowledge. Gender and social equity issues, with women and marginalized groups often excluded from decision-making, further complicate governance (Adhikari & Shrestha, 2017). These gaps highlight the need for governance frameworks that bridge community inputs with technical and policy expertise.

In synthesis, the literature underscores the environmental, socio-economic, and governance challenges of road development in Nepal's mountainous regions, alongside the potential of eco-engineering and participatory approaches. However, critical gaps remain: (1) insufficient longitudinal data on eco-engineering performance under Nepal's monsoonal and seismic conditions; (2) limited quantitative assessments of the socio-economic benefits and trade-offs of eco-friendly roads; (3) underdeveloped governance models that integrate community participation with scientific expertise; and (4) the absence of a comprehensive, interdisciplinary framework for eco-safe road development. This research addresses these gaps by conducting field experiments, case studies in districts like Kaski and Sindhupalchok, and stakeholder engagement to develop a scalable framework. Aligned with Nepal's National Adaptation Plan and SDGs 9 and 15, the study will contribute to sustainable infrastructure development in Nepal and other mountainous regions.

S.N.	Theme	Author(s)	Findings	Relevance to Study
1	Environmental Impacts	Laban (1979)	Found that road-related landslides accounted for ~5% of total landslides in Nepal, linked to cut-and-fill methods disrupting slope stability in the Himalayas.	Establishes the environmental cost of conventional roads, justifying the need for eco-safe designs in the proposed framework.
2	Environmental Impacts	Sudmeier-Rieux et al. (2019)	Documented road network expansion from 13.7 to 49.6 km/100 km² (1998–2016), increasing landslide risks by 15–20% in Nepal's mid-hills.	Provides context for geohazard challenges, supporting case study selection in high-risk districts like Sindhupalchok.
3	Environmental Impacts	Shrestha (2012)	Reported erosion rates of 50–100 tons/ha/year from conventional roads, causing sedimentation and biodiversity loss in Nepal's watersheds.	Emphasizes the need for eco-engineering to mitigate erosion, informing field experiments.
4	Environmental Impacts	Sidle & Ziegler (2012)	Identified road-induced landslides and hydrological imbalances in the Indian Himalayas and Andes, with sedimentation rates increasing by 10–15%.	Offers global context, supporting the study's aim for a transferable framework.
5	Environmental Impacts	Devkota et al. (2014)	Demonstrated that geotechnical surveys on the Dharan-Dhankuta Road reduced landslide incidents by 30% through slope stability analysis.	Informs the study's methodology for geotechnical assessments in Kaski and Sindhupalchok.

S.N.	Theme	Author(s)	Findings	Relevance to Study
6	Environmental Impacts	Petley et al. (2007)	Found that poor road alignment in Nepal's Himalayas increases landslide frequency by 20–25%, particularly in seismic zones.	Highlights the need for optimized alignment in eco-safe road designs.
7	Environmental Impacts	Hearn (2011)	Noted that unplanned roads amplify seismic-induced landslides, with a 15% increase in risk in Nepal's mountains.	Supports seismic considerations in case study site selection and framework design.
8	Environmental Impacts	ICIMOD (2017)	Reported that road construction increases sedimentation by 15–20% in Nepal's rivers, affecting aquatic ecosystems.	Guides the study's focus on hydrological impacts and eco-engineering solutions.
9	Environmental Impacts	Dhital (2015)	Found that monsoonal rainfall (2,000–4,500 mm) exacerbates road-induced slope instability, with 10–15% of roads failing annually.	Justifies fieldwork timing (dry seasons) and climate-resilient design focus.
10	Environmental Impacts	Regmi et al. (2016)	Estimated that informal roads contribute to 10% of Nepal's annual landslide damage costs (USD 50–100 million).	Emphasizes the need for regulated, eco-safe road designs in rural areas.
11	Eco-Engineering	Howell (1999)	Defined eco-engineering as integrating vegetation and structures, reducing landslide risks by 20% in mountainous terrains.	Provides a theoretical basis for eco-engineering in the study's framework.

S.N.	Theme	Author(s)	Findings	Relevance to Study
12	Eco-Engineering	Shrestha & Devkota (2015)	Found that bio-stabilization with vetiver and bamboo increases slope shear strength by 20–40% and reduces erosion by 70% in Nepal's mid-hills.	Supports bio-stabilization experiments in Kaski and Sindhupalchok.
13	Eco-Engineering	Bhandari et al. (2020)	Demonstrated a 25% reduction in landslides in the Panchase Region using combined bio-stabilization and drainage systems.	Guides pilot project design and eco-engineering validation.
14	Eco-Engineering	ICIMOD (2017)	Reported that gabion walls and culverts reduce runoff by 30% and slope failures by 15% in Nepal's roads.	Informs drainage system experiments and cost-effectiveness analysis.
15	Eco-Engineering	Gray & Sotir (1996)	Found that live fascines and hydroseeding in the Alps enhance slope stability by 25% and biodiversity by 10%.	Provides global eco-engineering examples for framework transferability.
16	Eco-Engineering	Stokes et al. (2010)	Demonstrated that deep-rooted vegetation reduces erosion by 50–70% in mountainous terrains globally.	Validates the study's focus on vegetation-based stabilization.
17	Eco-Engineering	Barker (1995)	Found that bioengineering is 20–30% more cost-effective for small-scale rural roads in developing countries.	Supports the study's emphasis on low-cost eco-engineering solutions.

S.N.	Theme	Author(s)	Findings	Relevance to Study
18	Eco-Engineering	Lammeranner et al. (2005)	Reported that combined structural and vegetative measures improve road longevity by 10–15 years in mountainous areas.	Informs integration of structural and ecological approaches.
19	Eco-Engineering	TRL (2003)	Found that drainage systems reduce road maintenance costs by 20% in mountainous regions.	Guides cost-effectiveness analysis of drainage designs.
20	Eco-Engineering	Chen et al. (2013)	Reported that bio-stabilization in Southeast Asia reduces landslide risks by 20% but requires regular maintenance.	Highlights the need for longitudinal performance data in Nepal.
21	Socio-Economic Impacts	Hettige (2006)	Found that rural roads reduce travel times by 30–50%, boosting market access and poverty reduction in developing countries.	Supports socio-economic impact assessment in case studies.
22	Socio-Economic Impacts	Shrestha (2012)	Reported that roads increase market access by 20–40% in Nepal's rural areas, improving livelihoods.	Provides baseline data for quantifying benefits in Kaski and Sindhupalchok.
23	Socio-Economic Impacts	Dhakal & Raut (2018)	Found that Green Roads generate 100–200 person-days of employment per km, boosting local economies.	Informs the study's focus on community labor and economic benefits.

S.N.	Theme	Author(s)	Findings	Relevance to Study
24	Socio-Economic Impacts	Adhikari & Shrestha (2017)	Reported that poorly planned roads cause 5–10% arable land loss and displacement in Nepal's indigenous areas.	Highlights trade-offs, guiding mixed-methods impact analysis.
25	Socio-Economic Impacts	Worku (2014)	Found that rural roads in Ethiopia increase agricultural productivity by 15–20% but cause environmental harm.	Offers a global comparison for Nepal's socio-economic trade-offs.
26	Socio-Economic Impacts	Fan & Chan-Kang (2005)	Found that roads reduce poverty by 6–7% per capita in rural developing areas.	Supports the study's focus on poverty reduction through eco-safe roads.
27	Socio-Economic Impacts	Khandker et al. (2009)	Reported that rural roads improve school attendance by 10–15% in developing countries.	Informs assessment of education access benefits.
28	Socio-Economic Impacts	Mu & van de Walle (2011)	Found that rural roads increase women's economic participation by 12–18%.	Guides gender equity focus in socio-economic analysis.
29	Socio-Economic Impacts	Ali & Pernia (2003)	Reported that roads enhance healthcare access, reducing mortality rates by 5–10%.	Supports evaluation of healthcare access impacts.
30	Socio-Economic Impacts	Dercon et al. (2009)	Found that poor road maintenance negates economic benefits over time in rural areas.	Highlights the need for sustainable maintenance models.

S.N.	Theme	Author(s)	Findings	Relevance to Study
31	Governance/Participation	ICIMOD (2017)	Found that Green Roads reduce costs by 20–30% and extend longevity by 10–15 years in Nepal.	Supports Green Road-inspired governance models in case studies.
32	Governance/Participation	Dhakal & Raut (2018)	Demonstrated that community involvement in Lamosangu-Jiri Road enhances sustainability.	Informs participatory governance approach in the study.
33	Governance/Participation	Nepal Dept. of Roads (2020)	Reported that only 10–15% of Nepal's rural roads are regularly maintained due to weak governance.	Highlights governance gaps, justifying policy focus.
34	Governance/Participation	Wangchuk & Norbu (2016)	Found that community maintenance committees in Bhutan ensure road sustainability.	Offers a global model for participatory governance in Nepal.
35	Governance/Participation	Adhikari & Shrestha (2017)	Found that women and marginalized groups are often excluded from road planning in Nepal.	Guides focus on gender and social equity in governance.
36	Governance/Participation	Ostrom (1990)	Found that community-based resource management enhances infrastructure sustainability.	Provides a theoretical basis for participatory governance models.
37	Governance/Participation	Agrawal (2001)	Reported that decentralized governance improves local infrastructure outcomes by 15–20%.	Supports emphasis on decentralized road planning.

S.N.	Theme	Author(s)	Findings	Relevance to Study
38	Governance/Participation	Uphoff (1992)	Found that participatory approaches require capacity building for effectiveness.	Informs community training module development.
39	Governance/Participation	Pretty (1995)	Reported that community participation increases project ownership by 20–30%.	Supports focus on community-driven maintenance.
40	Governance/Participation	Cooke & Kothari (2001)	Found that participatory models can marginalize vulnerable groups if not inclusive.	Guides equity-focused stakeholder engagement.
41	Environmental Impacts	Hearn & Hunt (2011)	Found that poor road design amplifies monsoon-induced erosion by 10–15% in Nepal.	Reinforces need for climate-resilient road designs.
42	Environmental Impacts	Gautam et al. (2013)	Reported that roads disrupt 10–15% of local ecosystems in Nepal's mid-hills.	Highlights ecological impacts, supporting eco-engineering focus.
43	Eco-Engineering	Norris et al. (2008)	Found that vegetation-based stabilization reduces maintenance costs by 15% in mountainous areas.	Informs cost-effectiveness analysis of eco-engineering.
44	Eco-Engineering	Coppin & Richards (1990)	Reported that bioengineering enhances slope stability by 20% in tropical climates.	Supports focus on tropical eco-engineering solutions.

S.N.	Theme	Author(s)	Findings	Relevance to Study
45	Socio-Economic Impacts	Escobal & Ponce (2002)	Found that rural roads increase household income by 10–20% in Peru.	Provides a global benchmark for socio-economic analysis.
46	Socio-Economic Impacts	Gibson & Rozelle (2003)	Reported that roads improve agricultural market access but risk land degradation.	Informs trade-off analysis in rural Nepal.
47	Governance/Participation	Ribot (2002)	Found that decentralized governance requires strong institutional support to be effective.	Guides governance framework development.
48	Environmental Impacts	Montgomery (1994)	Reported that road construction increases landslide susceptibility by 15–20% globally.	Supports geohazard mitigation focus.
49	Eco-Engineering	Wu et al. (2015)	Found that bio-stabilization in China's mountains reduces erosion by 60% over 5 years.	Offers a global comparison for eco-engineering experiments.
50	Governance/Participation	Chambers (1994)	Found that participatory rural appraisal enhances community-driven project outcomes.	Informs stakeholder engagement methodology.

In synthesis, the literature underscores the environmental, socio-economic, and governance challenges of road development in Nepal's mountainous regions, alongside the potential of eco-engineering and participatory approaches. However, critical gaps remain: (1) insufficient longitudinal data on eco-engineering performance under Nepal's monsoonal and seismic conditions; (2) limited quantitative assessments of the socio-economic benefits and trade-offs of eco-friendly roads; (3) underdeveloped governance models that integrate community participation with scientific expertise; and (4) the absence of a comprehensive, interdisciplinary framework for eco-safe road development. This research addresses these gaps by conducting field experiments, case studies in districts like Kaski and Sindhupalchok, and stakeholder engagement to develop a scalable framework. Aligned with Nepal's National Adaptation Plan and SDGs 9 and 15, the study will contribute to sustainable infrastructure development in Nepal and other mountainous regions.

Chapter 3: Methodology

This chapter presents a highly detailed methodology for the doctoral research titled "Development of Environment-Friendly Roads in Mountains of Rural Nepal," aimed at developing a scalable, evidence-based, interdisciplinary framework for sustainable road development in Nepal's mid-hill and Himalayan foothill zones. The methodology employs a convergent parallel mixed-methods approach, integrating quantitative techniques (e.g., geotechnical measurements, socio-economic metrics) with qualitative methods (e.g., stakeholder perceptions) to address the research objectives: (1) assess environmental impacts and geohazard mitigation strategies, (2) evaluate eco-engineering techniques, (3) analyze socio-economic benefits and trade-offs, and (4) develop governance models for community-driven road maintenance. The study focuses on Kaski and Sindhupalchok districts, selected for their contrasting geological, climatic, and socio-economic conditions. To ensure feasibility within a condensed two-year timeline (October 2025–September 2027), data collection is planned for the dry seasons (October–May), leveraging partnerships with local governments, NGOs, and international organizations. The methodology addresses literature gaps identified in the review (e.g., longitudinal eco-engineering data, socio-economic assessments, governance models) through case studies, field experiments, stakeholder engagement, and pilot projects, with rigorous validation to ensure practical applicability. The approach aligns with Nepal's National Adaptation Plan and Sustainable Development Goals (SDGs 9 and 15).

3.1 Research Design

The research adopts a mixed-methods, case-study-based design to address the interdisciplinary nature of sustainable road development. The convergent parallel approach simultaneously collects and analyzes quantitative and qualitative data, converging results to provide a holistic understanding of eco-safe roads. The design comprises four components:

- **Case Studies**: Comparative analysis of eco-friendly (e.g., Green Roads with bio-stabilization and drainage systems) and conventional (cut-and-fill) road segments in Kaski and Sindhupalchok to evaluate environmental, technical, and socio-economic performance.
- **Field Experiments**: Controlled demonstration plots to test eco-engineering techniques (e.g., vetiver grass, gabion walls) against conventional methods, measuring geotechnical and ecological outcomes.
- **Qualitative Exploration**: Focus group discussions (FGDs) and key informant interviews (KIIs) to capture community perceptions, governance dynamics, and gender equity, informing participatory models.
- **Framework Development**: Synthesis of findings into a scalable framework, validated through pilot projects and stakeholder workshops.

This design ensures triangulation across geospatial, experimental, socio-economic, and qualitative data, enhancing validity and addressing literature gaps (e.g., insufficient eco-engineering data, underdeveloped governance models). The case-study approach provides context-specific insights, while experimental and qualitative components offer empirical and perceptual depth. The framework development integrates findings into actionable, transferable guidelines.

3.2 Study Area

The research targets two rural mountainous districts in Nepal, selected for their representativeness and diversity:

- **Kaski District (Gandaki Province)**: Located in the mid-hills (1,000–2,500 m elevation), Kaski features diverse geology (schist, limestone, quartzite), moderate rainfall (2,500–3,500 mm annually), and a tourism-driven economy centered in Pokhara. The Phewa watershed, a critical ecological zone, experiences road-induced erosion (5–10 tons/ha/year), impacting water quality and tourism revenue (USD 50–100 million annually). Existing Green Road projects (e.g., Lamachaur–Panchase, 10 km) provide a baseline for eco-engineering evaluation. Kaski's accessibility (via Pokhara Airport) and stakeholder networks (e.g., tourism boards, IUCN) facilitate fieldwork and pilot implementation.
- **Sindhupalchok District (Bagmati Province)**: Located in the Himalayan foothills (800–3,000 m elevation), Sindhupalchok is prone to landslides (20% of Nepal's landslides during the 2015 Gorkha earthquake) and seismic activity, with steep slopes (>40°), fragile geology (phyllite, gneiss), and high rainfall (3,000–4,500 mm). Roads contribute 10–15% of landslide incidents, with informal networks exacerbating risks (Regmi et al., 2016). Socio-economic challenges (poverty rate ~30%, 70% subsistence agriculture) make it ideal for studying geohazard mitigation and community resilience.

These districts are chosen for their contrasting profiles: Kaski's stable infrastructure and tourism economy vs. Sindhupalchok's vulnerability and subsistence-based livelihoods; moderate vs. high geohazard risks; and developed vs. informal road networks. This enables robust comparative analysis and framework generalizability across Nepal's mountainous regions.

3.3 Data Collection Methods

The methodology employs five data collection methods, tailored to the research objectives, study areas, and two-year timeline, ensuring comprehensive and reliable data.

3.3.1 Geospatial Analysis

- **Purpose**: Quantify geohazard risks and environmental impacts by mapping road networks, landslide-prone areas, and ecological changes.
- **Methods**: Use Geographic Information Systems (GIS) and remote sensing to analyze:

    - **Topography**: Slope gradients (°), elevation profiles (m), and aspect using 30 m Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs) or 1 m LiDAR (if available via ICIMOD).
    - **Geology and Soils**: Map schist, phyllite, limestone, and soil erodibility (K-factor) using Nepal Geological Survey data and FAO soil maps.
    - **Vegetation and Land-Use**: Assess changes in forest cover (% loss) and land-use patterns (e.g., agriculture, settlements) using Sentinel-2 imagery (10 m resolution, 2015–2025).
    - **Landslide Trends**: Analyze historical landslide data (1990–2025) from ICIMOD, Nepal's Department of Hydrology and Meteorology, and post-2015 earthquake reports.
- **Sample**: 15 road segments (5–10 km each) per district (30 total), stratified by eco-friendly (8 segments with bio-stabilization/drainage) and conventional (7 segments with cut-and-fill) designs. Segments are selected based on slope (>30°), rainfall exposure (>2,500 mm), and proximity to settlements (<1 km).
- **Procedure**:

1. Collect geospatial data (October–November 2025) via open-source platforms (e.g., USGS EarthExplorer for Sentinel-2, SRTM).
2. Conduct ground-truthing during fieldwork (November 2025, April 2026) using GPS to verify landslide scars and road alignments.
3. Update maps quarterly (January, April, July 2026) to capture seasonal changes.

- **Tools**: ArcGIS Pro (version 3.3), QGIS (version 3.28), Sentinel-2 imagery, SRTM DEMs, handheld GPS units (Garmin eTrex), LiDAR data (if accessible).

3.3.2 Field-Based Experiments

- **Purpose**: Evaluate eco-engineering techniques for geohazard mitigation and sustainability, comparing performance with conventional methods.
- **Methods**: Establish demonstration plots (0.5–1 km segments) in Kaski and Sindhupalchok to test:
    - **Bio-stabilization**:
        - Plant vetiver grass (*Chrysopogon zizanioides*, 0.3 m spacing) and bamboo (*Bambusa* spp., 1 m spacing) on slopes (30°–45°).
        - Measure shear strength (kPa) using a shear vane tester (ASTM D2573), targeting a 20–40% increase (Shrestha & Devkota, 2015).

        - Quantify erosion rates (mm/year) using erosion pins (1 m intervals) and sediment traps (0.5 m^2), aiming for a 50–70% reduction.
        - Assess vegetation establishment (% cover, root density in g/cm^3) using 1 m^2 quadrat sampling.
    - **Drainage Systems**:
        - Install gabion walls (1–2 m height, wire mesh 2.7 mm) and culverts (0.5–1 m diameter, reinforced concrete) to manage runoff.
        - Monitor runoff coefficients (dimensionless) using flow meters and slope displacement (mm) using inclinometers.
    - **Control Sites**: Monitor conventional cut-and-fill segments (no vegetation or drainage) for landslide frequency (incidents/km/year), erosion, and maintenance costs (NPR/km/year).
- **Sample**: 8 plots per district (4 eco-friendly, 4 conventional, 16 total), selected for high landslide risk (based on GIS maps) and accessibility. Plots are 0.5–1 km, covering 30°–45° slopes.
- **Procedure**:

1. Establish plots in October 2025, with site preparation (e.g., clearing, grading) and planting by November 2025.

2. Monitor bi-monthly (November 2025–May 2026, October–December 2026) for shear strength, erosion, runoff, and vegetation growth.

3. Conduct final measurements in April 2027, comparing eco-friendly vs. conventional plots.

- **Tools**: Shear vane testers (Eijkelkamp), erosion pins (stainless steel, 50 cm), sediment traps, flow meters (OTT Hydrolab), inclinometers (RST Instruments), soil moisture probes (Delta-T Devices), GPS for plot mapping.

3.3.3 Socio-Economic Surveys

- **Purpose**: Quantify socio-economic benefits (e.g., travel time, market access, income) and trade-offs (e.g., land loss, displacement) of eco-friendly roads.
- **Methods**: Conduct household surveys using structured questionnaires, translated into Nepali, Gurung (Kaski), and Tamang (Sindhupalchok), to measure:
    - **Benefits**:
        - Travel time reductions (minutes/trip, e.g., to markets, schools).
        - Market access (trips/week, sales volume in NPR).

    - Income changes (% increase, disaggregated by gender, ethnicity).
    - Access to healthcare and education (visits/month, distance in km).
  - **Trade-offs**:
    - Land loss (hectares acquired for roads, % of household land).
    - Displacement (number of households relocated, compensation in NPR).
    - Cultural disruptions (qualitative reports, e.g., impact on sacred sites).
  - **Cost-Benefit Metrics**: Construction costs (NPR/km), maintenance costs (NPR/km/year), and economic gains (e.g., agricultural sales increase in NPR).
- **Sample**: 150 households per district (300 total), stratified by gender (50% women), ethnicity (e.g., 30% Gurung in Kaski, 30% Tamang in Sindhupalchok, 20% Dalit), and income level (low: <NPR 200,000/year, medium: NPR 200,000–500,000, high: >NPR 500,000). Households are within 1 km of case study roads.
- **Procedure**:

1. Develop and pre-test questionnaires (September 2025) with 10 households per district to ensure clarity and cultural relevance.

2. Train 6–8 local enumerators (October 2025) on survey administration, ethics, and data entry.

3. Administer surveys in November–December 2025 and November 2026, targeting 75 households per district per round.

4. Validate data through follow-up interviews with 10% of respondents (January 2026, December 2026).

- **Tools**: SurveyMonkey for digital data collection, SPSS (version 29) for statistical analysis, tablets (Samsung Galaxy Tab A) for field data entry, printed questionnaires for remote areas.

3.3.4 Qualitative Methods

- **Purpose**: Explore community perceptions, governance barriers, and gender equity to inform participatory road maintenance models.
- **Methods**:
  - **Focus Group Discussions (FGDs)**: Conduct 15 FGDs per district (7–9 participants each, 210–270 total participants), targeting women (50%), indigenous groups (e.g., Gurung, Tamang), and marginalized communities (e.g., Dalit). Topics include perceived road benefits, maintenance challenges, and participation barriers (e.g., gender exclusion).

    - **Key Informant Interviews (KIIs)**: Conduct 30 KIIs per district (60 total) with:
        - Local leaders (e.g., ward chairs, 10 per district).
        - Engineers (e.g., Department of Roads, 5 per district).
        - NGO representatives (e.g., IUCN, USAID's Paani Program, 10 per district).
        - Policymakers (e.g., provincial officials, 5 per district).
          Topics include governance structures, technical constraints, and policy gaps.
- **Sample**: 270–330 total participants (135–165 per district), ensuring 50% female representation and 30% indigenous/marginalized groups.
- **Procedure**:

1. Develop semi-structured FGD and KII guides (September 2025), pre-tested with 2 FGDs and 5 KIIs.
2. Schedule FGDs and KIIs in November–December 2025 (first round) and November 2026 (second round), conducted in Nepali, Gurung, or Tamang with translators.
3. Record interviews with consent, transcribe in Nepali, and translate to English for analysis.
4. Validate findings through member-checking with 10% of participants (January 2026, December 2026).

- **Tools**: Audio recorders (Zoom H1n), NVivo (version 14) for thematic coding, translation software (e.g., Google Translate API for initial drafts), secure cloud storage for transcripts.

3.3.5 Pilot Projects

- **Purpose**: Validate the proposed framework through real-world application, testing eco-engineering and governance models.
- **Methods**: Implement pilot projects (1–2 km road segments) in collaboration with local governments, NGOs (e.g., IUCN, USAID's Paani Program), and Nepal's Department of Roads. Projects will:
    - Apply eco-engineering techniques (vetiver grass, gabion walls, culverts) based on experimental findings.
    - Establish community maintenance committees (10–15 members per district, 50% women), trained in vegetation upkeep and drainage clearing.
    - Monitor performance over 9 months (January–September 2027), measuring:

        - Landslide incidents (number/km).
        - Maintenance costs (NPR/km/month).
        - Socio-economic impacts (e.g., travel time, market access).

- **Sample**: 2 pilot projects (1 per district), selected for high community engagement, landslide risk (based on GIS maps), and accessibility.
- **Procedure**:

1. Design pilot projects with stakeholders (October–December 2026), incorporating experimental results.
2. Implement pilots in January 2027, with community training workshops (February 2027).
3. Monitor quarterly (April, July, September 2027) using geotechnical sensors and stakeholder feedback.
4. Evaluate outcomes in September 2027, comparing with baseline data from conventional roads.

- **Tools**: Geotechnical sensors (inclinometers, flow meters), cost-tracking spreadsheets (Excel), feedback forms, training manuals adapted from ICIMOD (2017).

3.4 Data Analysis

The research employs advanced analytical techniques to integrate quantitative and qualitative data:

- **Geospatial Analysis**:
    - Generate landslide susceptibility maps using weighted overlay analysis in ArcGIS Pro, incorporating slope, geology, rainfall, and land-use data (weights based on Sudmeier-Rieux et al., 2019).
    - Quantify environmental impacts (e.g., erosion rates in mm/year, vegetation cover % loss) using raster calculations.
    - Perform statistical comparisons (ANOVA, Mann-Whitney U tests) in R (version 4.5) to assess differences between eco-friendly and conventional roads ($p < 0.05$).
- **Experimental Data**:
    - Analyze KPIs (shear strength in kPa, erosion rates, runoff coefficients) using paired t-tests and multiple regression models in R to evaluate eco-engineering performance.
    - Calculate cost-effectiveness (NPR/km saved) using life-cycle cost analysis, comparing construction and maintenance costs over 10 years.
- **Socio-Economic Data**:

    - Compute descriptive statistics (e.g., mean travel time reduction, income increase %) in SPSS (version 29).
    - Use ordinary least squares (OLS) regression to identify predictors of benefits (e.g., road type, household income) and trade-offs (e.g., land loss).
    - Perform cost-benefit analysis, calculating net present value (NPV) and benefit-cost ratio (BCR) for eco-friendly vs. conventional roads.
- **Qualitative Data**:
    - Code FGD and KII transcripts in NVivo (version 14) using thematic analysis, identifying patterns (e.g., community ownership, governance barriers, gender equity).
    - Apply grounded theory techniques to develop categories (e.g., “participatory barriers,” “equity challenges”) and triangulate with quantitative findings.
- **Framework Synthesis**:
    - Integrate findings using a systems approach, combining quantitative metrics (e.g., 25% landslide reduction, 20–40% income increase) and qualitative themes (e.g., community-driven maintenance).
    - Develop the framework as a decision-support tool, including geotechnical standards (e.g., shear strength thresholds), eco-engineering guidelines, socio-economic metrics, and governance models.
    - Validate through stakeholder workshops (August 2027), using Delphi techniques (3 rounds, 20–30 experts) to refine guidelines and ensure consensus.

3.5 Ethical Considerations

The research adheres to rigorous ethical standards:

- **Informed Consent**: Obtain written and verbal consent from all participants (surveys, FGDs, KIIs) using forms in Nepali, Gurung, and Tamang, explaining study purpose, data use, risks, and rights. Provide contact details for the researcher and ethics committee.
- **Cultural Sensitivity**: Respect indigenous practices (e.g., Gurung rituals in Kaski, Tamang traditions in Sindhupalchok) by involving community leaders in planning and ensuring 30% indigenous representation in FGDs.
- **Data Privacy**: Anonymize data using unique IDs, storing it on encrypted servers (e.g., Google Cloud with AES-256 encryption). Share only aggregated results in publications.
- **Approvals**: Secure ethical approvals from Prince of Songkla University’s Ethics Committee and Nepal’s National Research Council by October 2025. Obtain permits from Kaski and Sindhupalchok District Coordination Committees.

- **Community Benefits**: Disseminate findings through workshops (September 2027) and training modules on eco-engineering, providing communities with skills and improved road designs.
- **Conflict of Interest**: Disclose partnerships (e.g., ICIMOD, USAID) to ensure transparency, avoiding influence on research outcomes.

3.6 Limitations and Mitigation Strategies

- **Monsoon Constraints**: Inaccessibility during monsoons (June–September) will be mitigated by scheduling fieldwork for dry seasons (October–May) and using Sentinel-2 imagery for wet-season monitoring.
- **Data Availability**: Limited high-resolution geotechnical data (e.g., LiDAR) will be addressed by leveraging ICIMOD datasets, Nepal Geological Survey maps, and ground-truthing with GPS and sensors.
- **Resource Constraints**: Financial and logistical challenges (budget ~USD 20,000–30,000) will be mitigated through grants from the Asian Development Bank, World Bank, or USAID (applied by November 2025) and partnerships with NGOs (e.g., IUCN).
- **Stakeholder Resistance**: Potential resistance to eco-friendly designs will be addressed through early engagement (workshops in October 2025), pilot project demonstrations, and evidence-based advocacy (e.g., cost savings, landslide reduction).
- **Sample Bias**: Potential bias in surveys or FGDs will be minimized through stratified random sampling (gender, ethnicity, income) and triangulation with geospatial and experimental data.
- **Time Constraints**: The condensed two-year timeline will be managed by prioritizing dry-season fieldwork, outsourcing data entry to trained enumerators, and using automated tools (e.g., SurveyMonkey, NVivo).

3.7 Timeline

The research spans October 2025 to September 2027, condensed to ensure completion within two years:

- **Year 1 (October 2025–September 2026)**:
  - **October–December 2025**:
    - Finalize methodology and literature review.
    - Secure ethical approvals (Prince of Songkla University, Nepal National Research Council).
    - Conduct stakeholder mapping and initial workshops with local governments, ICIMOD, and IUCN.

        - Develop and pre-test survey/FGD/KII instruments.
    - **January–March 2026**:
        - Select 15 road segments per district using GIS data.
        - Collect initial geospatial data (Sentinel-2, SRTM DEMs).
        - Establish demonstration plots (site preparation, planting).
    - **April–September 2026**:
        - Conduct first season of field experiments (bi-monthly monitoring).
        - Administer household surveys (150 per district), FGDs (15 per district), and KIIs (30 per district).
        - Analyze preliminary geospatial and survey data.
- **Year 2 (October 2026–September 2027)**:
    - **October–December 2026**:
        - Conduct second season of field experiments (bi-monthly monitoring).
        - Administer follow-up surveys, FGDs, and KIIs for validation.
        - Design pilot projects with stakeholders.
    - **January–March 2027**:
        - Implement pilot projects (1 per district, January 2027).
        - Conduct quarterly monitoring (geotechnical, socio-economic).
        - Analyze experimental and qualitative data (R, NVivo).
    - **April–June 2027**:
        - Complete pilot project monitoring and data analysis.
        - Draft framework, integrating quantitative and qualitative findings.
    - **July–September 2027**:
        - Organize stakeholder workshops (August 2027) for framework validation (Delphi method).
        - Finalize framework and policy recommendations.
        - Complete dissertation writing and submit (September 2027).

3.8 Expected Outcomes

The methodology will produce:

- **Empirical Data**: Quantitative metrics on eco-engineering performance (e.g., 20–40% shear strength increase, 50–70% erosion reduction) and socio-economic impacts (e.g., 30–50% travel time reduction, 20–40% market access increase).
- **Qualitative Insights**: Themes on community perceptions (e.g., ownership, trust), governance barriers (e.g., policy fragmentation), and gender equity (e.g., women's participation).
- **Validated Framework**: A scalable, interdisciplinary framework for eco-safe roads, including:
  - Geotechnical standards (e.g., minimum shear strength thresholds).
  - Eco-engineering guidelines (e.g., vetiver planting protocols).
  - Socio-economic metrics (e.g., cost-benefit ratios).
  - Governance models (e.g., community maintenance committees).
- **Policy Recommendations**: Guidelines for Nepal's Department of Roads, District Coordination Committees, and international stakeholders (e.g., Asian Development Bank), aligned with Nepal's 15th Periodic Plan and SDGs 9 and 15.
- **Academic Outputs**: Two peer-reviewed articles (targeting *Natural Hazards*, *Sustainability*) and one conference presentation (e.g., International Symposium on Landslides) by September 2027.

3.9 Stakeholder Engagement

Stakeholder collaboration ensures practical relevance and community buy-in:

- **Local Governments**: Partner with Kaski and Sindhupalchok District Coordination Committees to select road segments, implement pilots, and disseminate findings. Engage ward chairs in FGDs and KIIs.
- **NGOs and International Organizations**: Collaborate with ICIMOD (geospatial data, technical expertise), IUCN (eco-engineering support), and USAID's Paani Program (funding, watershed focus) for data access and pilot implementation.
- **Communities**: Involve residents in FGDs, training modules (e.g., vegetation maintenance), and maintenance committees, ensuring 50% female and 30% indigenous representation.
- **Procedure**:
  1. Conduct stakeholder mapping (October 2025) to identify key actors (e.g., ward chairs, engineers, NGOs).
  2. Hold consultation workshops (November 2025, March 2026) to co-design pilot projects and align with local priorities.

3. Provide quarterly updates via community meetings (2026–2027) and final workshops (August 2027) to share results and train communities.

- **Tools**: Stakeholder mapping templates, workshop facilitation guides, training manuals adapted from ICIMOD (2017).

3.10 Validation and Quality Assurance

To ensure robustness:

- **Data Triangulation**: Cross-validate geospatial (e.g., landslide maps), experimental (e.g., shear strength), survey (e.g., income data), and qualitative (e.g., FGD themes) findings to confirm consistency.
- **Peer Review**: Share preliminary results with academic supervisors and external experts (e.g., ICIMOD researchers) in March 2027 for feedback.
- **Stakeholder Validation**: Conduct Delphi workshops (August 2027, 3 rounds, 20–30 participants) with engineers, policymakers, and community representatives to refine the framework.
- **Quality Control**:
  - Standardize geotechnical measurements using ASTM standards (e.g., D2573 for shear strength).
  - Train enumerators (October 2025) on survey administration, ethical protocols, and data entry accuracy.
  - Pre-test survey/FGD/KII instruments with 10 households and 5 informants to ensure clarity and cultural relevance.
  - Use double-entry verification for survey data and inter-coder reliability checks (Cohen's kappa > 0.8) for qualitative coding in NVivo.

3.11 Risk Management

To address potential risks:

- **Logistical Risks**: Road inaccessibility due to landslides will be mitigated by selecting alternate routes and using drones for aerial monitoring.
- **Financial Risks**: Budget overruns (~USD 20,000–30,000) will be managed through contingency funds (10% of budget) and in-kind contributions (e.g., NGO equipment).
- **Stakeholder Conflicts**: Disagreements on pilot designs will be resolved through consensus-building workshops and transparent decision-making.
- **Data Quality Risks**: Incomplete or inaccurate data will be mitigated through rigorous training, pilot testing, and triangulation.

- **Timeline Risks**: Delays due to approvals or weather will be managed by front-loading critical tasks (e.g., ethics approvals in October 2025) and outsourcing data entry.

This methodology provides a rigorous, feasible, and impactful approach to developing an interdisciplinary framework for eco-safe roads, addressing environmental, technical, socio-economic, and governance challenges in Nepal's mountainous regions within a condensed two-year timeline.

Conclusion

This doctoral research addresses the urgent need for sustainable rural road development in Nepal's mountainous regions, where rapid infrastructure expansion has often led to severe environmental degradation, increased geohazards, and socio-economic disruptions. By adopting an interdisciplinary approach that integrates geotechnical engineering, eco-engineering, socio-economic analysis, and participatory governance, the study aims to develop a comprehensive, evidence-based framework for environment-friendly roads. Through targeted field experiments, comparative case studies in diverse districts like Kaski and Sindhupalchok, and inclusive stakeholder engagement, the research will generate empirical insights into the efficacy of eco-engineering techniques, the socio-economic benefits of green roads, and the role of community participation in sustaining infrastructure projects.

The outcomes of this research are expected to fill critical knowledge and policy gaps, offering practical guidelines for policymakers, engineers, and local communities to implement resilient, low-impact, and cost-effective road development. Furthermore, the proposed framework will align with national priorities such as Nepal's National Adaptation Plan and global sustainability commitments like the SDGs, particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 15 (Life on Land). Beyond Nepal, the findings will hold broader applicability for other mountainous developing regions facing similar environmental and developmental challenges. Ultimately, this research aspires to redefine rural infrastructure planning in fragile landscapes, fostering a model of development that is both sustainable and socially inclusive.

References

The following references correspond to the 50 studies cited in the literature review for the doctoral research on "Development of Environment-Friendly Roads in Mountains of Rural Nepal." They are organized in APA format, covering key works in geotechnical engineering, environmental science, socio-economic analysis, and governance, with a focus on sustainable road development in Nepal's mountainous regions and global contexts. These references provide a robust foundation for the proposed interdisciplinary framework, addressing environmental impacts, eco-engineering techniques, socio-economic benefits and trade-offs, and participatory governance models.

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