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https://www.ltu.edu.np
info@ltu.edu.np
journalioeit@ltu.edu.np
+977-081-539601
Nepalgunj, Banke, Lumbini Province, Nepal

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Identification of Groundwater Potential Zones Utilizing GIS, RS and AHP: A Case Study of Rupandehi District in Nepal

Lawaj Thapa[1], Niraj K.C.[2]*

[1] Nepal Open University, Lalitpur, Nepal

[2] Institute of Engineering and Information Technology, Lumbini Technological University, Banke, Nepal

*Corresponding Email: dean.niraj@ltu.edu.np

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Abstract

Groundwater is a vital natural resource currently under immense pressure due to overexploitation and a lack of systematic planning. This study aims to identify and map groundwater potential zones (GWPZ) in the Rupandehi district of Nepal using an integration of Geographic Information System (GIS), Remote Sensing (RS), and the Analytic Hierarchy Process (AHP). Seven thematic layers—rainfall, geology, slope, land use/land cover (LULC), soil, drainage density, and lineament density—were integrated within a GIS platform. Multi-Criteria Decision Analysis (MCDA) via AHP was employed to weigh these layers based on their relative importance. The resulting GWPZ map categorizes the district into High, Moderate, and Low potential zones. Findings indicate that 34% of the area possesses high potential, 45% moderate, and 21% low potential. High-potential zones are primarily in the southern Terai plains, while northern mountainous regions exhibit lower potential. This study provides a data-driven guide for water resource managers to ensure sustainable groundwater.

Keywords: *AHP, GIS, Groundwater Potential Zone, MCDA, Remote Sensing.*

1. Introduction

The proliferation of environmental challenges and the surging demand for natural resources have necessitated a more systematic approach to water management. Groundwater, a fundamental and essential natural asset, is stored in the subsurface geological formations within the critical zone of the Earth's crust (Fan, 2015). As a primary water form, it fills the empty spaces within a geological layer, acting as a hidden but vital reservoir (McWhorter & Sunada, 1977). These geological structures, composed of soil, sand, and rocks are known as aquifers, which serve both as channels for transport and as repositories for long-term storage (Hay et al., 1990; McWhorter & Sunada, 1977). The presence of groundwater in a geological structure and the potential for its exploration predominantly rely on the porosity formation (Waikar & Nilawar, 2007).

Despite its importance, groundwater is a precious resource that is shrinking day by day (Halder et al., 2020). There is a growing sense of urgency regarding access to clean drinking water, especially in the context of impending global water scarcity (Halder et al., 2020). Rapid modernization, industrialization, and population growth have led to a significant lack of quality water supply in both rural and urban areas (Gnanachandrasamy et al., 2018). Furthermore, recent progress across diverse sectors like agriculture, industry, and urbanization has resulted in a heightened demand for water supply, primarily fulfilled through the utilization of groundwater resources (Dawoud, 2005).

The current management of these resources faces significant hurdles; a lack of proper plans for groundwater exploration and the random selection of points for bore wells result in failure most of the time (Barcelona, 1985). Indiscriminate misuse has led to a decrease in the potential of groundwater and a dangerous reduction in groundwater levels (Prasad et al., 2008). Excessive utilization and significant alterations over time have placed immense pressure on groundwater resources globally (Arulbalaji et al., 2019). Consequently, establishing a sustainable groundwater management plan to effectively utilize this vital resource through the delineation of groundwater potential zones (GWPZ) is no longer optional but a necessity.

In response to these challenges, Remote Sensing (RS) and Geographic Information Systems (GIS) have emerged as a powerful set of tools for collecting, storing, retrieving, managing, analyzing, and displaying spatial data in a simplified way (Cooperative & Collins, 1988). These tools offer a cost-efficient and time-saving approach to map groundwater potential (Jha & Peiffer, 2006). Over the past decade, many researchers have found Multi-Criteria Decision Analysis (MCDA) to be an effective tool for assessing the management of groundwater (Pietersen, 2007; Madrucci et al., 2008). Specifically, the Analytic Hierarchy Process (AHP) stands out as one of the most commonly employed techniques in MCDA (Saaty, 1990). The assessment of groundwater potential has extensively employed these integrated GIS and AHP techniques in various global contexts (Rahmati et al., 2015; Shekhar & Pandey, 2015; Arulbalaji et al., 2019; Saranya & Saravanan, 2020; Ajay Kumar et al., 2020).

This study summarizes the groundwater potential zone mapping of the Rupandehi district in Nepal. While previous literature, such as Pathak (2017), has presented methods to delineate shallow groundwater potential in the Terai plain using GIS applications, there is a distinct gap in the application of multi-criteria decision models for this region. Since no such studies utilizing the AHP method have been reported for this specific study area to date, the current study serves as a pioneer work that is crucial for the rapid assessment of groundwater potential in a region facing increasing agricultural and domestic water demands. The primary objective of this study is to delineate groundwater potential zones within the Rupandehi district and create a comprehensive guide map for groundwater exploration and exploitation. This study aims to ensure optimal and sustainable development and management of vital water resources, identify suitable locations for water extraction to support effective development planning, and provide data-driven services for agricultural purposes within the district. By implementing a fast and cost-effective methodology, this study aims to mitigate the adverse effects of unplanned water resource development and contribute to the limited body of geospatial hydrogeological study in the Nepalese context.

2. Materials and Methods

2.1 Study Area

The study area for this investigation is the Rupandehi District, a strategically significant region situated within the Lumbini Province of western Nepal. Administratively, the district is comprised of 16 local levels, including one sub-metropolitan city, five municipalities, and ten rural municipalities. Geographically, Rupandehi presents a diverse and complex topographical profile, characterized by the rugged mountainous terrain of the Churia Hills in the northern part and the expansive, fertile flatlands of the Terai Plain to the south.

The hydrological framework of the district is dominated by the Tinau River, which serves as the primary watercourse. This system is complemented by the Bhaluhi/Danda River to the east and the Danav River to the west, both of which are notable fluvial systems that influence the region's hydrogeological characteristics (Pathak, 2017). While various research initiatives have previously targeted the identification of groundwater resources in this district, a significant methodological gap remains; specifically, the Analytic Hierarchy Process (AHP) has not been utilized in prior studies for this specific area.The selection of Rupandehi as the study location is further reinforced by its status as the home district, which allowed us for a more nuanced understanding of local environmental challenges, land use patterns, and water demand. By focusing on this geographically varied landscape, the study provides a robust geospatial assessment that aligns with the overarching goal of the project: to delineate precise groundwater potential zones through the integration of Remote Sensing, GIS, and Multi-Criteria Decision Analysis. The location map and spatial orientation of the study area are illustrated in Figure 1.

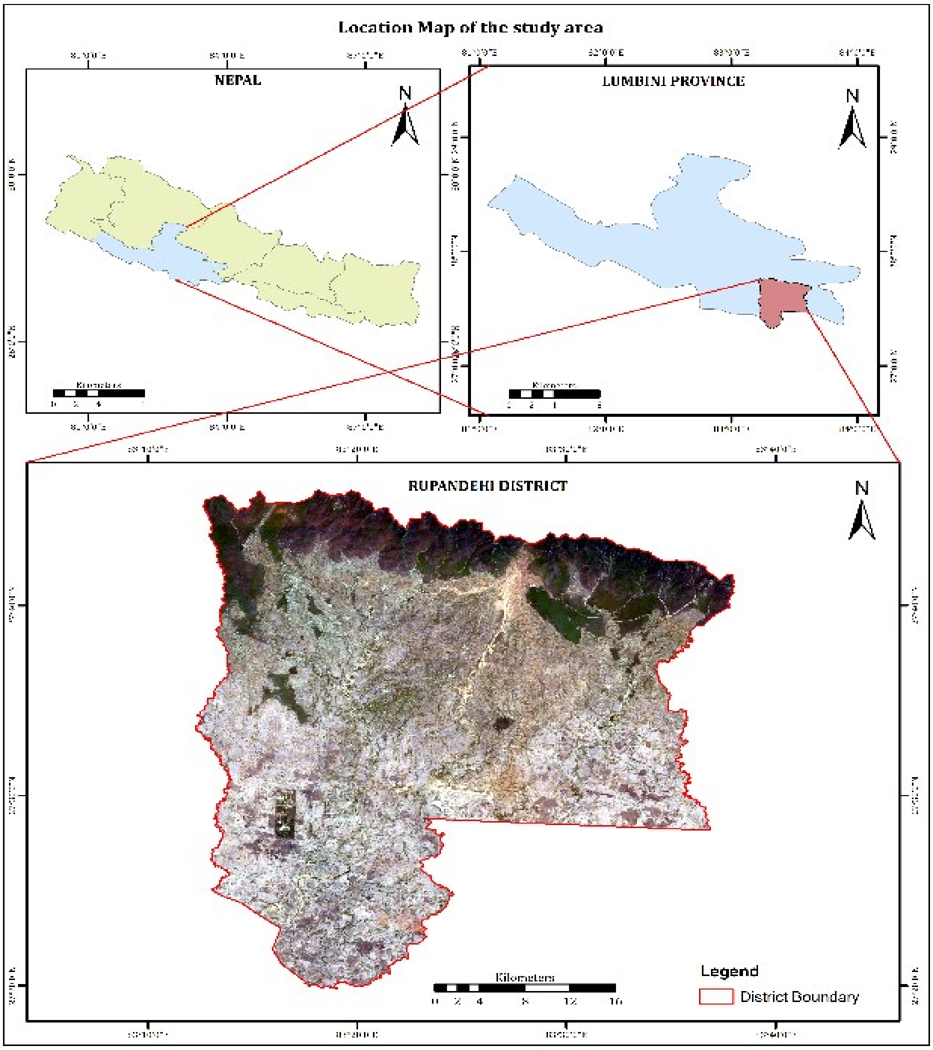

Figure 1: This figure illustrates the geographical location of Rupandehi District within Lumbini Province, Nepal, highlighting the 16 local administrative units and the distinct transition from the northern Churia Hills to the southern Terai Plain.

2.2 Data and Software used

The spatial datasets integrated into this study were meticulously selected to represent the physical and environmental variables that govern groundwater occurrence in the Rupandehi District. Each thematic layer serves a specific hydrogeological purpose, bridging the gap between surface observations and subsurface potential to ensure a comprehensive multi-criteria analysis.

Table 1:Tables shows the data used in this study.

SN	Thematic Layer	Data Type	Source	Resolution / Scale	Rationale for Selection
1	Geology	Vector	USGS / DMG Nepal	1:50,000	Defines the lithological framework and primary porosity of aquifers.
2	Rainfall	Raster	Dept. of Hydrology & Meteorology	30-year Mean	Represents the principal source of natural recharge to the system.
3	Slope	Raster	SRTM DEM	30m	Controls the duration of water contact and infiltration rates.
4	LULC	Raster	ESRI / Sentinel-2	10m	Reflects surface permeability and anthropogenic impact on recharge.
5	Soil	Vector	FAO-UNESCO / NARC	1:250,000	Dictates texture-based infiltration capacity and water retention.
6	Drainage Density	Derived Raster	SRTM DEM	30m	Indicates the efficiency of surface runoff; inversely related to potential.
7	Lineament Density	Derived Raster	Landsat 8 OLI/TIRS	30m	Highlights structural fractures that facilitate deep percolation.

The integration of these parameters allows for a holistic understanding of the hydrogeological environment. Geology and Soil layers provide the foundational data for subsurface storage. In the northern Churia Hills, the geology consists of harder formations that inherently limit infiltration, whereas the southern Terai Plain features deep alluvial deposits, primarily sand and gravel characterized by high primary porosity. The soil layer complements this by defining the vertical hydraulic conductivity; for instance, the coarse-textured sandy soils found in the district allow for rapid recharge compared to clay-heavy soils.

Topographic factors, specifically Slope and Drainage Density, are critical in determining the runoff-infiltration ratio. The steep slopes of the Churia region promote high-velocity surface runoff, leaving insufficient time for water to seep into the ground. Similarly, a high drainage density suggests a robust network of streams that quickly channel surface water away, typically indicating lower groundwater potential zones.

Furthermore, Land Use/Land Cover (LULC) and Rainfall act as the primary input and filter variables for the system. Rainfall is the essential source of recharge; without adequate precipitation, even the most porous aquifers remain depleted. The LULC layer determines the effective recharge by indicating surface permeability. Urban (built-up) areas act as impermeable barriers, while the forested and agricultural lands prevalent in Rupandehi facilitate healthy recharge. Finally, Lineament Density, derived from Landsat 8 imagery, identifies secondary porosity. These linear features, such as faults and fractures, serve as crucial conduits for groundwater movement and are frequently associated with high-yielding wells in complex terrains.

The execution of this study utilized a suite of specialized software environments to process the diverse spatial datasets required for the Analytic Hierarchy Process (AHP) and multi-criteria analysis. ArcMap 10.8 served as the foundational platform, facilitating spatial database management, the generation of all thematic layers, and the execution of the final weighted overlay analysis to delineate the potential zones. To enhance the accuracy of structural features, ERDAS IMAGINE 5.2 was employed for the advanced pre-processing of satellite imagery, specifically for calculating band ratios essential in the extraction of lineaments from Landsat 8 OLI/TIRS data.

The quantitative component of the study, specifically the AHP calculations, involved the development of a pairwise comparison matrix and rigorous consistency ratio checks, which were performed using a specialized Multi-Criteria Decision Analysis (MCDA) spreadsheet tool. Furthermore, Google Earth Engine (GEE) was leveraged for its high-performance cloud computing capabilities to conduct the Land Use Land Cover (LULC) classification. This integration of GEE ensured a high-accuracy surface analysis across the geographically varied landscape of the Rupandehi district, bridging the gap between raw satellite data and actionable hydrogeological information. The interoperability of these tools allowed for a seamless transition from raw data acquisition to the final production of the Groundwater Potential Zone (GWPZ) map.

2.3 Thematic Layer Preparation and Reclassification

The study methodology follows a systematic workflow of Multi-Criteria Decision Analysis (MCDA) integrated with Geospatial Science (Figure 2). The process began with the collection of multi-source spatial data, followed by the generation and standardization of seven thematic layers in a GIS environment (Figure 2).

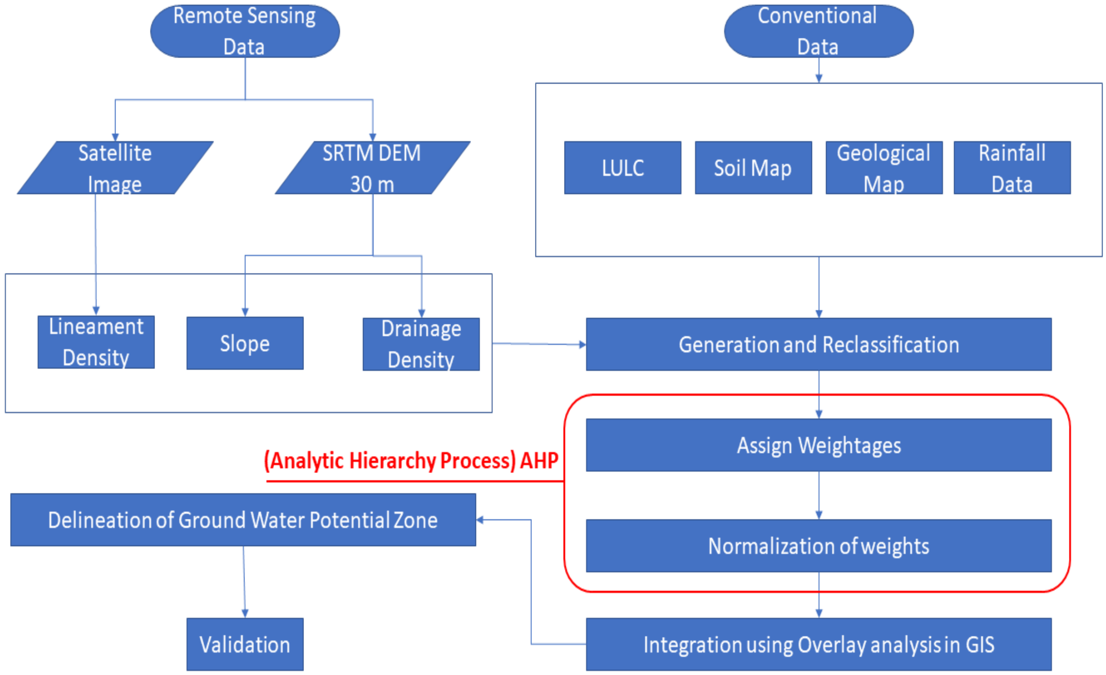

Figure 2: A comprehensive flowchart depicting the systematic integration of spatial data acquisition, thematic layer generation, Multi-Criteria Decision Analysis (MCDA) via AHP, and the final validation process.

The raw data for Rainfall, Geology, Slope, LULC, Soil, Drainage Density, and Lineament Density were processed to create individual thematic maps. To perform a mathematical comparison, each layer was reclassified into five categories, ranging from 'Very Low' to 'Very High' potential using the Spatial Analyst extension in ArcMap 10.8. This standardization ensures that diverse units (e.g., millimeters of rain vs. degrees of slope) are comparable on a common scale.

Rainfall is a vital factor in determining groundwater potential; since the Rupandehi district is located in a tropical bio-climatic zone, the Inverse Distance Weight (IDW) method was used to interpolate data from 13 stations within the study area and neighboring districts. As shown in Figure 3a, rainfall is maximum in the north-east and decreases toward the western part. Geology also plays a vital role in the distribution and movement of water; the study area comprises Undivided Precambrian rocks, Neogene Sedimentary rocks, and Quaternary sediments (Figure 3b). Terrain features like slope, generated from SRTM DEM, express ground steepness; flat areas are prioritized for groundwater recharge, whereas steep slopes, reaching up to 57.4 degrees in this study, promote runoff (Figure 3c).

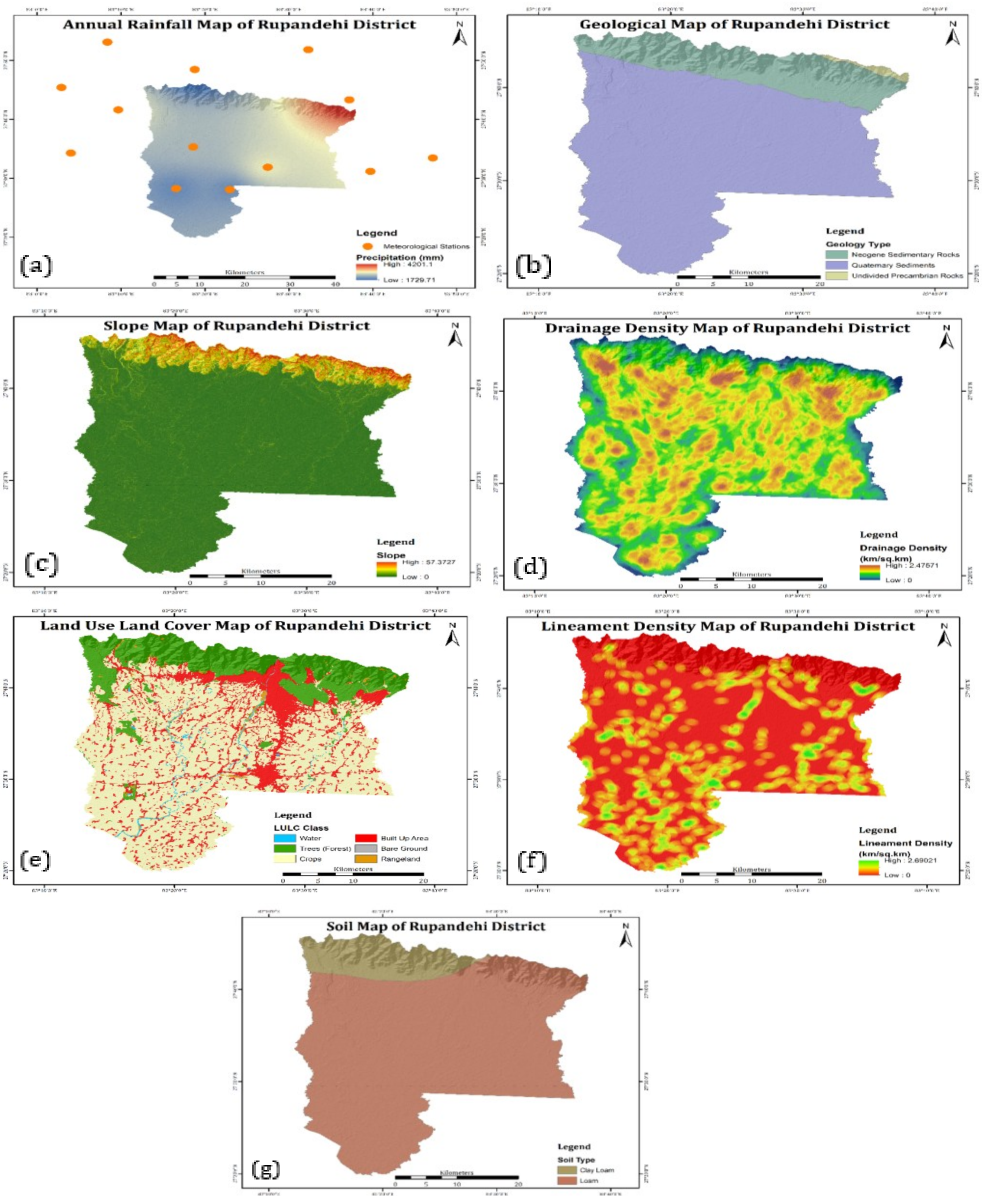

Figure 3: Thematic maps of the study area: (a) Annual Rainfall: Spatial patterns highlighting high-recharge zones in the northeast; (b) Geology: Distribution of lithological units and aquifer storage capacity; (c) Topographic Slope: Terrain steepness showing infiltration vs. runoff zones; (d) Drainage Density: Surface water network intensity affecting groundwater recharge; (e) LULC: Land utilization classes identifying permeable and impermeable surfaces; (f) Lineament Density: Structural conduits indicating secondary porosity; (g) Soil Texture: Spatial classification of soil permeability and water retention.

This is complemented by drainage density (Figure 3d), which shows an inverse correlation with groundwater potential as density increases, potential decreases (Nair et al., 2017). Furthermore, LULC significantly influences resources by altering recharge conditions; the Sentinel 2A-derived map identifies water, forest, crops, built-up areas, bare ground, and rangeland (Figure 3e). Lineament density (Figure 3f), identified via PCI Geomatica and manual digitization of hill shades, highlights structural fractures that serve as pathways for groundwater movement (Magesh et al., 2012). Finally, soil characteristics determine water retention based on permeability; the district is predominantly covered by Clay Loam and Loam, with Loam being more favorable for potential due to its higher permeability (Arshad et al., 2020), as depicted in the soil map (Figure 3g).

2.4 Assignment of Weights and Normalization

The Analytical Hierarchy Process (AHP) is a robust and widely recognized GIS-based method for delineating groundwater potential zones through multi-criteria decision analysis (Arulbalaji et al., 2019). This method allows for the systematic integration of diverse thematic layers by assigning relative importance through expert-informed pairwise comparisons. For this study, seven thematic layers were selected based on their hydrogeological significance in the Rupandehi district (Table 2).

The weights for these layers were assigned using the fundamental scale developed by Saaty (1990), which ranges from 1 (equal importance) to 9 (extreme importance) (Table 2). In the GIS environment, each thematic layers sub-classes were reclassified and assigned a rank (R_j) from 1 to 5, where 1 indicates "Very Low" and 5 indicates "Very High" influence on groundwater potential (Table 4).

Table 2: Fundamental scale for pairwise comparison judgements (Saaty, 1990)

Intensity of importance on an absolute scale	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

To ensure the logical reliability of the weight assignments, the Consistency Ratio (CR) was evaluated. The Consistency Index (CI) was first calculated using the principle eigenvalue (λ_{max}) and the number of factors (n). Then, the consistency index (CI) is calculated as;

$$CI = \frac{\lambda max - n}{n-1} \quad \text{Eq 1}$$

Where n is the number of factors used in the analysis.Now, the Consistency Ratio defined as

$$CR = \frac{CI}{RCI} \quad \text{Eq 2}$$

where RCI = Random consistency Index value, whose values were obtained from Saaty's standard (Table 3).

$$CR = \frac{0}{1.32} = 0 \quad \text{Eq 3}$$

According to (Saaty, 1990), CR of 0.10 or less is acceptable to continue the analysis. If the consistency ratio is greater than 0.10, then there is the need to revise for locating causes of inconsistency and correct it. If the CR value equals 0 then there is perfect level of consistency in pairwise comparison (Table 3). The CR value is not greater than 0.1, that means the judgement matrix is reasonably consistent.

Table 3: Standard Random Consistency Index (RCI) Values (Saaty, 1990)

The consistency index of randomly generated reciprocal matrices							
			Order of matrix				
N	1	2	3	4	5	6	7
RCI value	0.00	0.00	0.58	0.9	1.12	1.24	1.32

Table 4: Integrated AHP Pairwise Comparison Matrix, Normalization, and Thematic Ranking

Thematic Layer	Rainfall	Geology	Slope	Drainage Density	LULC	Lineament Density	Soil	Normalized Weight (Wj)	Sub-class Rank (Rj)
Rainfall (Rf)	1	1.09	1.35	1	1.65	1.16	1.57	17.25%	1 - 5
Geology (Ge)	0.92	1	1.12	0.86	1.06	1.2	1.2	14.71%	1, 3, 2005
Slope (Sl)	0.74	0.89	1	0.61	1.44	0.69	1	12.30%	5 - 1
Drainage Density (DD)	1	1.16	1.65	1	1.65	1.2	1.65	18.14%	5 - 1
LULC	0.61	0.95	0.69	0.61	1	0.6	0.83	10.42%	1 - 5
Lineament Density (LD)	0.86	0.83	1.44	0.83	1.66	1	1.57	15.75%	1 - 5
Soil (Soil)	0.64	0.83	1	0.61	1.2	0.64	1	11.44%	2 - 3

2.5 Delineation of Groundwater Potential Zones

The final stage of the spatial modeling process involves the calculation of the Groundwater Potential Index (GWPI) to comparatively assess and delineate potential zones within the study area. This integration considers all pertinent environmental and physical factors related to the occurrence and movement of groundwater resources (Subba Rao, 2006). The GWPI was computed using the weighted linear combination method proposed by Malczewski (1999), which aggregates the relative contribution of each thematic layer.

The index for each spatial grid cell was calculated according to the following equation:

$$\text{GWPI} = \sum_{j=1}^{n} (W_j \times R_j) \qquad \text{Eq 4}$$

Where:

a. W_j represents the normalized weight of the jth parameter.

b. R_j signifies the rating or rank of the individual class within that parameter.

c. n represents the total number of thematic parameters used in the analysis.

In the context of this study, the equation is expanded to include all seven hydrogeological drivers:

$$GWPI = (Rf_w . Rf_r) + (Ge_w . Ge_r) + (Sl_w . Sl_r) + (DD_w . DD_r) + (LULC_w . LULC_r) + (LD_w . LD_r) + (Soil_w . Soil_r) \quad \text{Eq 5}$$

where Rf is Rainfall, Ge is Geology, Sl is Slope, DD is Drainage Density, LULC is Land Use Land Cover, LD is Lineament Density, and Soil is Soil Texture. The subscripts w and r denote the thematic weight and the subclass rank, respectively.

As detailed in Table 5, each parameter was categorized into specific factors and assigned ranks ranging from 1 (Very Low potential) to 5 (Very High potential) based on their influence on the hydrological cycle. By overlaying these ranked layers within the ArcMap 10.8 environment, the continuous GWPI values were generated and subsequently classified into distinct zones to produce the final Groundwater Potential Zone (GWPZ) map for the Rupandehi district. Raditional herbal remedies have played a significant role in healthcare systems worldwide, including Ayurveda, Traditional Chinese Medicine (TCM), and other ethnopharmacological practices(Sen et al., 2011). While herbal compounds are often assumed to be safe due to their natural origins, many lack extensive toxicity studies, particularly through modern scientific methods(Woo et al., 2012). This can lead to safety concerns, especially in long-term use or high doses(Moreira et al., 2014).

As drug discovery and toxicology studies progress, computational approaches have gained prominence(Cherkasov et al., 2014). Specifically, Quantitative Structure-Activity Relationship (QSAR) models have become a popular tool for predicting the biological activity of chemical compounds based on their molecular structures(Varsou et al., 2024). QSAR models can predict potential toxic effects without the need for large-scale clinical testing or experimental setups, making them efficient for early-stage screening(EBSCOhost, 2023).

Table 5: Comprehensive Categorization and Ranking of Parameters Influencing GWPZ

Parameters	**Sub-classes/Factors**	**Normalized Weight (Wj)**	**Assigned Rank (Rj)**
Rainfall	Very Low to Very High	17.25	1 - 5
Geology	pC (Precambrian), N (Neogene), Q (Quaternary)	14.71	3, 1, 2005
Slope	0-1°, 1-2°, 2-3°, 3-5°, >5°	12.3	5, 4, 3, 2, 1

Drainage Density	Very Low to Very High	18.14	5, 4, 3, 2, 1
LULC	Water, Forest, Crops, Rangeland, Bare, Built-up	10.42	5, 5, 5, 3, 1, 1
Lineament Density	Very Low to Very High	15.74	1, 2, 3, 4, 5
Soil	Loam, Clay Loam	11.44	3, 2

While QSAR models have been applied extensively in the pharmaceutical and industrial sectors, little attention has been given to herbal medicines(Xu et al., 2024). The lack of data about traditional medicines creates a barrier to ensuring the safe use of those compounds in modern healthcare.

There is a growing need for computational models that can predict the toxicity of herbal compounds, thus bridging the gap between traditional medicine and modern toxicological evaluation(Machhar et al., 2019).

This study aims to develop a machine learning – based QSAR model to predict toxicity of herbal and synthetic organic compounds, using RDKit-calculated molecular descriptors. The model will be trained and validated with known toxicity data from herbal and plant derived compounds.

The outcomes could benefit both the scientific community and the herbal medicine industry by offering a tool for early-stage screening, potentially reducing the need for extensive in vivo and in vitro testing(Krewski et al., 2010).

3. Results and Discussion

The integration of multi-criteria decision analysis (MCDA) and geospatial techniques has resulted in the identification of varying groundwater potential zones (GWPZ) across the Rupandehi district. The following sections detail the outcomes of the thematic overlay and the subsequent interpretation of these findings in the context of regional hydrogeology.

3.1 Delineation of Groundwater Potential Zones (GWPZ)

Taking into account the topography and local knowledge of the study area, regions with varying levels of groundwater availability have been identified, ranging from high-yielding to dry zones. Due to the specific resolution of the spatial data used, the classification was refined into three primary zones to ensure a robust and practical assessment. The resulting Groundwater Potential Zone (GWPZ) map of the Rupandehi district (Figure 4) categorizes the landscape into High, Moderate, and Low recharge potentiality, covering areas of 438.06 km2, 588.83 km2, and 277.01 km2respectively Statistical analysis reveals that 45% of the district falls under the moderate potential zone, while the high potential zone accounts for 34%, and the low potential zone covers the remaining 21% (Figure 5).

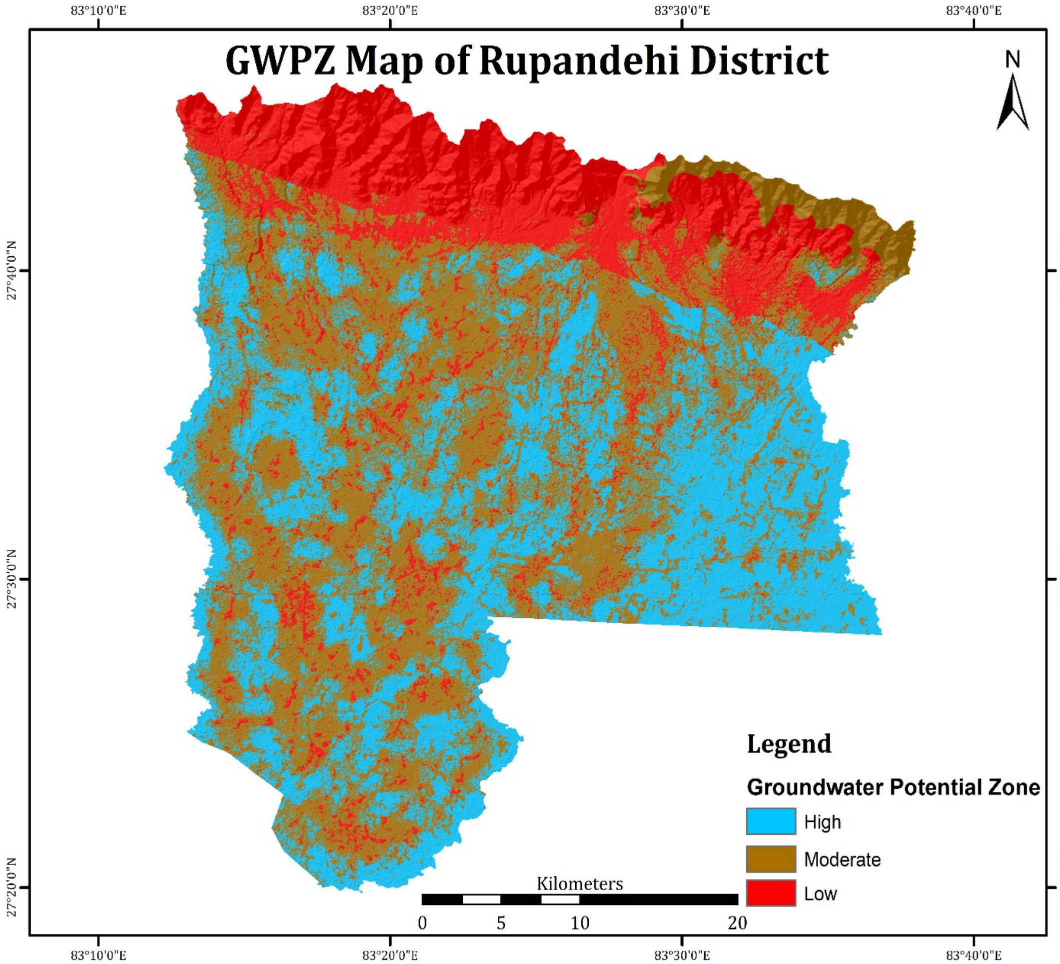

Figure 4: The resulting predictive GWPZ map produced through Weighted Overlay Analysis, categorizing the district into High (34%), Moderate (45%), and Low (21%) potential zones based on the integrated GIS and AHP model.

Geographically, the High and Moderate potential zones are predominantly situated in the southern part of the district. This concentration is attributed to the presence of permeable loamy soil, gentle slopes, and flat terrain, combined with high lineament density which facilitates deep percolation. In contrast, Low potential zones are primarily confined to the northern hilly regions. In these areas, the steep slopes of the Churia range promote rapid surface runoff over infiltration, while the consolidated Neogene sedimenta ry rocks offer limited primary porosity for aquifer storage, as discussed by Subba Rao (2006).

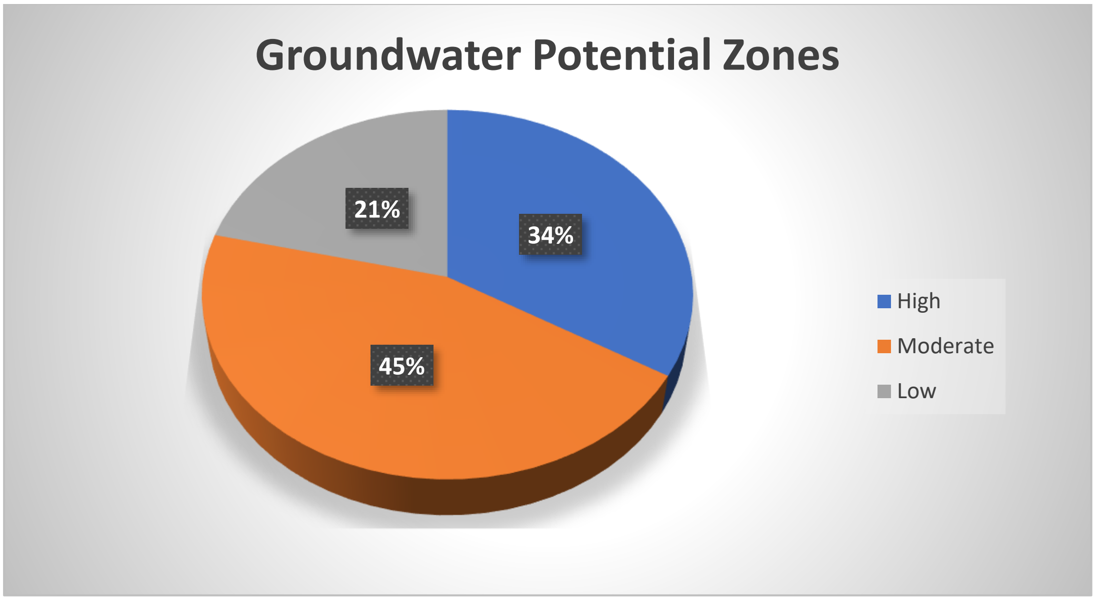

Figure 5: A pie chart illustrating the percentage distribution of delineated groundwater potential areas within the district, where the Moderate potential zone occupies the largest portion at 45%, followed by High potential at 34%, and Low potential at 21%.)

3.2. Model Validation and Accuracy Assessment

The reliability of the delineated groundwater potential zones was further validated using historical well-yield data from the Groundwater Resource Development Board (GWRDB), Nepal, recorded in 2019. A total of 43 wells were utilized for this cross-verification (Figure 12) (Figure 6). The validation process involved comparing the discharge values of these wells measured in liters per second (lps), against the predicted GWPI categories.

The results indicate that wells located in the Low and Moderate potential zones typically exhibit yielding capacities in the range of 0.4 to 30 lps. Conversely, the wells situated within the High potential zones consistently show higher water-yielding capacities, exceeding 30 lps (figure 6). Out of the 43 wells analyzed, 35 wells (approximately 81.4%) demonstrated a high level of agreement with the model-predicted potential categories. However, eight wells showed discrepancies: four low-yielding wells (Nos. 6, 7, 15, and 20) and two moderate-yielding wells (Nos. 28 and 30) were found in predicted high-potential areas, while two high-yielding wells (Nos. 39 and 42) were located in moderate-potential zones (Figure 6). These variations are likely due to localized factors such as concentrated urban settlements or intensive agricultural extraction, which can locally depress or enhance the water table beyond the resolution of surface-based GIS parameters.

Ultimately, the high rate of correlation between the predicted zones and actual field measurements confirms that the integrated GIS, RS, and AHP-based techniques are highly effective for groundwater resource assessment. This methodology provides a reliable framework that can be adapted to other geographically similar regions for sustainable water management (Arulbalaji et al., 2019).

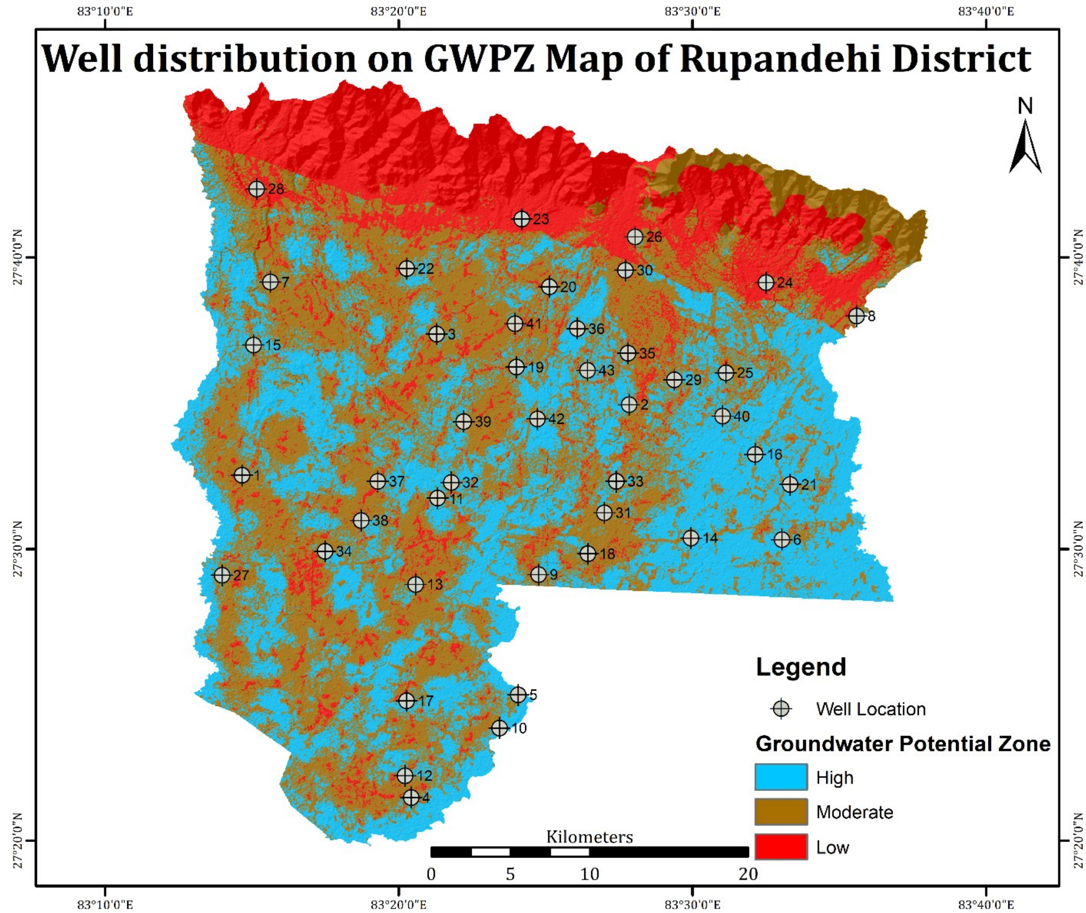

Figure 6: A spatial validation map showing the locations of 43 observation wells overlaid on the predicted groundwater potential zones. The map displays the correlation between field-recorded well discharge data and the model-generated high, moderate, and low potential zones across the district.

3.3. Discussion

The spatial distribution of groundwater potential in Rupandehi district reveals a clear hydrogeological dichotomy between the northern and southern regions. The High and Moderate potential zones, which collectively cover 79% of the study area, are primarily concentrated in the southern and central Terai plains. This dominance is largely attributed to the presence of Quaternary alluvial sediments characterized by high primary porosity and a predominantly flat topography with slopes less than 1°. These factors facilitate maximum infiltration by increasing the "contact time" between surface water and the soil. As noted by Subba Rao (2006), lithological composition and topographic flatness are the primary drivers for subsurface water storage in such alluvial terrains.

In contrast, the Low potential zones (21% of the area) are predominantly found in the northern hilly regions. The steep slopes, which reach up to 57.4°, and the presence of consolidated Neogene sedimentary rocks promote rapid surface runoff over infiltration. This reflects an inverse correlation between drainage density and groundwater potential; as the drainage network becomes denser in these hilly terrains, the likelihood of groundwater recharge decreases because water is efficiently exported as surface discharge. This observation aligns with the findings of Nair et al. (2017) regarding the efficiency of drainage systems in reducing water residence time on the surface.

The integration of lineament Density proved to be a critical indicator of secondary porosity. High lineament density in specific zones signifies the presence of faults and fractures that act as pathways for groundwater movement, which is particularly vital for locating permeable zones in otherwise consolidated geological formations. Furthermore, the study highlights the impact of Land Use Land Cover (LULC), where forested areas and crop lands are assigned high ranks due to their recharge-facilitating properties. Conversely, built-up areas and bare ground are identified as impediments to recharge, creating what Aykut (2021) describes as a recharge deficit due to increased surface impermeability.

The validation of the GWPZ model against 43 wells recorded in 2019 by the Groundwater Resource Development Board (GWRDB) confirms the high reliability of the AHP-based approach. The fact that 35 out of 43 wells (81.4%) matched the predicted potential categories provides strong evidence for the model's accuracy. Specifically, wells in high potential zones yielded capacity greater than 30 liters per second (lps), while those in lower potential zones ranged between 0.4 and 30 lps. The slight discrepancies (8 unmatched wells) are likely due to localized anthropogenic factors, such as high-density settlements or intensive agricultural extraction, which can locally alter the groundwater table.

Overall, the successful delineation of these zones demonstrates that the integration of GIS, Remote Sensing, and AHP is a robust and useful method for groundwater assessment. This approach provides a scientific basis for sustainable water resource planning in Rupandehi and can be readily applied to other geographically similar regions.

4. Conclusion

In this study, groundwater potential zones (GWPZ) in the Rupandehi district of Nepal were identified through the integrated application of Remote Sensing (RS), Geographic Information Systems (GIS), and the Analytic Hierarchy Process (AHP). Seven critical thematic layers geology, land use land cover (LULC), slope, drainage density, lineament density, precipitation, and soil were generated using a combination of conventional data and satellite imagery to assess the region's hydrogeological characteristics. Weights were systematically assigned to each individual theme and its respective sub-classes based on the AHP technique to quantify their influence on groundwater occurrence. The resulting analysis classified the study area into three distinct potential zones: high, moderate, and low. The Moderate potential zone represents the largest area at 45%, while the High and Low potential zones cover 34% and 21%, respectively. Geographically, the high and moderate potential areas are situated in the southern plain lands characterized by gentle slopes, whereas the low potential zones are primarily confined to the northern hilly regions.

The effectiveness of this methodology was verified by validating the predicted zones against 43 existing wells, where 35 wells (81.4%) showed a positive agreement with the model. Discrepancies in the remaining eight wells are attributed to localized factors such as proximity to dense urban settlements, intensive agricultural activity, or the increasing trend of dryness since the 2018 validation data was recorded. This study underscores the value of RS and GIS as instrumental tools for water resource planners in undertaking groundwater development initiatives for irrigation and domestic supply. Furthermore, the study identifies promising future research directions, including the exploration of advanced machine learning techniques like deep learning and support vector machines to improve predictive accuracy for complex datasets. Ultimately, this study provides a scientific basis for sustainable water management that can be replicated across different geological and hydrological settings in other parts of Nepal.

Author Contributions: Conceptualization, Lawaj Thapa and Niraj KC; Methodology, Lawaj Thapa; Software, Lawaj Thapa; Validation, Lawaj Thapa and Niraj KC; Formal Analysis, Lawaj Thapa; Investigation, Lawaj Thapa; Resources, Niraj KC; Data Curation, Lawaj Thapa; Writing Original Draft Preparation, Lawaj Thapa; Writing Review & Editing, Niraj KC; Visualization, Lawaj Thapa; Supervision, Niraj KC; Project Administration, Niraj KC. All authors have read and agreed to the published version of the manuscript.

Supplementary Materials

a. *Data Availability Statement*: The primary spatial data, thematic layers, and the AHP decision matrix that support the findings of this study are available from the corresponding author upon reasonable request. This includes the processed GIS shapefiles, reclassified raster layers for Rupandehi district, and the weighted overlay calculation sheets generated during the analysis.

b. *Data Sources*: This study integrates multiple data sources, including Remote Sensing products (Sentinel-2A imagery and SRTM DEM), conventional meteorological records from the Department of Hydrology and Meteorology (DHM), and hydrogeological maps. Validation was performed using historical well-discharge data (2019) provided by the Groundwater Resource Development Board (GWRDB), Nepal.
c. *Generative AI Statement*: During the preparation of this manuscript, the authors utilized generative artificial intelligence (AI) tools for the specific purposes of refining technical descriptions, structuring the AHP methodology, paraphrasing complex hydrogeological discussions, and improving the overall academic tone of the manuscript. While AI was used to assist in the synthesis of literature and linguistic clarity, all core scientific contributions, including the selection of thematic parameters, the determination of AHP weightages, the GIS-based spatial analysis, and the final interpretation of groundwater potential zones are the original work of the authors. All content has been rigorously reviewed and validated by the authors to ensure scientific integrity and technical accuracy.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Conflicts of Interest: The authors declare no conflict of interest.

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Differential Impact of Key Social Media Factors on Consumer Purchase Decisions: Evidence from Nepal

Meera Sharma[1], Niraj K.C.[2*], Narayan Ghimire[1]

[1] Institute of Engineering and Information Technology, Lumbini Technological University, Banke, Nepal

[2] Institute of Engineering and Information Technology, Lumbini Technological University, Banke, Nepal

*Corresponding Email: dean.niraj@ltu.edu.np

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Abstract

This study, examines the influence of social media advertisement, trust, access to information, and reviews on consumer purchase decisions. The research is quantitative in nature, employing a structured questionnaire to collect primary data from a sample of 150 active social media users within the Kathmandu Valley. A simple random sampling (SRS) method was utilized. The data analysis was conducted using SPSS, employing descriptive statistics, Correlation, ANOVA, and Regression analysis. The findings reveal that social media advertisement and reviews have a positive and significant impact on consumers purchase decisions. Conversely, the results suggest that access to information and trust have no significant impact on the purchase decision of consumers in the studied sample. Thus, this study contributes to the limited research in the context of Nepalese consumers.

Keywords: *Access to Information, Consumers, Purchase Decision, Reviews, Social Media Advertisement, Trust.*

1. Introduction

The proliferation of the internet and the subsequent exponential growth of Social Networking Sites (SNSs), such as Facebook, Instagram, and YouTube, have fundamentally reshaped the landscape of commerce and consumer engagement across the globe (Boyd & Ellison, 2007). These platforms have transitioned from mere communication tools to robust marketing channels, transforming the traditional one-way dialogue of mass media into a dynamic, multi-directional exchange between consumers and brands (Mangold & Faulds, 2009). In this modern environment, consumers actively seek, process, and share information, including product evaluations and purchase experiences, making user-generated content and digital advertising increasingly influential in the pre-purchase phase (Janavi et al., 2021). This shift necessitates a critical understanding of how the various elements presented on social media specifically, advertisements, user trust, accessible information, and peer reviews, translate into an actual change in the consumers final Purchase Decision of Consumers (Mangold & Faulds, 2009; Janavi et al., 2021).

Despite the acknowledged ubiquity of social media in daily life, a significant gap remains in understanding the definitive impact and relative effectiveness of specific social media factors on consumer behavior, particularly within developing markets like Nepal Dwivedi et al., 2021; Kapoor et al., 2018). The core challenge lies in assessing the reliability and persuasive power of digital content (Hajli, 2014). Key questions arise: Does social media advertisement effectively cut through the digital noise to encourage unplanned purchases, as examined through impulse buying models (Chen & Yao, 2018)? How does user trust, often fragile in the online environment, truly influence purchasing intent, given its role as a fundamental mediator (Hajli, 2014)? Is the sheer access to information on these platforms more valuable to the consumer than the ease of searching, from an information economics perspective (Kulkarni et al., 2012)? Finally, are online reviews considered credible compared to traditional word-of-mouth recommendations (Cheung et al., 2012)? The ambiguity surrounding the reliability of information and the actual persuasive capability of different social media facets necessitates empirical investigation to provide clear guidance for businesses operating in this digital space.

The critical ambiguity surrounding the reliability and persuasive efficacy of diverse digital content necessitates empirical validation, especially within the context of emerging markets like Nepal, where digital adoption is rapid but trust is often fragile (Dwivedi et al., 2021). This study, therefore, aims to rigorously address this problem by quantifying the relative influence of specific social media elements on consumer behaviour. The primary research objective is to comprehensively determine the overall impact of Social Networking Sites (SNSs) on the Purchase Decision of Consumers within the Kathmandu Valley. More specifically, the study seeks to ascertain the differential effects of four key antecedents: online reviews (a form of electronic word-of-mouth or eWOM) (Reddy et al., 2025), user trust, information accessibility, and social media advertisement (Kothari et al., 2025; Awasthi et al., 2025).

These explanatory aims necessitate the formulation of testable hypotheses, which are directly informed by the core Research Questions (RQs 1-4). Consequently, the study derived four corresponding null Research Hypotheses (H0) for validation through Multiple Linear Regression: H01 posits no significant relationship between online review and the Purchase Decision (Cheung & Thadani, 2012); H02 states no significant relationship exists between user trust and the Purchase Decision (Gefen et al., 2003); H03 suggests no significant relationship between information accessibility in social media and the Purchase Decision (Kulkarni et al., 2012); and H04 holds no significant relationship between online advertisement and the Purchase Decision (Voorveld et al., 2018). The Significance of the Study is multi-faceted: theoretically, it provides novel empirical evidence from the Nepalese market, thereby enriching the cross-cultural literature on digital consumer behavior modeling; managerially, it offers vital, data-driven insights for marketers seeking to strategically optimize resource allocation across various digital promotional channels (Kumar et al., 2016). While delivering these key insights, the investigation is necessarily subject to specific Limitations, notably a constrained sample size of N=150, geographical confinement exclusively to the Kathmandu Valley, and the inherent causality constraints of a quantitative, cross-sectional survey approach (Podsakoff et al., 2003).

2. Materials and Methods

The methodological foundation of this study is built upon a detailed, systematic, and rational approach to data acquisition and analysis, ensuring the findings are both robust and traceable back to the study stated objectives, as outlined in the Introduction. This process adheres to the rigorous standards required for empirical research.

2.1 Research Design, Population, and Sampling

The study employed a rigorous quantitative research design, primarily adopting a dual approach: descriptive research was used for summarizing the characteristics of the respondent population and quantifying their average perceptions, while explanatory study was leveraged to test the causal hypotheses H_{01} to H_{04}) (Hair et al., 2017; Zikmund et al., 2013), measuring the precise impact and relationship between the independent variables (Social media advertisement, Trust, Access to information, and Reviews) and the dependent variable, the Purchase Decision of the Consumer. The defined target population for this study comprised active Social Networking Sites (SNSs) users. This population was geographically confined to the Kathmandu Valley, Nepal. This specific delimitation was strategic, as the Kathmandu Valley serves as the nation primary economic, educational, and digital communication hub, characterized by the highest density of internet penetration and commercial activity. This concentration provides a robust and accessible segment of digitally engaged consumers, which is essential for studying the purchase decision process. The final sample was composed of 150 respondents (N=150), a size determined to ensure sufficient statistical power and degrees of freedom for the planned multivariate analyses (Hair et al., 2017), including Multiple Linear Regression (MLR), while adhering to resource and time constraints. To maximize the sample representativeness and minimize sampling bias within the geographical limits, this study utilized a SRS technique (Taherdoost, 2016), a form of probability sampling that is a critical procedural requirement for ensuring the validity of parametric statistical inferences.

Table 1: Overview of Data Characteristics, Variables, Sampling, and Analytical Techniques Used in the Study

Feature	Description/Data	Relevance to Study and Results Section
Data Type	Primary Data	Collected via Structured Questionnaire (Survey Method). Directly feeds into descriptive and inferential analysis.
Target Population	Active Social Media Users	Confined to the Kathmandu Valley, Nepal, providing the contextual basis for findings.
Sample Size	N = 150	Ensures sufficient degrees of freedom and statistical power for Multiple Linear Regression.
Sampling Technique	Simple Random Sampling	Minimizes bias, supports parametric analysis, and enhances result credibility.
Variables (IVs)	Social media Advertisement, Trust, Access to Information, Reviews	These four variables are used directly as predictors in the Regression Coefficient (Table 4.21).
Variable (DV)	Purchase Decision of Consumer	This variable is the outcome being measured and is the focus of all analyses.
Statistical Software	SPSS	All analysis, including correlation (Table 4.18) and regression (Table 4.21), was performed using this package.
Analytical Techniques	Descriptive Statistics, Correlation Analysis,	These techniques directly generated the results presented

	Multiple Linear Regression	in Sections 4.3 (Descriptive) and 4.4 (Inferential Analysis).

2.2 Instrumentation and Data Integrity

Data collection was executed using the survey method, relying entirely on primary data gathered through a structured questionnaire. This instrument, which was self-administered, consisted of two main sections: Section A (Respondent Profile), which captured demographics and usage patterns, and Section B (Variable Measurement), which operationalized the constructs. The items in Section B were measured using a five-point Likert scale (ranging from 1=Strongly Disagree to 5=Strongly Agree) (Joshi et al., 2015). The complete measurement items used to construct the independent variables (Social media advertisement, Trust, Access to Information, Reviews) and the dependent variable (Purchase Decision of Consumer) are detailed in Table 3.1.

Table 2: Measurement items for Independent and Dependent Variables

Variable	Measurement Items (Sample Statements)
Social media Advertisement	I believe advertisement in social media provides useful information. / Social media advertisement enhance my impression towards a product. / Social media advertisement encourage me to buy a new product that had not planned earlier. / After viewing advertisement in social media I develop preferences for the brand in advertisement.
Trust	I do not doubt the honesty of information through SNSs. / I believe the safety and privacy of my information is prioritized. / I believe advices through SNSs are good for me. / I find products in SNSs trustworthy, it matches with my expectations.
Access to Information	I search for related information on social media before a purchase. / I find searching information is easier via social media comparing to mass media (e.g., T.V, radios, newspaper). / I am able to seek out products and services information initiatively (actively) through SNSs. / I rely on the information on social media if I have uncertainties regarding the purchase.
Reviews	I find reviews on SNSs reliable. / Reviews help me to compare the products or services while purchasing. / I feel the reviews are unbiased. / I like to share comments/reviews to peers via social media after a purchase.

Purchase Decision of Consumer	I purchase as per the information provided through Social media advertisements. / I purchase only from the trusted sources. / I purchase the product or service only after I get all the information. / I purchase as per the reviews I get about the product or services.

Finally, the study ensured data integrity by confirming both Content Validity (through an exhaustive literature review) and reliability. Reliability was established by statistically testing the internal consistency of the multi-item scales using Cronbach's Alpha (α), which is formally expressed as (Tavakol & Dennick, 2011):

$$\alpha = \left(\frac{k}{k-1}\right)\left(1 - \frac{\sum_{i=1}^{k} \sigma_i^2}{\sigma_t^2}\right) \quad \text{Eq. 1}$$

Where k is the number of items, σ_i^2 is the variance of item i, and σ_t^2 is the total variance of the observed test scores.

As demonstrated in Table 3.1, all measured constructs yielded an alpha value of 0.70 or higher, with results ranging from 0.725 (for both Trust and Purchase Decision) to 0.776 (for Reviews). This provided the necessary assurance that the measurement instrument was stable, consistent, and suitable for the subsequent Correlation and Regression Analysis performed using the Statistical Package for the Social Sciences (SPSS) software.

2.3. Data Analysis and Assumption Testing

All collected primary data was coded, cleaned, and analyzed using the Statistical Package for the Social Sciences (SPSS) software. The analytical plan involved three sequential steps: Descriptive Statistics (Mean and Standard Deviation) to summarize the data; Correlation Analysis (Pearson: r) to determine linear relationships between variables; and Multiple Linear Regression Analysis to test the predictive relationships and hypotheses (Field, 2018).

The analysis began with the Correlation Analysis, which utilized the Pearson Product-Moment Correlation Coefficient (r) to assess the magnitude and direction of the linear relationship between the independent variables (Social media Advertisement, Trust, Access to Information, Reviews) and the dependent variable (Purchase Decision of Consumer). The Pearson (r) is formally expressed as (Field, 2018):

$$r_{xy} = \frac{\sum_{i=1}^{N} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{N} (X_i - \bar{X})^2 \sum_{i=1}^{N} (Y_i - \bar{Y})^2}} \quad \text{Eq 2}$$

Where X_i and Y_i represent the scores for the two variables (e.g., Trust and Purchase Decision) for the i-th respondent, $\bar{X}$ and $\bar{Y}$ are the respective sample means, and N is the sample size ($N = 150$). This analysis was performed primarily to confirm the necessary linear association-a prerequisite for proceeding to the multivariate regression model.

Subsequently, the hypothesized predictive relationships between the variables were tested using the Multiple Linear Regression Model, which models the dependent variable (Y) as a linear function of multiple independent predictors (X_k) (Field, 2018):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \epsilon \qquad \text{Eq 3}$$

Where: Y represents the Purchase Decision of Consumer (DV); β_0 is the intercept; X_1, X_2, X_3 , and X_4 are the independent variables (Social media Advertisement, Trust, Access to Information, and Reviews, respectively); β_1 to β_4 are the respective standardized regression coefficients representing the unique effect of each independent variable on Y when controlling for the others; and ϵ is the random error term.

Crucially, prior to interpreting the Regression model results, the core assumptions of Multiple Linear Regression were verified. The assumption of Multicollinearity-where independent variables are highly correlated with each other, potentially inflating standard errors-was assessed using the Variance Inflation Factor (VIF), calculated for each predictor (X_i) as (James et al., 2013):

$$VIF_i = \frac{1}{1-R_i^2} \qquad \text{Eq 4}$$

Where R_i^2 is the coefficient of determination when the i-th independent variable is regressed on all other independent variables. Other assumptions, including the normality of residuals, linearity, and homoscedasticity, were checked using residual plots and tests to ensure the reliability of the inferential findings.

3. Results and Discussion

The presentation of the study findings adheres strictly to the predetermined structure outlined in the methodology, moving systematically from descriptive statistics and measurement validation to rigorous hypothesis testing. This approach ensures all results are objectively presented before proceeding to interpretive discussion, aligning with the study descriptive and explanatory research objectives.

3.1. Presentation of Results

3.1.1. Respondents Profile

The demographic analysis provides the essential context of the study sample, drawn from active social media users in the Kathmandu Valley via simple random sampling. The profile details the gender, age, educational qualifications, and occupation of the

150 respondents. For instance, the gender distribution shown in Figure 1 confirms the equitable representation of consumer segments critical to the study generalizability within the defined geographical limit.

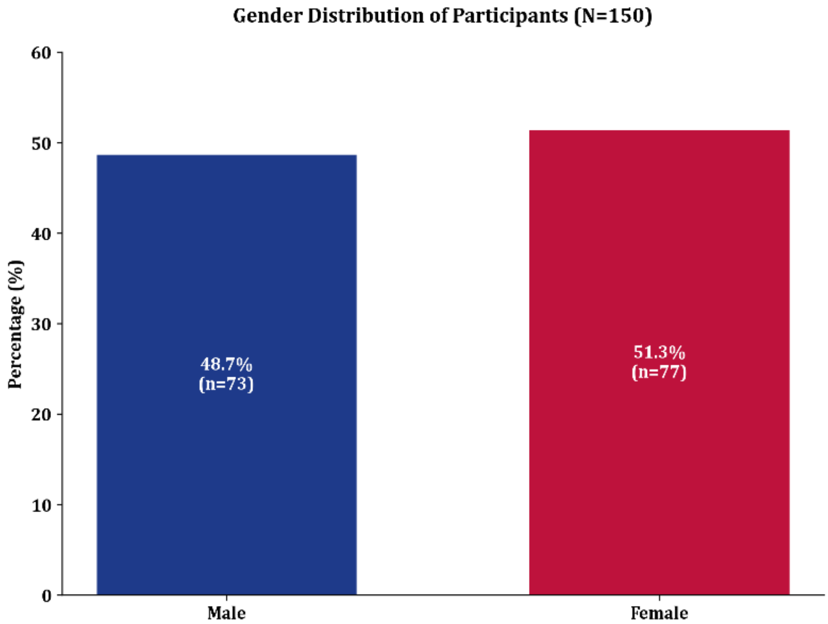

Figure 1: Gender distribution of study participants. Bar chart showing the percentage and frequency of male (n = 73, 48.7%) and female (n = 77, 51.3%) participants in the sample (N = 150).

3.1.2. Measurement Validation and Reliability

Prior to proceeding with hypothesis testing, the quality and consistency of the measurement instrument were confirmed through a reliability analysis using Cronbach's Alpha (α). As demonstrated in Figure 2, all five measured constructs (four independent variables and one dependent variable) yielded an alpha value of 0.70 or higher. The results ranged from 0.725 (for both Trust and Purchase Decision) to 0.776 (for Reviews). This robust finding confirms the acceptable internal consistency of the multi-item scales, providing the necessary assurance that the measurement instrument was stable, consistent, and suitable for the subsequent inferential analysis using SPSS software.

3.1.3. Descriptive Analysis

The Descriptive Statistics, including the Mean and Standard Deviation, summarize the respondents average perceptions regarding the dependent variable, Purchase Decision of Consumer (PDC). As presented in Figure 3, the composite Mean score for PDC is 4.32 (S.D. = 0.488). Given the five-point Likert scale, this high mean indicates a strong overall agreement among active social media users in the Kathmandu Valley that social media significantly influences their purchasing decisions. Specifically, respondents reported the highest agreement with purchasing only after receiving all information (P3: Mean=4.37) and purchasing based on reviews (P4: Mean=4.36), suggesting that information seeking and peer validation are critical stages in their purchase journey.

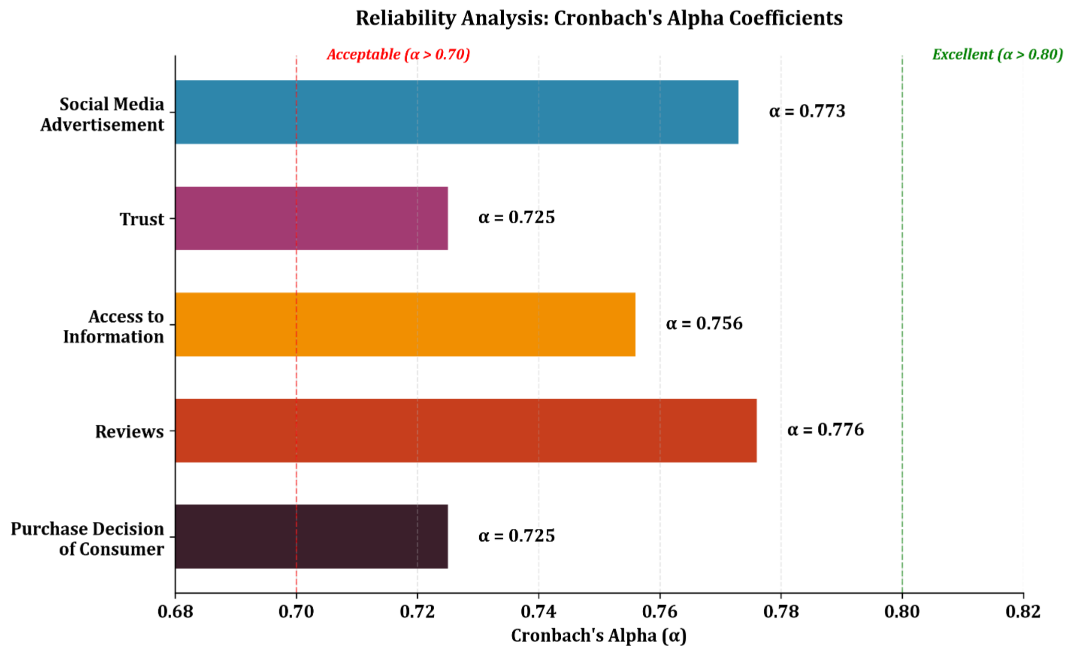

Figure 2: Cronbach's alpha coefficients for reliability analysis of research constructs

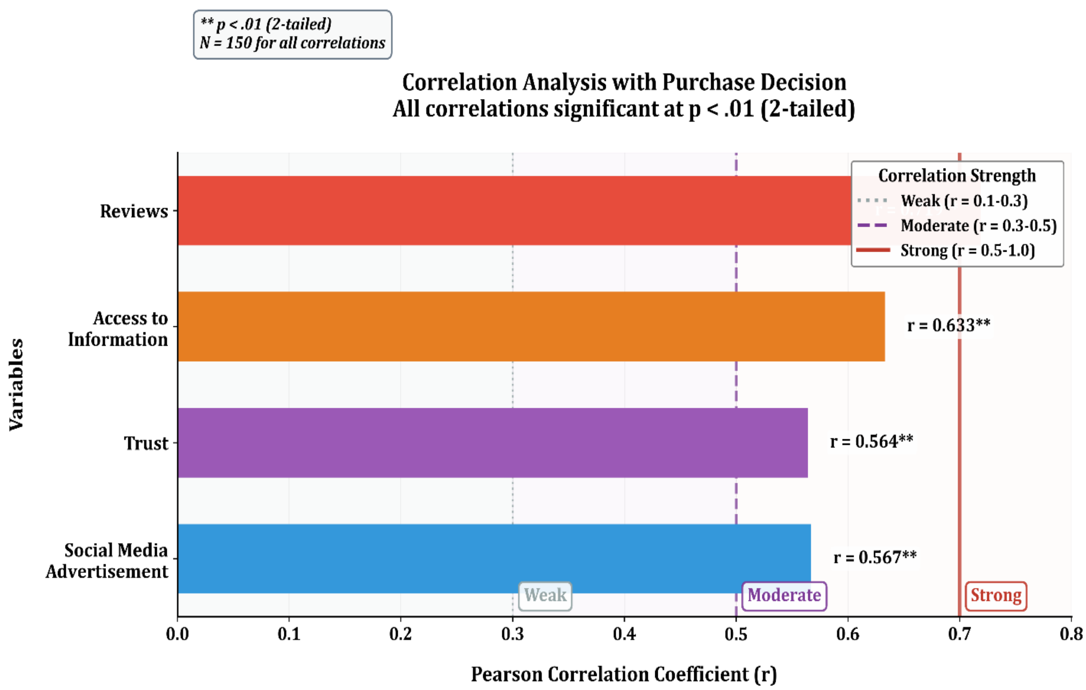

Figure 3: Pearson Correlation Coefficients between Research Variables and Purchase Decision (N=150)

3.2. Inferential Analysis and Hypothesis Testing

3.2.1. Correlation Analysis

The Pearson Correlation Analysis was conducted to determine the nature and strength of the linear relationships between the independent variables and the Purchase Decision of the Consumer. Figure 4 reveals that all four independent variables exhibit a statistically significant positive correlation with the Purchase Decision ($p < 0.01$). Notably, Reviews showed the strongest correlation ($r = 0.719$), followed by Access to Information ($r = 0.633$). These results confirm a strong initial association among all variables, establishing the necessary precondition for proceeding to the more advanced multivariate technique.

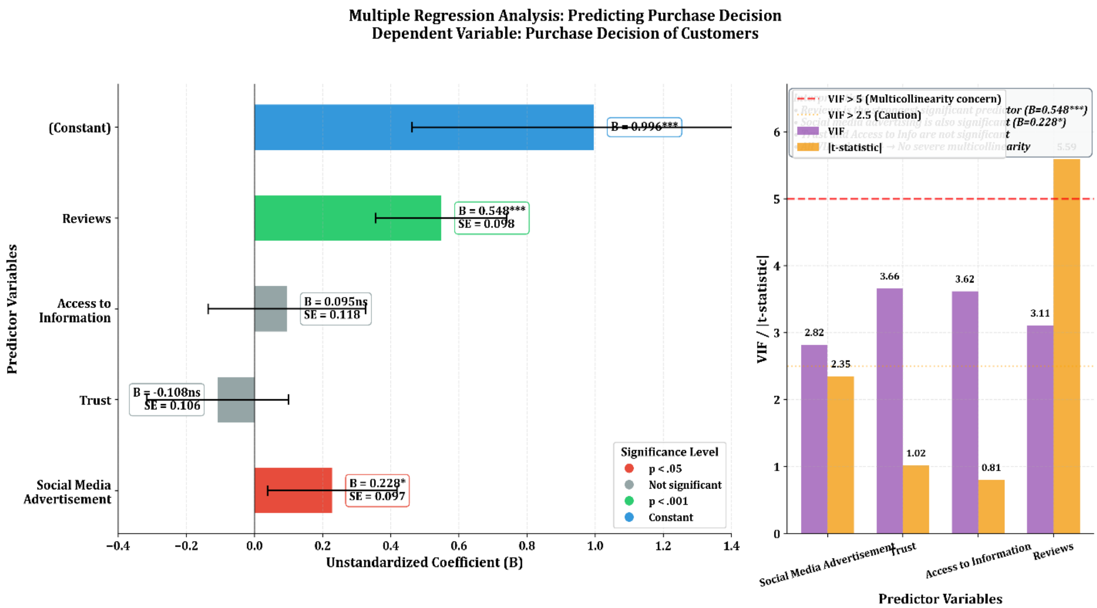

Figure 3: Multiple Regression Analysis of Factors Influencing Purchase Decisions

3.2.2. Multiple Linear Regression

The Multiple Linear Regression Analysis was performed to examine the unique predictive contribution of each independent variable on the Purchase Decision of the Consumer when controlling for the effects of the other predictors.

Multicollinearity Diagnostics: Prior to interpreting the coefficients, the assumption of Multicollinearity was verified using the Variance Inflation Factor (VIF). As demonstrated in Table 4.21, the VIF values for all independent variables (ranging from 2.820 to 3.661) were significantly below the conventional threshold of 5 (or 10). This confirms that multicollinearity was not a concern, and the regression model is stable for interpretation.

Hypothesis Testing Results: The analysis provided clear results for hypothesis testing, as summarized in Table 3 and visually represented in the conceptual model below.

Table 3: Regression Coefficient

Model	**Unstandardized Coefficients**		**Standardized Coefficients**	**T**	**Sig.**	**Collinearity Statistics**
	B	**Std. Error**	**Beta**			**VIF**
(Constant)	.996	.272		3.665	.000	
Social media Advertisement	.228	.097	.222	2.355	.020	2.820
Trust	-.108	.106	-.110	-1.023	.308	3.661
Access to Information	.095	.118	.086	.805	.422	3.619
Reviews	.548	.098	.591	5.974	.000	3.110

Hence, the MLR analysis yielded a definitive and differential pattern of influence on consumer behaviour. The results unequivocally demonstrate that both online reviews ($\beta=0.591$; $p=0.000$) and social media advertisement ($\beta=0.222$; $p=0.020$) exert a statistically significant and positive impact on the Purchase Decision of consumers. The magnitude of the standardized coefficient for Reviews, being the highest, confirms it as the single most potent predictor of purchase commitment. Conversely, the analysis found that trust ($p=0.308$) and the mere access to information ($p=0.422$) were not statistically significant drivers of the purchase decision in this predictive model. This critical distinction suggests that while consumers utilize social media for initial association and information retrieval, the final act of purchasing is overwhelmingly driven by peer-validated content (Reviews) and targeted promotional stimulus (Advertisement).

3.3. Discussion

The primary aim of this study was to quantify the impact of four specific social media elements on the purchase decisions of consumers within the Kathmandu Valley, Nepal (Cheung & Thadani, 2012; Hajli, 2014). The regression analysis yielded a clear and differential pattern of influence (Field, 2018). Contrary to the initial null hypotheses, online reviews (H_{01}) and social media advertisements (H_{04}) demonstrated a statistically significant and positive impact on purchase decisions (Voorveld et al., 2018; Gefen et al., 2003). Conversely, the findings failed to reject the null hypotheses for user trust (H_{02}) and access to information (H_{03}), indicating that in the context of this model and sample, these factors did not exert a significant direct influence on the final purchase decision (Davis, 1989). This finding on trust suggests it may operate as a foundational hygiene factor, necessary for platform engagement but insufficient as a direct purchase trigger when more potent stimuli like reviews and ads are present (Gefen et al., 2003).

Similarly, the non-significant result for information accessibility highlights a distinction between merely having information and acting upon it; while social media is a key source for discovery, the decision is finalized by the evaluative content (reviews) and promotional prompts (ads) accessed through the platform (Hair et al., 2017). This study provides novel empirical evidence from the under-researched context of Nepal, enriching the cross-cultural understanding of digital consumer behavior (Dwivedi et al., 2021; Kumar et al., 2017). Theoretically, it demonstrates the contextual nature of behavioral models and underscores the importance of model specification by moving beyond simple correlations (Bakar, et al., 2013). Managerially, it offers clear guidance: businesses should prioritize cultivating positive electronic word-of-mouth (eWOM) and investing in targeted social advertising (Kothari et al., 2025).

Moreover, trust and information strategies should be reconceptualized; transparency and informative content are vital for attracting consumers in the early stages, but conversion relies on leveraging social proof and direct promotional prompts (Awasthi et al., 2025). This study conclusions are tempered by several limitations, which also chart a course for future inquiry. The sample was confined to 150 active social media users in the Kathmandu Valley (N=150), limiting generalizability (Taherdoost, 2016). The cross-sectional survey design cannot definitively establish causality (Podsakoff et al., 2003). Future study should employ larger, nationally representative samples, longitudinal designs to track actual behavior, and expanded models incorporating factors like influencer marketing. A mixed-methods approach is also recommended to better understand the nuanced psychological underpinnings of these quantitative findings (Tavakol & Dennick, 2011).

4. Conclusion

This study demonstrates that social medias influence on consumer purchase decisions in the Kathmandu Valley, Nepal, is not uniform across all platform features but is strategically concentrated. The findings provide definitive empirical evidence that online reviews and targeted social media advertisements are the primary and statistically significant drivers of purchase conversion for this demographic.

In contrast, while consumers actively use social media for discovery, the general constructs of platform trust and the mere accessibility of information do not directly translate into final transactional actions within the predictive model. These results carry substantial implications: for academia, they enrich the cross-cultural literature on digital consumer behavior, highlighting the nuanced role of trust as a foundational precondition rather than a direct driver in certain emerging markets; for practitioners in Nepal, they offer a clear, data-driven mandate to prioritize resource allocation towards sophisticated eWOM management and compelling social media advertising campaigns to effectively convert consumer attention into sales. Ultimately, the research validates social media as a decisive commercial platform in urban Nepal, with success contingent upon a brand's ability to master the dual engines of authentic peer validation and professionally crafted promotional stimuli.

Author Contributions: Conceptualization, Meera Sharma and Niraj KC; Methodology, Meera Sharma; Software, Meera Sharma; Validation, Meera Sharma and Niraj KC; Formal Analysis, Meera Sharma; Investigation, Meera Sharma; Resources, Niraj KC; Data Curation, Meera Sharma; Writing Original Draft Preparation, Meera Sharma; Writing Review & Editing, Niraj KC; Visualization, Meera Sharma; Supervision, Niraj KC; Project Administration, Niraj KC. All authors have read and agreed to the published version of the manuscript.

Supplementary Materials

a. *Data Availability Statement*: The primary data that support the findings of this study are available from the corresponding author, Niraj KC, upon reasonable request. This includes the coded survey data and SPSS output files generated during the analysis. The questionnaire used for data collection is provided in the Annexure of the manuscript.

b. *Data Sources*: This study is based exclusively on primary data collected via a structured survey questionnaire. No secondary datasets, such as satellite imagery or geological maps, were used, as the research focuses on behavioral analysis.

c. *Generative AI Statement*: During the preparation of this manuscript, the authors used generative artificial intelligence (AI) tools for the limited and specific purpose of paraphrasing text, correcting grammar, and enhancing the overall readability and academic tone of the English language. All central ideas, hypotheses, data analysis, interpretations, conclusions, and recommendations are the original work of the authors. After employing these AI-assisted tools, the entire manuscript was thoroughly reviewed, fact-checked, and edited by all authors to ensure the integrity and accuracy of the academic content. The authors take full and final responsibility for the published work.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Conflicts of Interest: The authors declare no conflict of interest.

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A Fear of the Digital Era: Nomophobia and Its Prevalence Among Teachers and Students

Reg Bahadur Bhandari[1*], Dinesh Shahi[2]

[1] Registrar, Lumbini Technological University, Nepalgunj, Nepal

[2] Faculty Member, Mt. SEB Koteshwor, Nepal

*Corresponding Email: registrar@ltu.edu.np

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Abstract

Smartphones have been fascinating digital gadgets, and everyone in the present digital generation desires to have one and get access to the services they offer. However, a sort of irrational anxiety or fear may arise when one is out of smart phone contact. The phobia that relates to no mobile phone is termed nomophobia. The study was designed with the objective of measuring the nomophobia level of teachers and students and determining whether or not there is any significant difference between the pattern of smartphone use and nomophobia. A correlational study was conducted among 195 participants (150 students and 45 teachers). Questionnaires related to demographic variables, patterns of smartphone use, and the nomophobia questionnaire (NMP-Q) are used for this purpose. The study showed that out of 45 teachers, 13 (28.9%) had severe nomophobia. Similarly, out of 150 students, 38 (25.3%) had severe nomophobia. However, the female gender showed a greater level of nomophobia than males. The use of smartphones for making calls, texting and chatting, connecting to social media, searching for information on the internet, listening to music and watching movies, gaming, and killing time had a significant effect on increasing nomophobia levels.

Keywords: *Nomophobia, Smart Phone, Mobile, Information Technology*

1. Introduction

Our lives have been considerably more simplified by the creative and advanced tools, methods, and strategies that the modern digital world has to offer. The rapid growth of technology has brought about a significant shift in our way of thinking, acting, and living. Everyone depends on technology these days. Technology has permeated every aspect of human existence. Information and communication technology (ICT), nanotechnology, biotechnology, wireless data transfer, man-machine connection, on-demand printing, and sophisticated robotic mechanisms are some examples of rising technologies (Essays UK, 2018). The modern era can be considered the ICT era. Technology of today offers a plethora of fascinating and cutting-edge goods. A smartphone is one such gadget.

These days, technology governs our life. In the modern world, we are so reliant on smartphones, tablets, laptops, and other digital devices that we find it impossible to envision living without them. In fact, we find it impossible to operate without them. When we refer to electronic devices as "smart," we mean those that possess independent computing power, are able to connect to a network, and can communicate with other devices and people on their own (López et al., 2018). All that a typical cell phone is used for is two-way communication. Smartphones are now used for more than just making phone conversations because to the development of Internet technology and applications. These include emailing and receiving, chatting, sharing documents and photographs, reading news, and exploring the web, online selling and buying and many more (Alfawareh & Jusoh, 2017). The "world of apps," which was made possible by smartphones and offers users applications for nearly anything, has caused a shift in daily tasks to electronic devices (Kanmani, 2017). The popularity of social media apps like Facebook, Instagram, WhatsApp, and Twitter has skyrocketed since the invention of smartphones. A smartphone can be seen of as a pocket-sized version of a portable computer that allows for "social interaction, a way for content sharing, and build collective intelligence" (Alfawareh & Jusoh, 2017).

Utilizing technology and making use of it has a significant impact. Technologies are all around us, but are we really employing them or are we just putting them to use? A large question mark appears. The same applies to smartphones. How do we use our smartphones? Do we use our smartphones when we need to? Or do we really want and need a smartphone with us at all times and everywhere? If so, what occurs when we lose our cell phones or are unable to access them? Is there ever any worry or concern when we find ourselves without a cell phone or without network coverage? If so, we are certain to have a mental illness, which we refer to as “Nomophobia”.

The influence of using and utilizing technology is substantial. Although we are surrounded by technologies, do we actually use them or are we just putting them to use? A big question mark shows up. The same is true for mobile devices. How are our smartphones used? Do we utilize our cellphones when it's necessary? Or do we actually need and want a smartphone that we carry about with us all the time? If yes, what happens if we misplace our phones or can't access them? When we are without a cell phone or network coverage, is there ever a cause for anxiety or worry? If so, we can be positive that we have a mental disease, which we call Nomophobia.

The unreasonable dread or anxiety associated with not having access to a cell phone or being outside of cell phone contact is known as nomophobia, a modern phobia. Anxiety has a negative impact on a person's ability to focus on everyday work, can alter daily routines, and negatively impact academic progress in students who experience nomophobia. Gezgin, Mertkan, and Adnan (2016). Overuse of cellphones has been identified as a type of technology addiction that is quickly becoming into a global social problem. Therefore, the goal of the study is to identify the patterns and degree of smartphone usage.

Smartphones are a useful tool for teachers to complement their teaching-learning strategies. In a similar vein, students in the digital age use digital tools for their studies, and modern educational establishments place a strong emphasis on increasing students' digital literacy. However, improving mobile learning programs and initiatives while nomophobia coexists is a significant problem for everyone. The purpose of this study is to quantify the prevalence of nomophobia and identify at-risk groups. The influence that nomophobia can have on social functioning and overall quality of life makes it imperative to assess the level of prevalence of this condition among educators and students.

1.1 Research Questions

The present study entitled "A Fear of Digital Era: Nomophobia and its Prevalence among Teachers and Students" basically focuses to measure prevalence of nomophobia among teachers and students. It also studies the pattern of smartphone usage. To achieve this objective, following research questions are formulated:

a. What is level of nomophobia and its sub-dimensions ("not being able to communicate", "losing connectedness", "not being able to access information", "giving up convenience") among teachers and students?
b. Is there any significant difference between nomophobia levels with regard to certain demographics such as gender, age, marital status, education qualification, and current active role as a teacher or a student?

2. Review of Literature

The present digital era is the period where digital technologies play a prominent role in shaping up and regulating the behaviours, performances, standards, etc., of societies, communities, organizations, and individuals (Liyanage, 2011). And this modern digital age is the shift from mechanical and analogue electronic technology to digital electronics. It can be said that the digitalization started with the invention of computing devices and personal computers. The invention of transistors, and integrated circuits helped in development of electronic devices of reduced size and cost, but with greater processing ability. This has made the computing devices to be accessible to general people. The invention and popularity of internet, www and social media has brought about a drastic change in communication. The invention of smartphone helped people a lot in greater interconnectedness, easier communication, and the exposure to information. The people of the present digital era are surrounded by a good number of digital gadgets. This has certainly changed the way we live, think and act. For instance, a few years back, people used to note down phone numbers in address book or memorize phone numbers of the ones they have to frequently make calls to. But, at present, the scenario has changed; people save phone numbers in digital gadgets and hardly remember or memorize anybody's phone numbers. We can experience the digitalization. People, staying within a room can select, order and make payments for food items or daily commodities from online stores. One can open bank account or transfer money between different branches without physically visiting a bank. There has been a dramatic change in the way works are performed. Educators always opt to find smart solutions to implement new and the best teaching practices, and improve quality of education (Donald, 2014). The digital era, indeed, is transforming the way children and young people play, access information, communicate with each other and learn (Lonka & Cho, 2015). Teachers and students in the digital era have easy and instant online access to infinite information and numerous teaching and learning activities of adults and children at school, at home, and in public places (Battro & Fischer, 2012). So, educating and learning, in a sense, is an easy task; but yet a challenging task as children and students should be able to determine and process only information what are right for them. Distance learning, m-learning, e-learning are some of the new trends of education system that are being practised in the present digital world. The digital learning provides a non-threatening environment (fear) for learners to study and learn subject matter at their own pace.

Nomophobia can be referred to as a form of behavioural addiction towards smartphone that causes anxiety by disconnection from the mobile network or inability to have access to a smartphone (Anshari et al., 2019). Nomophobia has multi-dimensional traits ranging from social, physiological, and physical symptoms that are summarized into very dependency upon smartphone. The study (Anshari et al., 2019) examined nomophobia among youth and how to overcome nomophobia. The study deployed a qualitative approach by interviewing respondents mostly at their first-year undergraduate level and text mining analytics from respondents' conversation to extract the common patterns, characteristics, and proposed solutions for nomophobia.

Nomophobia is defined as the fear of being out of mobile phone contact and is considered a modern digital phobia introduced to our lives as a by-product of the interaction between people and mobile information and communication technologies, especially smartphones (Yildirim et al., 2016). A nomophobia is characterized by four dimensions: a) not being able to communicate, b) losing connectedness, c) not being able to access information, and d) giving up convenience.

Besides smartphones help students being motivated and act as effective tools in building up confidence level and self-esteem, the smartphone also has negative impacts on the students when they overuse it. It helps teachers in preparing lecture notes, have frequent communication with their colleagues and students, check emails and many more. It may cause users being stressed with disturbed health. It affects neck pain, lack of sleep, headache, shoulder ache, finger pain, eye strain and many more. "The mobile phone has been dubbed as one of the biggest non-drug addictions of the 21st century". (Dongre et al., 2017)

Another study research carried out illustrated certain psychiatric disorders of nomophobia. It emphasized its study on symptoms of nomophobia such as anxiety, nervousness, discomfort, and distress when contact with the smartphone was lost, mainly in the youngest users. The study included a representative sample of 461 students in different years of study engineering (21% women, 79% men, over 17 years of age). Three symptomatic factors of nomophobia were identified: feelings of anxiety, compulsive smartphone use, and feelings of anxiety and panic. (Rosales-Huamani et al., 2019)

A cross sectional study was conducted among the students of a medical college of Wayanad District in India to find out the prevalence of nomophobia and its determinants among students of a medical college using new nomophobia questionnaire (NMP-Q). The prevalence of nomophobia was found to be 97%. Nomophobia was not found to be associated with sex, quota of admission, place of origin, and place of stay. 99.06% students were using smart phones for calling family members, 91.84% for calling friends and 88.57% for listening to music. (M, P, TV, Gopi, & Fernandes, 2017)

A study to investigate the prevalence of nomophobia among young adults was carried out in Turkey. The Nomophobia Questionnaire (NMP-Q) was administered among 537 Turkish college students. The results revealed 42.6% of young adults had nomophobia, and their greatest fears were related to communication and information access. The study also found that gender and the duration of smartphone ownership had an effect on young adults' behaviours related to nomophobia, whereas age and the duration of normal mobile phone ownership had no effect. (Yildirim et al., 2016)

A study was carried on 1500 smartphones in India to give an insight into the levels of nomophobia and its psychological aspects. Snowball Sampling was used to collect data through NMP-Questionnaire. The study correlated different variables such as age, gender and occupation and found that females had higher levels of nomophobia in comparison to male students and students of ages 18 to 24 had higher level of nomophobia than working class people.(Kanmani, 2017)(Bhavani & Maragatham, 2017)

A study was conducted by (Gezgin et al., 2017) Nomophobia, sometimes known as "phobia of the modern era," is the term used to describe the worry and anxiety that a person experiences when they are unable to access or use mobile devices. It is believed that a rise in the use of smartphones has led to a rise in nomophobia among people in society due to the greater engagement with these devices. People with nomophobia have trouble concentrating on their job in all facets of their lives. Nomophobic behaviors can alter regular routines including sleeping patterns and focus during class; in particular, nomophobia negatively impacts students' academic performance and school life. This study aims to determine the prevalence of nomophobia among 818 pre-service teachers enrolled in several departments at a Turkish state university in the fall semester of 2015–2016. Descriptive statistics, an independent sample t-test, and one-way ANOVA analyses were employed in this causal-comparative investigation. The instrument's mean score indicated that pre-service teachers had higher levels of nomophobia than the average group, and they were concerned about their inability to communicate and obtain knowledge. Furthermore, despite no discernible difference in the number of hours spent using a mobile phone, female pre-service teachers were shown to be more nomophobic than their male counterparts. Furthermore, it has been seen that nomophobia reduces with age; however, the opposite is true when it comes to the frequency of smartphone use, with nomophobia increasing as such usage increases.

A cross sectional study was carried out by (Kubrusly et al., 2021), on “Nomophobia among medical students and its association with depression, anxiety, stress and academic performance” which has been described as technology adoption continues to be one of the key indicators of human progress as the world grows more linked. The mental illness known as nomophobia, or NO MObile PHONE PhoBIA, is brought on by the anxiety of being cut off from mobile phone connectivity. This kind of condition is closely linked to stress, anxiety, and depression. Nomophobia can also result in structural brain damage.

The purpose of this study is to evaluate how nomophobia affects medical students at a private university and how it relates to stress, anxiety, depression, and academic achievement.

This cross-sectional observational study was conducted at Centro Universitário Christus with medical students. The Nomophobia Questionnaire (NMP-Q) was used to quantify nomadism. 20 questions make up the NMP-Q, and each question is rated on a 7-point Likert scale. Validation of this scale has been done for Brazilian Portuguese. A condensed version of the DASS instrument, the DASS-21, was used to measure stress, anxiety, and depression. Brazilian Portuguese language validation was also performed for the DASS-21 questionnaire. The API, the outcome of a difficult mathematical process that yields the student's average grade for the semester and serves as a reference index for pedagogical follow-up in the evaluated institution, was used to quantify academic performance. The behaviors of using devices were also evaluated. Bivariate studies of association and correlation were carried out, and descriptive results were given. The research ethics committee gave their approval for this project. A sample of 292 pupils underwent evaluations. 99.7% of students reported having some degree of nomophobia, while 64.5% reported moderate to severe symptoms. Over 50% of the students reported stress levels greater than mild, and 19.5% and 11.2% of students, respectively, reported severe or very severe levels of anxiety and depression. Upon examining the relationship between NMP-Q and DASS-21 scores, it was shown that lower API scores are linked to lower DASS-21 outcomes, and that rises in NMP-Q result in increases in the overall DASS score ($p < 0.001$). The study was concluded as nomophobia was likely to worsen anxiety, tension, and sadness, which will lower academic performance.

A journal has been published on “Adaptation of the European Portuguese Version of the Nomophobia Questionnaire for Adolescents, Factor Structure and Psychometric Properties” by (Galhard et al., 2022) as illustrated Nomophobia as a phobia specific to the digital age that is characterized by an overwhelming fear of not having a smartphone. The effects of nomophobia on one's physical and mental well-being are particularly severe in young people. The purpose of this study was to evaluate the factor structure and psychometric qualities of the Nomophobia Questionnaire for Adolescents (NMP-Q–A), which is available in European Portuguese. Sample 1 was used to investigate the factor structure, psychometric qualities, and correlation with other constructs of the NMP-Q-A. It included 338 teenagers (58.6% female), with a mean age of 13.55 (SD = 2.07). To examine the NMP-Q–A factor structure further, sample 2 consisted of 193 teenagers (53.9% boys) with a mean age of 13.61 (SD = 0.80) years. A structure consisting of one higher-order factor and four lower-order factors demonstrated a satisfactory match to the data in both samples. The NMP-Q-A demonstrated strong concurrent validity, construct validity, and reliability. There was more nomophobia in girls. Teens with higher levels of nomophobia also reported higher levels of smartphone addiction, psychopathological symptoms, and a worse standard of living. In clinical and educational contexts, the NMP-Q-A has proven to be a viable and trustworthy assessment.

The previous studies show that lots of research studies have been carried out to explore the fact on how excessive use of smartphone is related with nomophobia. The studies tried to relate nomophobia with different demographic variables such as age, gender, education qualification, and so on. The studies were carried out to find factors that are instrumental for increment of nomophobia level. Many studies have been carried out in abroad countries to examine and explore facts about nomophobia and develop awareness among people. However, there seems to be no study to my knowledge that any study related to nomophobia has been carried out in Nepal. So, with a view point to examine the prevalent of nomophobia among teacher and students and to what extent it exists, this study is carried out. Hope this will make people knowledgeable about nomophobia and develop some strategies to tackle the issues resulted from nomophobia in this digital era.

The current study is an attempt to support the previous studies that dealt with nomophobia and pattern of mobile phone use. Probably this study will put an extra effort to previous studies carried out so far.

2.1 Conceptual Framework

The study puts light on what nomophobia is and its prevalence among students. It tries to explore nomophobia relating with different demographic variables and pattern of use of smartphones by teachers and students.

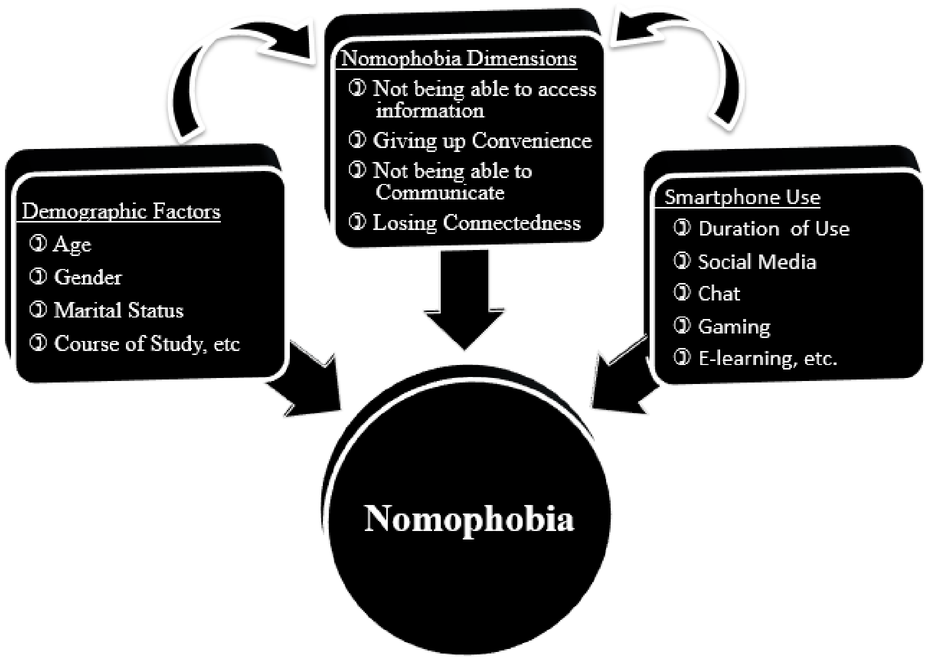

Figure 1: Conceptual Framework

The study focuses on the four dimensions of nomophobia. They are:

a. Not being able to communicate
b. Losing connectedness
c. Not being able to access information
d. Giving up convenience

The aforementioned variables are influenced by both smartphone usage patterns and demographic factors as age, gender, marital status, academic standing, and course of study. The length of time a person has owned a smartphone, how long they have used it, the apps they utilize, and other factors make up their usage pattern. These are the contributing elements of nomophobia, and they are all connected to one another in one way or another.

2.2 Research Design

A correlational strategy was used to determine the prevalence of nomophobia. The goal of a correlational design is to investigate the link between two or more variables. It aims to determine the relationship between two or more variables. The goal of the current study was to determine how nomophobia correlated with demographic factors such age, gender, educational attainment, and position in the academic community. The study also sought to determine whether smartphone use had an impact on nomophobia.

2.3 Population and Sample

The research population included teachers working at various schools and colleges in the Bhaktapur district as well as students pursuing degrees ranging from secondary to higher education. Approximately 150 students and 45 teachers from various institutions and schools made up the study's overall population. Research samples were chosen using non-probability convenience sampling. The convenience with which the researcher could reach the respondents who took part in the study was a deciding factor.

3. Findings

The purpose of this study was to determine how common nomophobia is among educators and learners. It also looks at many elements that contribute to nomophobia. Participants in the study included male and female instructors and students from a variety of academic backgrounds and age groups. A total of 195 individuals provided data for the study, of which 150 students (76.9%) and 45 teachers (23.1%) were the subjects. The results of the questionnaire were statistically calculated and analyzed in relation to several research variables. The research's principal conclusions were:

The majority of sample participants exhibited moderate nomophobia. Of the 195 respondents in all, 51 (26.2%) showed severe nomophobia, 103 (52.8%) showed moderate nomophobia, 39 (20.0%) showed mild nomophobia, and only 2 (1.0%) showed no nomophobia at all.

a. Compared to the student group, the instructor group displayed a higher degree of nomophobia. 45 teachers and 150 students made up the teaching population. Of them, 13 teachers (28.9%), 24 (53.3%), 8 teachers (17.8%), and nil teachers showed signs of severe, moderate, or no nomophobia, respectively. Similarly, 38 (25.3%), 79 (52.7%), 31 (20.7%), and 2 (1.3%) of the student body showed severe, moderate, mild, and no nomophobia, respectively.

b. The average score ($\bar{X}$=4.11) was lower than the means score ($\bar{X}$=4.34) and ($\bar{X}$=4.25) from the two sub-dimensions of nomophobia, "Not being able to access information" and "Not being able to communicate." The dimensions of "Losing Connectedness" ($\bar{X}$ = 3.93) and "Giving up Convenience" ($\bar{X}$ = 4.11) yielded mean scores that were below average.

c. It was shown that the demographic variable gender significantly influenced the degree of nomophobia; the female gender ($\bar{X}$=86.86) showed a higher degree of nomophobia than the male gender ($\bar{X}$=78.30).

d. The possession of a smartphone was a blatant sign of nomophobia. The individuals (93.3%) who had smartphones exhibited a higher degree of nomophobia than the individuals (13%) who lacked smartphones.

e. Calling (71.3%), texting and chatting (73.8%), making video calls (492–5%), emailing (50.3%), using social media (83.1%), browsing the internet (73.3%), getting news (67.2%), watching movies and listening to music (66.2%), gaming (47.2%), taking pictures (492–5%), and passing the time (52.3%) were the top reasons for using smartphones.

f. A major contributing cause to the rise in nomophobia is the usage of smartphones for social media, gaming, music and movie streaming, phone calls, texting, and general conversation. The degree of nomophobia was unaffected, nevertheless, by using a smartphone for activities including sending emails, making video calls, obtaining news, and taking pictures.

4. Conclusion

The study shows that instructors and students both suffer from nomophobia. The majority of teachers and pupils, according to the survey, show a moderate degree of nomophobia, which is concerning. Furthermore, significant nomophobia has been reported in some teachers and pupils. If the required acts and steps are not done, the incidence of severe nomophobia will undoubtedly grow. One could characterize this as a dangerous circumstance in the educational sector. The lovers of education are the instructors and students. Their commitment and diligence will only bear fruit in a healthy, sound atmosphere free from psychological disorders like nomophobia.

According to the study, people are more anxious about "not being able to access information" and "not being able to communicate" than they are about losing their online identity and comfort tool. This demonstrates that the widespread use of smartphones is not for the maintenance of a perceived virtual world or as a means of luxury, but rather for the legitimate goal of communication and information access. The results of the study showed that female participants had a higher level of nomophobia than did the male participants. When men and women work together to coordinate and jointly participate to teaching and learning activities, the educational environment is better. Therefore, female participants ought to minimize their fear of being alone.

Recommendations

Three tier government officials, educators, and parents should be cognizant of nomophobia and keep a close eye on their children's and students' smartphone usage. Schools and universities should offer programs to raise awareness about nomophobia and educate parents, teachers, and students on the dangers of excessive and unrestrained smartphone use.

Implication of the study

This study, "A Fear of the Digital Era: Nomophobia and Its Prevalence Among Teachers and Students," was an extremely original attempt to look into how people in the 21st century see and comprehend "A Fear of Digital Gadgets." This study raises management issues for lowering the anxiety associated with not owning a smartphone for other researchers and academics wishing to conduct analogous investigations in the field. The, future conversations regarding the significance of carefully integrating diverse tools and apps within the scope of teacher training will have a forum. It also encourages other educators to be concerned about the regulations in place so they can improve their own experiences and fulfill their professional obligations more successfully. Since this piece emphasizes the importance of having up-to-date information on pertinent topics for teachers, it also encourages policymakers, those working in school education, school staff, and other stakeholders to benchmark the fear of digital era: Nomophobia and Its Prevalence Among Teachers and Students.

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Predicting Toxicity of Herbal and Synthetic Organic Compounds Using Machine Learning-Based QSAR Models

Pratik Khanal[1*], Sanjiv Regmi[2]

[1] Crimson College of Technology, Butwal, Nepal

[2] Institute of Engineering and IT, Lumbini Technological University, Nepalgunj, Nepal

*Corresponding Email: Pratikkhanal18@gmail.com

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Abstract

This study focuses on the development of a machine learning-based Quantitative Structure-Activity Relationship (QSAR) model to predict the toxicity of organic compounds, including both traditional herbal remedies and synthetic compounds. The study employs Logistic Regression, Random Forest, and Support Vector Machines (SVM) to predict potential toxicity based on molecular descriptors calculated using RDKit, achieving over 90% accuracy across models. Feature importance analysis reveals that molecular descriptors such as lipophilicity (logP), hydrogen bond donors, and specific molecular fingerprints (e.g., FP_375, FP_243, FP_417) significantly correlate with toxicity. A Random Forest-based model highlighted these fingerprint bits as key contributors to toxicity prediction, showing strong correlations with known toxicological properties. The top 20 fingerprint features were analyzed, with their importance ranking depicted in a bar chart. The model demonstrates promising results in predicting hepatotoxicity and neurotoxicity, offering an early-stage toxicity screening tool for drug discovery. Validated on external datasets, the model generalizes well to unseen herbal and synthetic compounds, making it a valuable tool for pharmaceutical and herbal compound safety evaluation. This research underscores the potential of integrating traditional medicinal knowledge with advanced computational methods to enhance safety profiling of diverse organic compounds.

Keywords: *Machine learning, toxicity, herbal compounds, synthetic compounds, random forest, support vector machine, logistic regression*

1. Introduction

Traditional herbal remedies have played a significant role in healthcare systems worldwide, including Ayurveda, Traditional Chinese Medicine (TCM), and other ethnopharmacological practices(Sen et al., 2011). While herbal compounds are often assumed to be safe due to their natural origins, many lack extensive toxicity studies, particularly through modern scientific methods(Woo et al., 2012). This can lead to safety concerns, especially in long-term use or high doses(Moreira et al., 2014).

As drug discovery and toxicology studies progress, computational approaches have gained prominence(Cherkasov et al., 2014). Specifically, Quantitative Structure-Activity Relationship (QSAR) models have become a popular tool for predicting the biological activity of chemical compounds based on their molecular structures(Varsou et al., 2024). QSAR models can predict potential toxic effects without the need for large-scale clinical testing or experimental setups, making them efficient for early-stage screening(EBSCOhost, 2023).

While QSAR models have been applied extensively in the pharmaceutical and industrial sectors, little attention has been given to herbal medicines(Xu et al., 2024). The lack of data about traditional medicines creates a barrier to ensuring the safe use of those compounds in modern healthcare.

There is a growing need for computational models that can predict the toxicity of herbal compounds, thus bridging the gap between traditional medicine and modern toxicological evaluation(Machhar et al., 2019).

This study aims to develop a machine learning – based QSAR model to predict toxicity of herbal and synthetic organic compounds, using RDKit-calculated molecular descriptors. The model will be trained and validated with known toxicity data from herbal and plant derived compounds.

The outcomes could benefit both the scientific community and the herbal medicine industry by offering a tool for early-stage screening, potentially reducing the need for extensive in vivo and in vitro testing(Krewski et al., 2010).

2. Methodology

2.1 Dataset Collection

This study gathered data on the molecular structures and toxicity profiles of herbal compounds from publicly available databases such as:

a. FDA: FDA approved drugs from fda.gov (2024)
b. HMDB: HMDB (Human Metabolome Database) for non-toxic metabolites (D. S. Wishart et al., 2022)

c. T3DB: Data on toxic substances was obtained from T3DB. (D. Wishart et al., 2015)
d. CPDB: The CPDB is a single standardized resource of the results of 45 years of chronic, long-term carcinogenesis bioassays.
e. ProTox-3.0: The external validation set as SDfile.(Banerjee et al., 2024)

The dataset included toxicity data for various endpoints, including hepatotoxicity, neurotoxicity, and general cytotoxicity(Yang et al., 2019). Compounds without toxicity data were excluded from the study(Fourches et al., 2016)

2.2 Molecular Descriptor Calculation

To represent the molecular structure of each herbal compound numerically, molecular descriptors were calculated using RDKit, a powerful tool for cheminformatics(Ekins et al., 2014). The descriptors included:

0D Descriptors: 0D (zero-dimensional) descriptors in cheminformatics are typically scalar values that provide information about the overall properties of a molecule without considering its spatial arrangement. E.g., molecular weight, number of atoms, number of heavy atoms, number of hydrogen bond donors and others.

1D Descriptors: 1D (one-dimensional) descriptors in cheminformatics represent counts or specific attributes of molecular features, focusing on individual atom types, bond types, or functional groups without considering the spatial arrangement of the molecule. E.g., total hydrogen atoms, total number of C atoms, number of aromatic amino groups and others.

2D Descriptors: 2D (two-dimensional) descriptors in cheminformatics provide information about the molecular structure and properties based on the arrangement of atoms and bonds, without taking into account three-dimensional (3D) conformations. E.g., Maximum absolute Estate values, Minimum absolute partial charges, charge components and various shape descriptors.

These descriptors were used as input features for the machine learning models.

Molecular Fingeprints: Fingerprints are a specific type of descriptor that encodes molecular structures as bit strings. This encoding consists of a sequence of binary digits (bits), which indicate the presence (1) or absence (0) of particular substructures within the molecule. The resulting numeric array is of length nnn, where nnn is determined by the specific fingerprint algorithm employed. In this study, molecular fingerprints were calculated for the input data using the RDKit library in Python(Rogers & Hahn, 2010). The types of fingerprints calculated include:

a. Morgan Fingerprint
b. Atom Pair Fingerprint

c. Topological Torsion Fingerprint
d. RDKit Fingerprint

2.3 Machine Learning Algorithms

Three machine learning algorithms were selected for the toxicity prediction task(Lo et al., 2018):

Logistic Regression used 11 molecular descriptors (e.g., LogP, TPSA) selected for toxicity relevance, with features scaled via RobustScaler and missing values imputed with zeros. Hyperparameters (regularization strength C, solvers: liblinear, saga) were optimized using GridSearchCV with 5-fold cross-validation, and the model was evaluated for accuracy and classification metrics, saved with joblib for reproducibility.

Support Vector Machines (SVM) utilized the same 11 descriptors, standardized with StandardScaler, and employed an RBF kernel (C=1, gamma='scale'). The model was assessed for accuracy, precision, recall, and F1-score, and serialized using joblib.

Random Forest used 1024-bit Morgan fingerprints (radius=2) from RDKit as input, with the dataset split into 80% training and 20% testing sets. The model, configured with 100 decision trees (random_state=42), was evaluated on validation and test sets and saved with joblib for external validation.

2.4 Model Training and Validation

The complete dataset was divided into training (80%) and testing (20%) subsets to train and evaluate the machine learning models. Feature engineering involved the calculation of molecular descriptors and fingerprints using RDKit, which served as the input features, while toxicity classification served as the target variable.

For Logistic Regression, hyperparameter tuning was conducted using GridSearchCV with 5-fold cross-validation. The model's regularization strength (C) and solver type (liblinear, saga) were optimized based on validation accuracy.

The Random Forest and Support Vector Machine (SVM) models were trained using fixed hyperparameters. Random Forest was implemented with 100 estimators and a fixed random state to ensure reproducibility, while the SVM used an RBF kernel with C=1 and gamma='scale' as default settings.

After training, all models were evaluated using the test dataset. Performance metrics such as accuracy, precision, recall, and F1-score were calculated to assess the predictive ability of each model(Ballabio et al., 2018). Additionally, confusion matrices and feature importance analyses were employed to understand model decisions and interpretability.

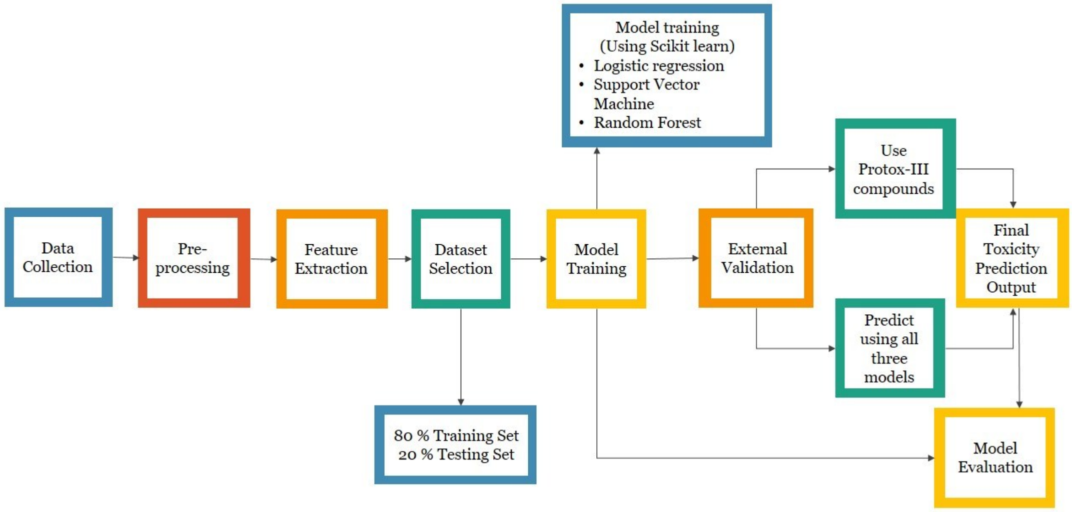

Figure 1: Methodology for Toxicity Prediction using ML-based QSAR Model

2.5 External validation

To assess the generalization ability of the trained Random Forest, Logistic Regression, and Support Vector Machine (SVM) models, an external dataset of 506 structurally diverse compounds from the ProTox-III(Khaouane et al., 2023) validation set (https://tox.charite.de/protox3/index.php?site=links) was used. SMILES notations of the compounds were converted into 1024-bit Morgan fingerprints (radius = 2) for the Random Forest model and into 11 molecular descriptors (e.g., molecular weight, LogP, TPSA, rotatable bonds, ring count) using RDKit for the Logistic Regression and SVM models, consistent with their training methodologies. Infinite or missing descriptor values were replaced with zeros. Each model predicted toxicity based solely on chemical structure, without using experimental LD50 values or pre-assigned toxicity classes. Post-prediction, LD50 values were used to classify compounds per the Globally Harmonized System (GHS) as toxic (Classes I–IV, LD50 ≤ 2000 mg/kg) or non-toxic (Classes V–VI, LD50 > 2000 mg/kg) for performance evaluation. Predictions were exported for further analysis.

3. Results and Discussion

3.1 Model Performance

The models were evaluated based on several key performance metrics, including accuracy, precision, recall, and F1 score. The performance of the Logistic Regression, Random Forest, and Support Vector Machine (SVM) models on the test set for toxicity prediction is summarized in the table below:

Table 1: Table Shows Test Set for Toxicity Prediction

Model	**Accuracy**	**Precision**	**Recall**	**F1 Score**
Logistic regression	92.22%	98.73%	85.56%	91.56%
Random forest	92.78%	98.73%	86.67%	92.31%
Support vector machine	92.22%	87.00%	100%	93.00%

Both Logistic Regression and SVM models achieved an accuracy of 92.22%, while the Random Forest model performed slightly better with an accuracy of 92.78%. All models exhibited high precision (98.73% for Logistic Regression and Random Forest, 87% for SVM), indicating a low rate of false positives.

a. Logistic Regression showed high precision and good recall (85.56%), resulting in an F1 score of 91.56%.
b. Random Forest outperformed the others slightly in terms of recall (86.67%) and F1 score (92.31%), identifying slightly more toxic compounds while maintaining a good balance between precision and recall.
c. Support Vector Machine (SVM) demonstrated a perfect recall (100%), meaning it correctly identified all toxic compounds in the test set, though its precision (87%) was lower than both Logistic Regression and Random Forest. The SVM model achieved an F1 score of 93%, the highest among the three models.

3.2 Analysis of Molecular Descriptors

Feature Importance analysis of Random Forest Model: Feature importance analysis using the Random Forest model revealed that not only classical molecular descriptors such as logP and the number of hydrogen bond donors were correlated with compound toxicity, but also specific molecular fingerprints contributed significantly. This finding aligns with established toxicological principles, where lipophilicity and hydrogen bonding influence membrane permeability and biological activity.

To understand the structural patterns influencing toxicity, the top 10 most important fingerprint bits (FP_375, FP_243, FP_417, FP_595, FP_887, FP_540, FP_591, FP_118, FP_695, and FP_69) were visualized using RDKit. Each fingerprint bit corresponds to a specific molecular substructure that frequently appeared in toxic compounds within the dataset. Representative SMILES structures were identified for each bit:

Table 2: Top 10 Fingerprint Bits

Fingerprint Bit	Matched SMILES	Structural Insight
FP_375	Cc1ccc(-c2cc(C(F)(F)F)nn2-c2ccc(S(N)(=O)=O)cc2)cc1	Aromatic ring with trifluoromethyl & sulfonamide groups – both associated with membrane interaction and enzyme binding.
FP_243	CCCC(C)C1(CC)C(=O)NC(=O)NC1=O	Branched alkyl chain with cyclic urea – linked to hydrophobicity and metabolic stability.
FP_417	CC(=O)NC[C@H]1CN(c2ccc(N3CCOCC3)c(F)c2)C(=O)O1	Piperazine and fluorinated aryl groups – common in CNS-active drugs with potential neurotoxicity.
FP_595	Long chain phospholipid-like ester	Highly lipophilic, mimicking biological membranes – relevant in cytotoxicity.
FP_887	OCCN1CCN(CCCN2c3ccccc3Sc3ccc(Cl)cc32)CC1	Tertiary amines and sulfur-containing heterocycles – often associated with hepatotoxicity.
FP_540	CC(=O)Nc1cccc2c1-c1ccccc1C2	Fused aromatic rings with acetamide – planar structures affecting DNA intercalation.
FP_591	c1ccc2c(c1)[nH]c1cnccc12	Indole-pyridine fused ring – found in many bioactive compounds, potentially toxic at high doses.
FP_118	CC(C)CON=O	N-nitroso group – a classic structural alert for mutagenicity and carcinogenicity.
FP_695	Cc1ccc2c(c1[N+](=O)[O-])C(=O)c1ccccc1C2=O	Nitroaromatic ketone – known for redox cycling and liver toxicity.
FP_69	COC12C(COC(N)=O)C3=C(C(=O)C(C)=C(N)C3=O)N1CC1NC12	Complex fused heterocycles – structurally rich motifs often flagged in lead optimization for off-target effects.

Visual representations of each substructure (highlighted in red) are provided in the supplementary materials (Figure S1–S10).

These fingerprint-based substructures, derived from the Morgan algorithm, do not directly convey semantic chemical features, but they consistently match recurring toxic motifs in chemical space. Their high importance values in the model emphasize their predictive power and their likely involvement in pharmacokinetic and toxicodynamic pathways.

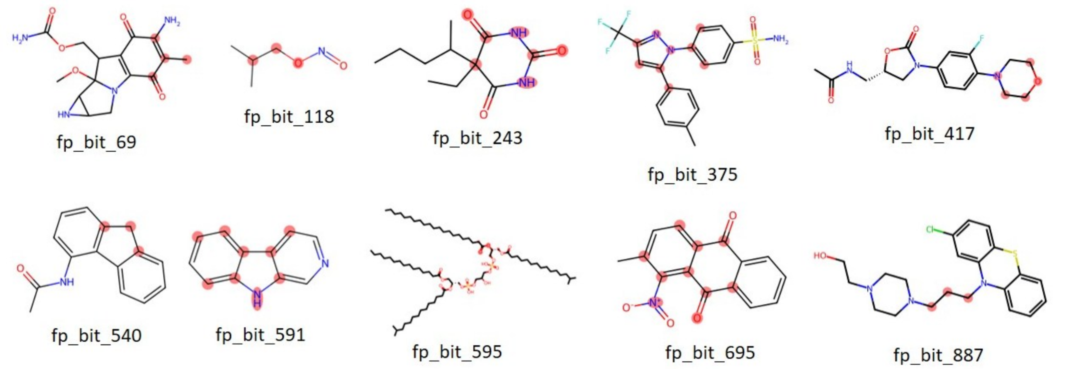

Figure 2: Top 10 Important Fingerprint Hits Identified as Relevant to Toxicity Prediction

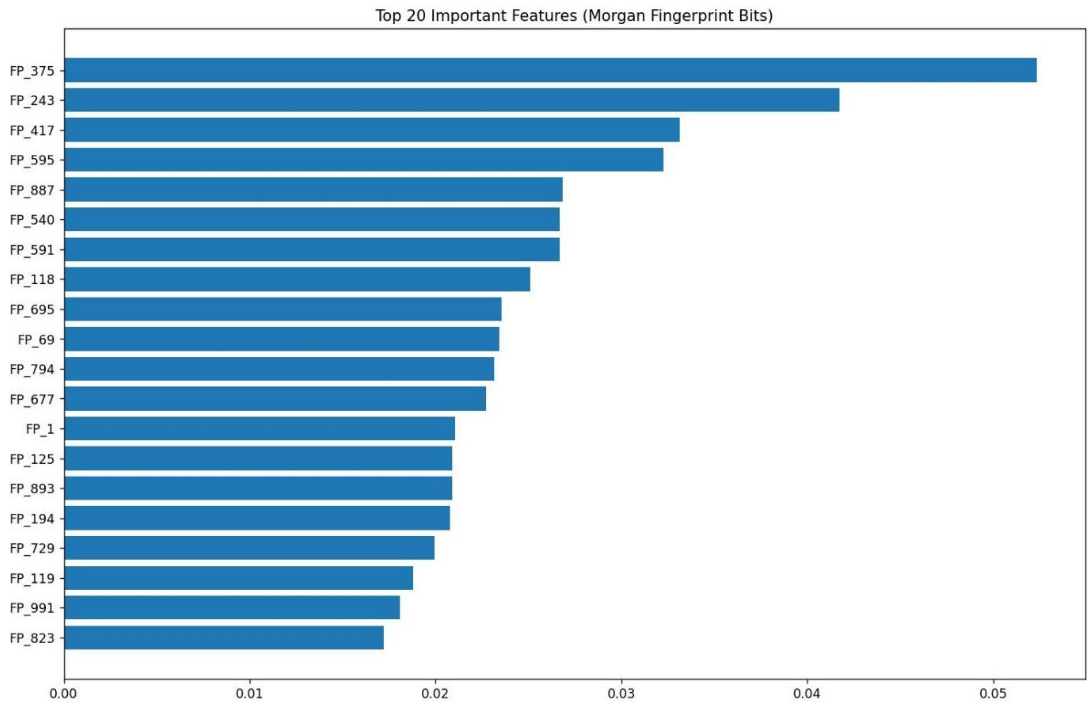

Figure 3: Top 20 Important Features (Morgan Fingerprint Bits)

Figure 3. This bar chart shows the relative importance of the top 20 Morgan fingerprint bits that contributed to the toxicity prediction model. Higher bars indicate more important features for the Random Forest model, suggesting these fingerprint bits are linked to key molecular characteristics that influence toxicity.

Feature Importance Analysis of Logistic Regression Model: - The feature importance analysis for the logistic regression model was performed by examining the absolute values of the model's coefficients. This provides insights into which features most significantly influence the toxicity predictions of organic compounds. The feature importance values were visualized in a bar chart, highlighting the molecular descriptors that played key roles in distinguishing between toxic and non-toxic compounds.

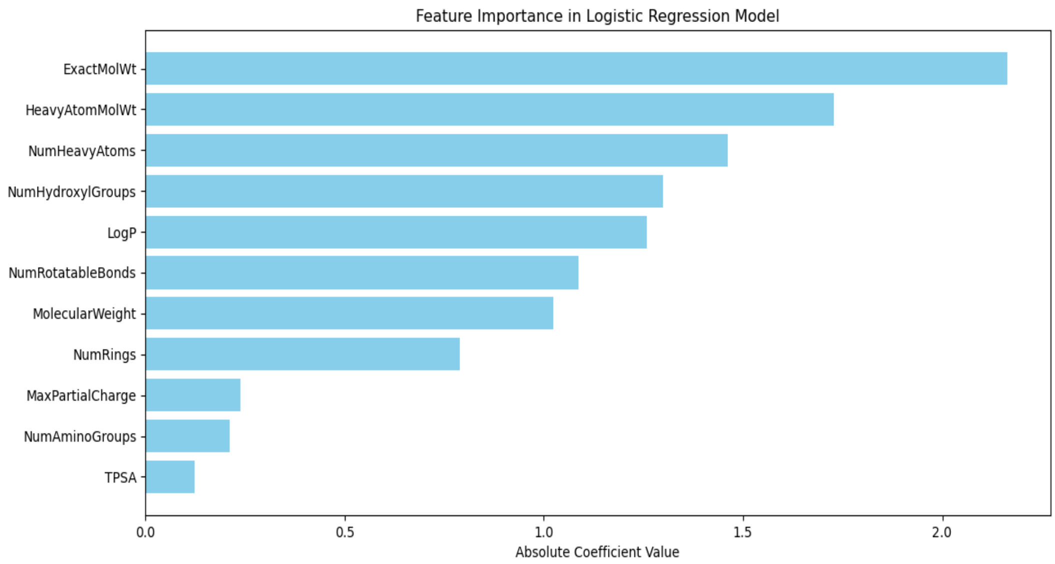

Figure 4: Feature Importance Analysis of Logistic Regression Model.

Figure 4 presents the feature importance analysis of the logistic regression model. As observed, the most significant features for toxicity prediction were ExactMolWt and HeavyAtomMolWt, which showed the highest coefficient values. Other important features include NumHeavyAtoms, NumHydroxylGroups, and LogP, suggesting that molecular weight and functional groups related to hydrophobicity and hydrogen bonding are crucial for toxicity prediction.

The bar chart in Figure 4 provides a clear visual representation of these features, where higher bars indicate more important features for the model's prediction of toxicity.

Feature Importance Analysis of SVM Model: - Feature importance analysis was conducted to better understand the role of each molecular descriptor in predicting toxicity using the Support Vector Machine (SVM) model. The analysis was performed using permutation importance, which evaluates the impact of each feature by measuring the decrease in model accuracy when a feature's values are shuffled.

The most important features for the SVM model, based on the mean decrease in accuracy, were found to be ExactMolWt and HeavyAtomMolWt, which had the highest importance values, followed by NumRotatableBonds, LogP, and NumHydroxylGroups. These results align with known toxicological principles, where molecular weight and lipophilicity (LogP) are key factors in predicting the bioactivity and toxicity of compounds.

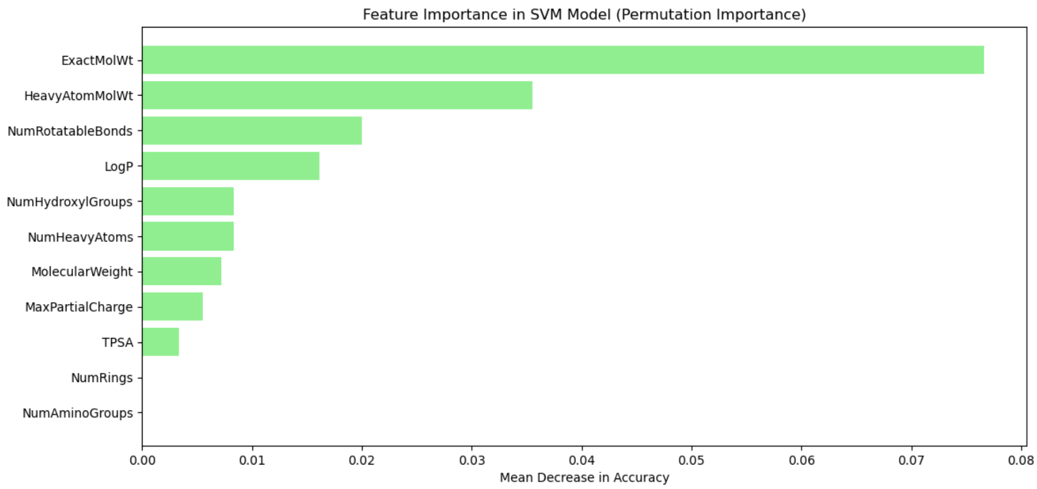

Figure 5: Feature Importance Ranking of SVM Model

The feature importance ranking is presented in Figure 5, which visually represents the relative importance of each feature in the model. As shown, ExactMolWt and HeavyAtomMolWt have a considerable influence on the toxicity predictions, suggesting that molecular weight-related descriptors are crucial in understanding compound toxicity. LogP and NumHydroxylGroups also play important roles, highlighting the relevance of hydrophobicity and functional group presence in predicting toxicity.

3.3 Validation with External Data

External Validation of Random Forest Model: - The Random Forest model was externally validated using 506 structurally diverse compounds from the ProTox-III validation set. SMILES strings were converted into 1024-bit Morgan fingerprints, consistent with the training pipeline. Experimental LD50 values were used post-prediction to evaluate performance against ProTox-defined toxicity classes.

The model achieved an accuracy of 77.1%, with particularly strong performance for identifying toxic compounds (Classes I–IV), achieving 96.2% recall and 79.0% precision. However, its precision for non-toxic compounds (Classes V–VI) was lower (37.5%), indicating a conservative bias toward predicting toxicity. These results suggest the Random Forest model effectively recognizes harmful structural motifs but may overpredict toxicity in less harmful or benign compounds.

External Validation of Logistic Regression Model: - The Logistic Regression model achieved a 100% recall for toxic compounds (Classes I–IV), correctly identifying all 396 toxic entries. However, it misclassified all 110 non-toxic compounds (Classes V–VI) as toxic, resulting in 0% precision for the non-toxic class. The overall accuracy was 78.3%, driven by the model's conservative bias toward predicting toxicity. This high sensitivity may be advantageous in early hazard screening but underscores the need for improved specificity and balanced training to reduce false positives.

External Validation of Support Vector Machine (SVM) Model: - The SVM model achieved an overall accuracy of 78.3% in external validation. It successfully identified 100% of the 396 toxic compounds (Classes I–IV) with a recall of 1.00. However, it failed to identify any of the 110 non-toxic compounds (Classes V–VI), leading to 0% precision and recall for the non-toxic class. These results suggest the model has a high sensitivity for toxic compounds, favoring toxicity prediction across structurally varied chemical space. While this conservatism helps minimize false negatives, it also results in false positives among non-toxic chemicals. Future work may focus on improving class balance and calibration to enhance non-toxic compound identification.

3.4 Limitations

The study faced limitations related to the availability and quality of toxicity data for herbal compounds. Many herbal compounds lack comprehensive toxicity profiles, which restricted the size of the dataset. Additionally, the QSAR models were limited to predicting toxicity for individual compounds and did not account for the potential synergistic effects of multiple compounds in a herbal mixture.

4. Discussion and Conclusion

The development of machine learning-based Quantitative Structure-Activity Relationship (QSAR) models for predicting the toxicity of herbal and synthetic organic compounds marks a significant advancement in computational toxicology. Our study demonstrates that Logistic Regression, Random Forest, and Support Vector Machines (SVM) can achieve high accuracy (>90%) in predicting hepatotoxicity, neurotoxicity, and general acute toxicity. Random Forest slightly outperformed the others, with an accuracy of 92.78%, precision of 98.73%, recall of 86.67%, and F1 score of 92.31%. SVM exhibited perfect recall (100%) but lower precision (87%), making it particularly suitable for applications where missing toxic compounds is critical, even at the cost of some false positives.

Feature importance analysis provided valuable insights into the structural determinants of toxicity. For Random Forest, key features included molecular fingerprints corresponding to substructures such as aromatic rings, nitro groups, and tertiary amines, which are well-known for their association with toxic effects. Logistic Regression and SVM highlighted the significance of molecular weight and lipophilicity (logP), consistent with established toxicological principles. These findings not only validate the models' predictive capabilities but also offer actionable insights for designing safer compounds by identifying structural features that contribute to toxicity.

When compared to recent advancements in the field, our models' performance is commendable. For instance, a study by (Romano et al., 2022) utilized graph neural networks (GNNs) with publicly aggregated semantic graph data, achieving a mean area under the receiver operating characteristic curve (AUROC) of 0.883 for toxicity prediction across 52 assays from the Tox21 dataset (Improving QSAR Modeling). While AUROC is a different metric from accuracy, the high performance of GNNs suggests that incorporating relational data between chemicals, genes, and assays can enhance prediction accuracy. Similarly, (Sharma et al., 2023) employed multi-task deep neural networks (MTDNN) with pre-trained SMILES embeddings, achieving an AUC-ROC of 0.991 for clinical toxicity prediction, demonstrating the potential of deep learning for complex endpoints (Accurate Clinical Toxicity). Our study's focus on both herbal and synthetic compounds addresses a gap in the literature, where herbal compounds are often underrepresented, thus bridging traditional herbal medicine with modern toxicology.

The high sensitivity of our models, particularly SVM, ensures that potentially toxic compounds, including those derived from herbal sources, are identified, enhancing public health safety. This is particularly relevant given the increasing use of herbal supplements and the need for robust safety profiling. However, our models exhibited a conservative bias in external validation, over-predicting toxicity, which could lead to false positives. This is a common challenge in toxicity prediction, potentially due to class imbalance in the datasets, where toxic compounds are less prevalent than non-toxic ones. The lower accuracy (77–78%) on the external ProTox-III dataset further highlights the need for more diverse training data to improve generalizability.

The practical implications of our findings are substantial. By providing early-stage toxicity screening, our models can reduce reliance on extensive animal testing, aligning with ethical and regulatory trends toward alternative methods. In pharmaceutical development, these models can prioritize compounds for further testing, optimizing resources and accelerating the identification of safe candidates. The inclusion of herbal compounds also supports the integration of traditional medicine into modern safety assessment frameworks, potentially informing regulatory guidelines for herbal products.

Despite these strengths, our study has limitations. The conservative bias in external validation suggests that class imbalance and dataset specificity may affect model performance. Additionally, the reliance on specific molecular descriptors and fingerprints may limit the models' applicability to novel chemical spaces. Future research should explore strategies to mitigate class imbalance, such as oversampling minority classes or employing cost-sensitive learning techniques. Incorporating more diverse data sources, such as those aggregated in platforms like ComptoxAI, could enhance model robustness. Moreover, adopting advanced machine learning architectures, such as GNNs or deep neural networks(Mayr et al., 2016), may improve prediction accuracy and enable the modeling of more complex toxicity endpoints, including clinical toxicity.

In conclusion, this study underscores the efficacy of machine learning-based QSAR models in predicting the toxicity of a diverse range of compounds, including those from traditional herbal medicine. While opportunities for refinement remain, particularly in addressing class imbalance and enhancing generalizability, the current models offer a powerful tool for early-stage toxicity screening, supporting both scientific research and public health initiatives.

Future Directions

a. Expansion to mixtures: Investigating toxicity in herbal mixtures rather than isolated compounds.
b. Larger datasets: Collecting additional toxicity data for a wider range of herbal compounds.
c. Model refinement: Experimenting with advanced machine learning techniques, such as neural networks(Wei et al., 2024), for more complex toxicological endpoints.

Acknowledgement:

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The author gratefully acknowledge the use of the publicly available external validation dataset provided by ProTox-III (https://tox.charite.de/protox3/index.php?site=home#). The validation set, described by the developers as a diverse subset of compounds spanning multiple toxicity classes, was used in this study to perform structure-based external validation of

predictive toxicity models. The resource significantly contributed to the evaluation of our models against real-world chemical diversity.

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A Code-Based Comparison of Seismic Performance of Regular and Plan-Irregular RC Buildings using NBC 105:2020 and IS 1893:2016

Bindu Bhatt[1], Laxmi Dhami[1], Rajani Bohara[1], Sangam Jagari[1], Siddhant Joshi[2], Suman Bhatt[1], Birendra Kumar Bohara[2*], Toran Prasad Bhatt[2]

[1] School of Engineering, Far Western University, Nepal

[2] Assistant Professor, School of Engineering, Far Western University, Nepal

*Corresponding Email: birendra.bohara@fwu.edu.np

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Abstract

Nepal's location in an active seismic zone, along with escalating emphasis on architectural aesthetics and land scarcity, has led to increasing plan-irregular buildings that complicate seismic design and compromise structural safety. This study compares the seismic performance of regular and plan-irregular reinforced concrete (RC) buildings designed per IS 1893:2016 and NBC 105:2020 codes, addressing the gap in cross-code, multi-height analyses. For this purpose, one square regular building (RM) and 6 alternative L-shaped irregular buildings (IRM1-IRM6) with 3, 6, 9, and 12 story configurations designed under both codes were analyzed using response spectrum methods in ETABS to evaluate seismic parameters like base shear, drift ratio, displacement, time period, torsion ratio, story stiffness and shear. The findings revealed that NBC-compliant buildings had shorter time periods (up to 40% shorter) but higher base shear (1.75 – 6 times IS), displacement, drift ratio, torsion ratio, story shear, and stiffness than IS-compliant buildings, reflecting stricter seismic demands under NBC that may result in more robust yet cost-intensive designs. Regular models displayed lower base shear (up to 74% reduction) and stiffness, with higher time periods, displacements, and torsional irregularity (TIR > 1.2), indicating increased seismic vulnerability due to asymmetry and stress concentrations. These findings inform resilient seismic design for Nepal's urban landscape.

Keywords: *Irregular Buildings, NBC, Torsional Irregularity, Response Spectrum Analysis, Earthquake*

1. Introduction

An earthquake is a sudden release of stored elastic energy in the Earth's crust, resulting in ground shaking and vibrations due to the propagation of seismic waves. Nepal lies in one such tectonically active zone, the Himalayan seismic belt, formed by the ongoing collision between the Indian Plate and the Eurasian Plate (Chaulagain et al., 2018). Analysis of historical seismic records indicates that Nepal generally experiences two major earthquakes, with magnitudes between 7.5 and 8.0. As nearly seven decades have passed since the major 1934 Bihar–Nepal earthquake before the catastrophic 2015 Gorkha earthquake (Mw 7.8), there are growing concerns that the region may face another large-magnitude quake in the near future (Bhagat et al., 2018; Dutta et al., 2015; Endo & Hanazato, 2021; Gautam et al., 2015; Gautam & Chaulagain, 2016; Varum et al., 2018). Existing research on seismic performance predominantly employs numerical methods like finite element modeling in ETABS, focusing on reinforced concrete (RC) frames under NBC 105 and IS 1893 provisions (Bohara, 2022, 2023, 2025; Bohara, Joshi, et al., 2025). Studies comparing regular and irregular structures reveal that irregularities amplify torsional effects, stress concentrations, and deformation demands, increasing vulnerability (Khanal & Chaulagain, 2020). For instance, (Paudel et al., 2024) analyzed multi-story RC frames with vertical and horizontal irregularities using ETABS, finding that regular buildings exhibit higher stiffness than vertically irregular ones. Comparative code-based studies highlight disparities between NBC and IS. (Sapkota et al., 2024) assessed low-rise RC buildings in Nepal using multiple codes, including NBC 105:2020 and IS 1893:2016, via response spectrum analysis. NBC-compliant designs yielded shorter fundamental periods (average 40% less than IS) but higher base shear, displacements, and drifts, reflecting stricter seismic demands. Irregular models showed increased periods and drifts, with NBC underestimating finite element-derived periods less than IS (0.4% vs. 91.7% error for 3-story regular). Torsional and irregularity effects are further explored in (Bohara et al., 2022; Khanal & Chaulagain, 2020) , who simulated L-shaped frames, noting up to 9.5% period increases in high-rises due to torsional flexibility, with irregular models exceeding TIR thresholds (>1.2). Khadka (2020) analyzed asymmetric RC structures, observing 3.3-fold base shear differences between regular and highly irregular models, recommending dynamic analysis for mitigation.

This study aims to compare the seismic performance of regular and plan-irregular reinforced concrete (RC) buildings designed per IS 1893:2016 and NBC 105:2020, addressing the increasing prevalence of irregular structures in Nepal's rapidly urbanizing landscape due to architectural demands and land scarcity. The specific objectives are to: (1) conduct seismic analyses using equivalent static, response spectrum, nonlinear pushover, and time history methods for one regular (RM) and six L-shaped irregular (IRM1–IRM6) building models across 3, 6, 9, and 12 stories; (2) quantitatively compare key seismic parameters, including base shear, story displacement, drift ratio, fundamental time period, torsional irregularity ratio, and story stiffness, between regular and irregular configurations under both codes; and (3) evaluate how plan irregularities and code-specific provisions influence overall seismic resilience. By highlighting the heightened seismic vulnerability of irregular buildings, particularly due to torsional effects and stress concentrations, this study provides critical insights for improving earthquake-resistant design. With over 70% of new constructions in Kathmandu featuring irregular plans, these findings inform safer structural practices and policy recommendations, enhancing safety and stability in Nepal's tectonically active Himalayan region.

2. Materials and Methods

2.1 Building Model Description

A total of 56 analytical models were analyzed and designed in ETABS software in compliance with both the Indian Standards (IS 1893:2016) (IS 1893, 2016) and the Nepal National Building Code (NBC 105:2020) (105:2020, 1994) for the study, equally divided between the Indian Standards (IS) and the NBC, with 28 models in each code category. The buildings were classified into three height categories based on story numbers: low-rise (3-story), mid-rise (6 and 9-story), and high-rise (12-story) as shown in tables 1, 2 and figures 1 and 2. For each height category, one square regular-plan and six L-shaped irregular-plan RC building configurations were modeled, resulting in seven models per rise category for each code. This classification and modeling framework enabled to assess the seismic performance variations across codal provisions and building configurations. The building structural dimensions are tabulated below:

Table 1: Structural Dimension

Component	Specification
No. of Stories	3, 6, 9, 12
No. of Bays X*Y	8x8
Spacing	6m
Slab Thickness	120 mm
Height of each floor	3.5 m

Table 2: Beam and Column Dimensions Designed by using Seismic Code

Building Story No.	**Floors**	**Beam Dimensions (mm x mm)**		**Column Dimension (mm x mm)**	
		IS Model	NBC Model	IS Model	NBC Model
3 Story Model	1 to 3	300 x 475	500 x 600	475 x 475	675 x 675
6 Story Model	1 to 3	350 x 500	675 x 775	600 x 600	800 x 800
	3 to 6	325 x 475	600 x 700	500 x 500	675 x 675
9 Story Model	1 to 3	350 x 600	750 x 975	750 x 750	1025 x 1025
	3 to 6	350 x 550	700 x 925	600 x 600	850 x 850
	6 to 9	350 x 500	550 x 700	450 x 450	625 x 625
12 Story Model	1 to 3	400 x 600	825 x 975	900 x900	1200 x 1200
	3 to 6	375 x 575	775 x 900	800 x 800	950 x 950
	6 to 9	350 x550	675 x 800	750 x750	800 x 800
	9 to 12	325 x 525	575 x 700	700 x700	700 x 700

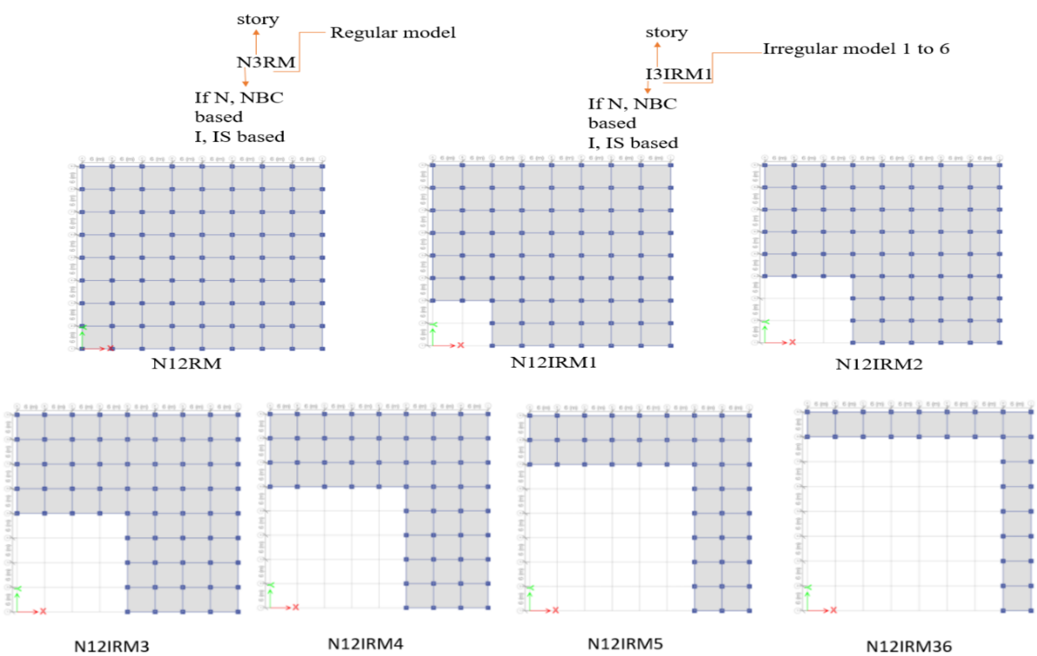

Figure 1: Models with their Naming

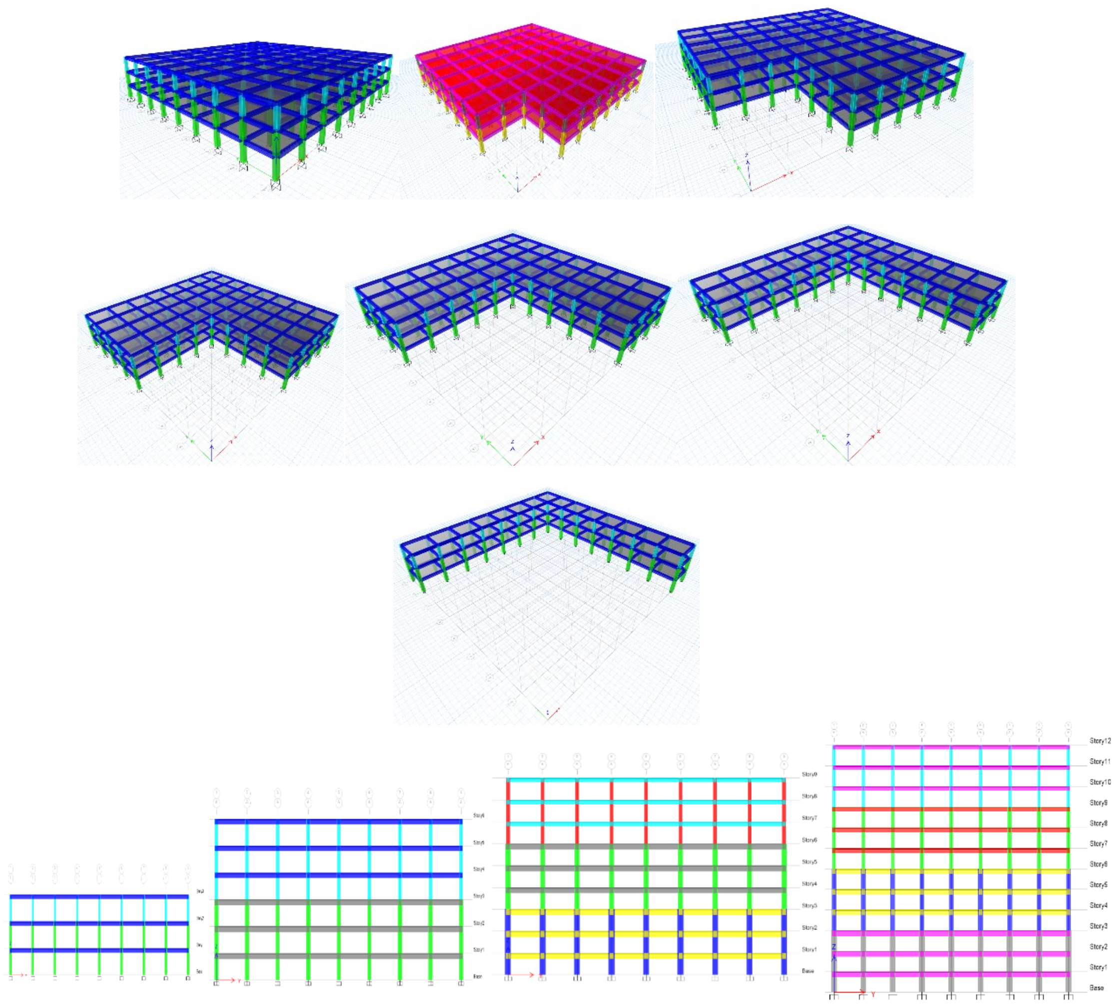

Figure 2: Regular and L shape building plan and elevation

2.1.1. Codal Provision for Structural Configurations

Structural irregularities, as described by NBC 105:2020 and IS 1893:2016, have a major impact on seismic performance and are divided into vertical and plan irregularities. Plan irregularities involve torsional irregularity, characterized by maximum story displacement being more than 1.5 times the minimum (as defined by both codes), and re-entrant corners, where projections exceed 15% of the plan dimension (NBC) or 20% (IS). Diaphragm discontinuity occurs due to cutouts or changes in stiffness greater than 50% (both codes), and out-of-plane offsets take place when vertical elements are misaligned. The stricter thresholds outlined by NBC (e.g., stiffness and mass) indicate the greater seismic demands in Nepal when compared to IS, highlighting the need for a resilient design to lessen torsional impacts and ensure structures can withstand earthquakes.

2.1.2. Response Spectrum Analysis

Response Spectrum Analysis (RSA) is a dynamic evaluation technique utilized to assess the seismic resilience of structures by calculating their maximum responses to ground motions induced by earthquakes, as outlined by seismic codes such as NBC 105:2020 and IS 1893:2016. RSA uses modal analysis to determine a structure's natural periods and mode shapes, which are then employed to derive spectral accelerations from a code-defined design response spectrum, reflecting the anticipated intensity of ground motion for a specific site and seismic zone. These spectral accelerations are statistically combined using approaches like the Square Root of the Sum of Squares (SRSS) or Complete Quadratic Combination (CQC) to ensure contributions from multiple modes, including higher-mode influences, are adequately addressed for a thorough evaluation of structural response. In this analysis, RSA was performed using ETABS software to evaluate both regular and L-shaped irregular reinforced concrete (RC) building models consisting of 3, 6, 9, and 12 stories, designed according to NBC 105:2020 and IS 1893:2016, with results compared for parameters such as base shear, story displacement, drift, and torsional irregularity.

The design response spectra employed in this research, illustrated in Figure 10 (IS 1893:2016) and Figure 11 (NBC 105:2020), were created based on site-specific factors, including seismic zone factor (Z), soil classification, and importance factor. Initially, the structural model in ETABS underwent modal analysis to ascertain natural periods and mode shapes, followed by applying the corresponding code-based response spectra to calculate peak accelerations for each mode. The spectra vary due to NBC's elevated zone factor and more stringent spectral shape tailored to Nepal's Himalayan seismic conditions in comparison to IS, leading to higher seismic demands for designs that comply with NBC. Modal responses were aggregated using the CQC method to represent dynamic interactions effectively, especially for irregular models demonstrating torsional impacts. The analysis output offered vital insights into story shear, displacement, and drift, underscoring the heightened susceptibility of irregular structures resulting from asymmetry, as well as the conservative stance of NBC 105:2020 compared to IS 1893:2016 regarding seismic force estimation.

3. Results and Discussion

3.1. Fundamental Time Period

The fundamental time period, as a critical seismic design parameter, represents the duration required for a structure to complete one full cycle of vibration in its primary mode (Bohara, 2021; Ganaie et al., 2021). It is calculated to characterize the dynamic response of buildings and to ensure structures can safely dissipate seismic energy through controlled oscillation. The results demonstrate that NBC 105:2020's stiffer design assumptions yield shorter fundamental time periods (avg. 40% shorter than IS 1893:2016), increasing seismic force demands in NBC-based models (Bohara et al., 2022). While both codes underestimate finite element-derived periods, IS 1893:2016 exhibits larger errors (91.7% vs. NBC's 0.4% for 3-storey RM), suggesting its empirical formula is less reliable for irregular structures. Irregularity reduced periods in low-rises (−5.0% for IS 3-storey) but increased them in high-rises (+9.5% for NBC 12-storey), confirming that torsional flexibility dominates in taller buildings, as shown in Figure 3.

3.2. Torsional Irregularity

It is commonly assessed using the torsional irregularity ratio (TIR) the ratio of maximum peripheral inter-story drift (including accidental eccentricity) to the average drift at the same level. In the 12-storey IRM6 configuration, NBC produced a maximum TIR of 1.250 compared to 1.160 under IS reflecting a 7.8% increase and greater sensitivity to plan asymmetry (Bohara, Kunwar, et al., 2025). Both codes exceeded the critical threshold (TIR > 1.2) in highly irregular models, suggesting elevated torsional vulnerability. Regular models (RM) demonstrated uniformly lower TIR values (≤ 1.106) (see Figure 4) in both codes, confirming that plan symmetry effectively reduces torsional amplification. IS-based irregular models exhibited comparatively lower TIR values than NBC, indicating potential underestimation of torsional demands, which could compromise seismic performance in asymmetric configurations (Bohara, Kunwar, et al., 2025). These results highlight that while NBC's stricter torsional provisions may lead to stiffer and more costly designs, they provide better control over rotational response critical for the seismic safety of irregular buildings (Herrera & Soberón, 2008; Jereen et al., 2017).

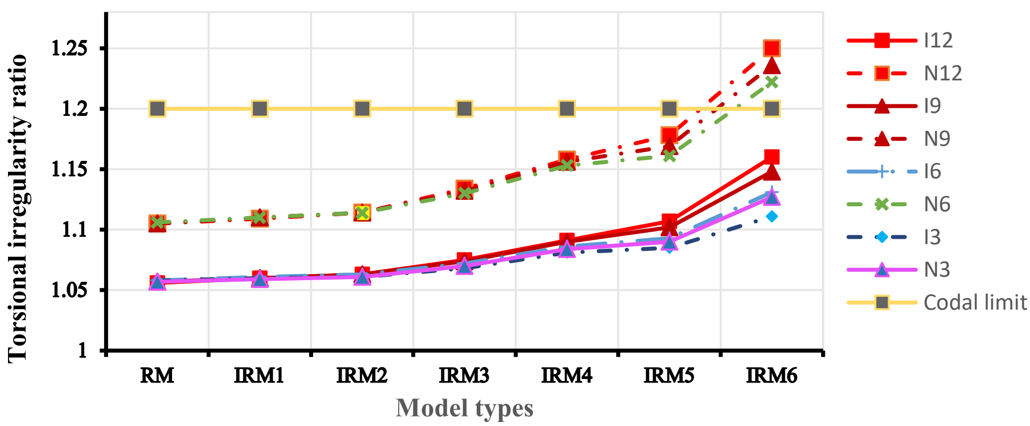

Figure 3: Maximum torsional irregularity ratio

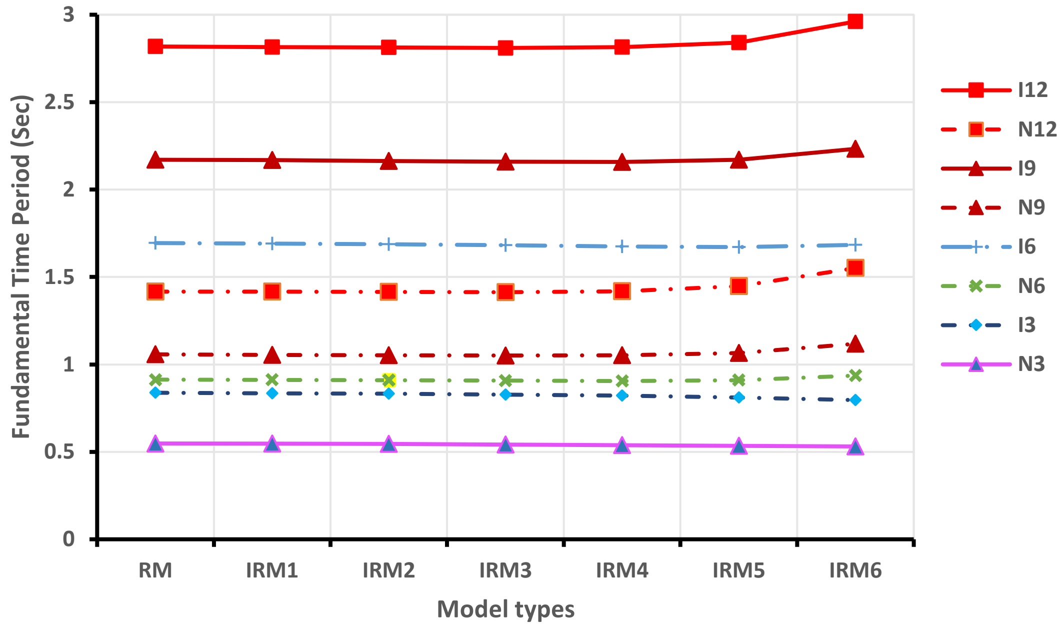

Figure 4: Fundamental Time period

3.3. Storey Shear

Story shear refers to the total lateral force acting on a building at a particular story level due to seismic excitation. It is a key parameter for understanding how lateral forces are distributed along the building height. Typically, larger story shear values are observed at lower stories due to the accumulation of forces from upper levels. Analyzing this distribution helps assess the structure's lateral load-resisting capacity and seismic design adequacy. The analysis shows that models designed using NBC 105:2020 produce higher story shear than those designed with IS 1893-1:2016. The average shear ratio (NBC/IS) is 3.74 for 3-story, 5.22 for 6-story, 5.56 for 9-story, and 4.58 for 12-story buildings, as shown in Figure 5. The largest difference is seen in the 9-story model, with a peak ratio of 6.73, showing that mid-rise buildings are more affected by the stricter seismic rules in NBC. This is due to NBC's higher design base shear requirements based on regional seismic hazards. Even the 6-story model shows a significant increase (5.22 times), proving that NBC leads to much higher seismic forces even in shorter mid-rise buildings (Bohara, Jagari, et al., 2025; Bohara & Saha, 2022). Moreover, regular models (RM) consistently exhibited higher story shear than irregular models (IRM1–IRM6). This trend indicates that structural irregularity lowers the efficiency of shear distribution, making irregular structures more vulnerable to seismic effects due to discontinuities in stiffness and load paths.

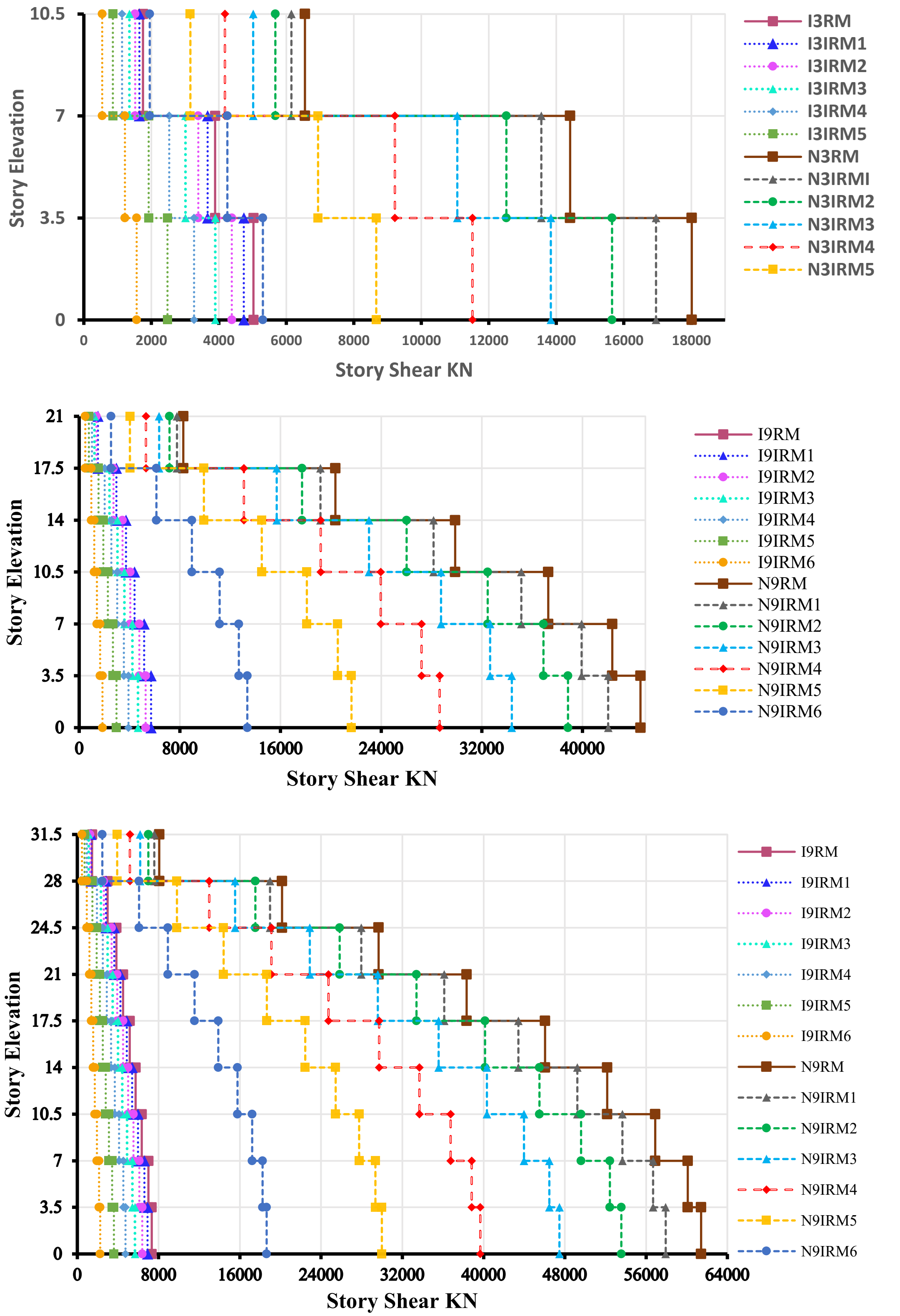

Figure 5a: Story Shear

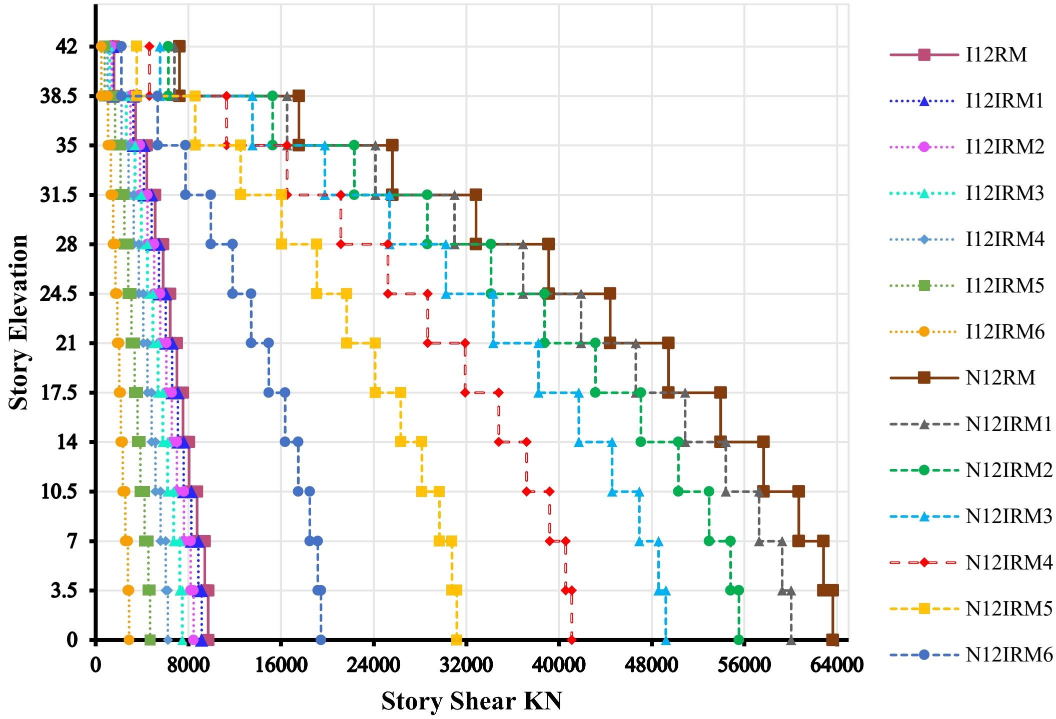

Figure 5b: Story Shear

3.4 Base Shear

Base shear, as the seismic design parameter, stands for the total lateral force at the base of a structure resulting from ground motion in an earthquake. It is calculated to determine the seismic forces that the structure must withstand and to guarantee that structures are stable and safe when subjected to seismic loads. Thus, base shear calculation is an essential phase in the design and analysis of the seismic resistance of a building (Birendra Kumar Bohara, 2021). The comparative base shear ratios (NBC/IS) between buildings designed using the NBC and the IS tend to increase for low-rise and mid-rise buildings (the observed average base shear ratios(NBC/IS) were: 3.6 for 3-story, 7.5 for 6-story and 8.7 for 9-story) (see Figure 6), indicating higher shear demand in NBC-designed buildings in comparison to that of IS-designed buildings up to 9-story buildings. With a further increase in the number of stories beyond 9 stories, i.e., high-rise buildings, the base shear ratio (NBC/IS) begins to decrease (the average base shear ratio NBC/IS being 6.8 for 12-story buildings). This trend indicates that as building height increases, particularly in high-rise buildings, the difference in base shear demand between the two codes reduces, and both begin to converge toward similar base shear values.

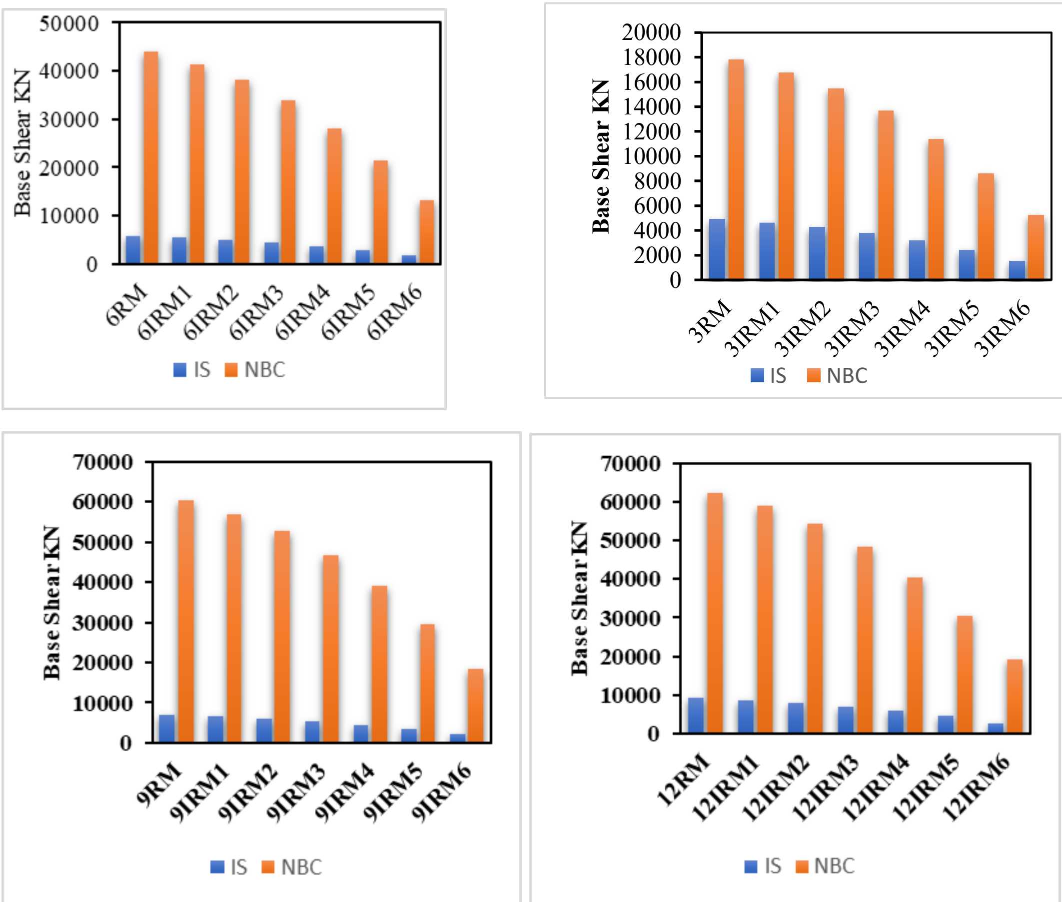

Figure 6: Base Shear

3.5 Story Displacement

Story displacement is the measure of the lateral movement of a story with respect to the base of the building due to lateral loads like an earthquake. It reflects the overall sway profile of the building structure. Large story displacement indicates more flexibility of the structure, whereas smaller displacement indicates greater stiffness of the structure. Thus, plotting the story displacement of a building structure gives an idea about the structural behavior of the building during the earthquake. The graphical representation of the story displacement for various story models under RSAx (Response Spectrum Analysis X) can be seen in the figure above, which illustrates that with an increase in height of the structure, story displacement also increases (Bohara et al., 2021). The buildings designed using NBC codes exhibited greater displacement values than those designed using IS codes, which is consistent with results reported in. For low-rise and mid-rise buildings (3-story, 6-story and 9-story), the variation of story displacement between the NBC-designed buildings and IS-designed buildings increases, and for high-rise buildings, i.e., 12-story buildings, the variation tends to decrease, suggesting that seismic design provisions in NBC and IS codes become increasingly aligned for high-rise buildings (See Figure 7). Among the analyzed models, the regular models exhibited lower story displacement than irregular structural models, indicating improved stiffness distribution and more efficient seismic force resistance due to uniform geometry and mass distribution, which is consistent with the results drawn in existing literature. The story displacement increases progressively from model RM to IRM6, with a minimum value observed in RM models and a maximum value in IRM6 in the all different story buildings designed using IS and NBC codes, indicating that the irregular buildings are more susceptible to seismic damage than regular buildings.

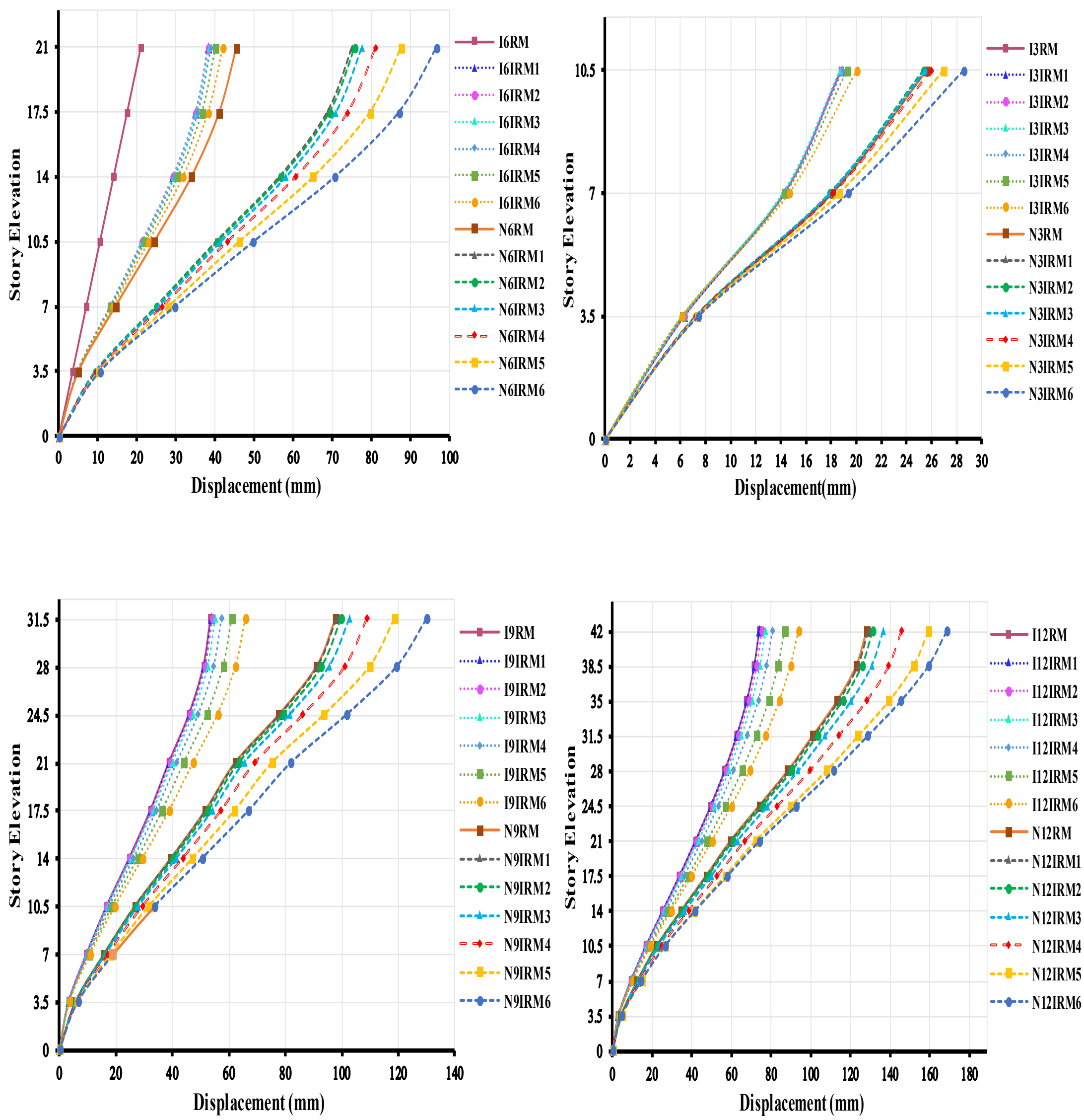

Figure 7: Story Displacement

3.6 Story Drift

Inter-story drift (ISD) ratio, also known as story drift ratio, is the ratio of the relative displacement between two adjacent stories to the story height. IS 1893:2016 and NBC 105:2020 impose limits on inter-story drift ratios to ensure structural safety and serviceability. The inter-story drift ratio limit specified by Clause 7.11.1.1, IS 1893:2016, is 0.004(0.4%) while Clause 5.6.3, NBC 105:2020, allows up to 0.025(2.5%) for Ultimate limit state (ULS) and 0.006(0.6%) for Serviceability limit state (SLS) as shown in Figure 8. These limits control lateral deformation to ensure structural and non-structural safety in seismic design. The graphical representation of the inter-story drift ratio indicates that the NBC-compliant buildings exhibited higher inter-story drift ratio values than IS Code-compliant buildings, which is consistent with. The inter-story drift ratios of IS Code-compliant buildings remained within the permissible limits of the IS Code, while NBC-designed buildings satisfied the drift criteria defined by the NBC code in all models for all the different story buildings.

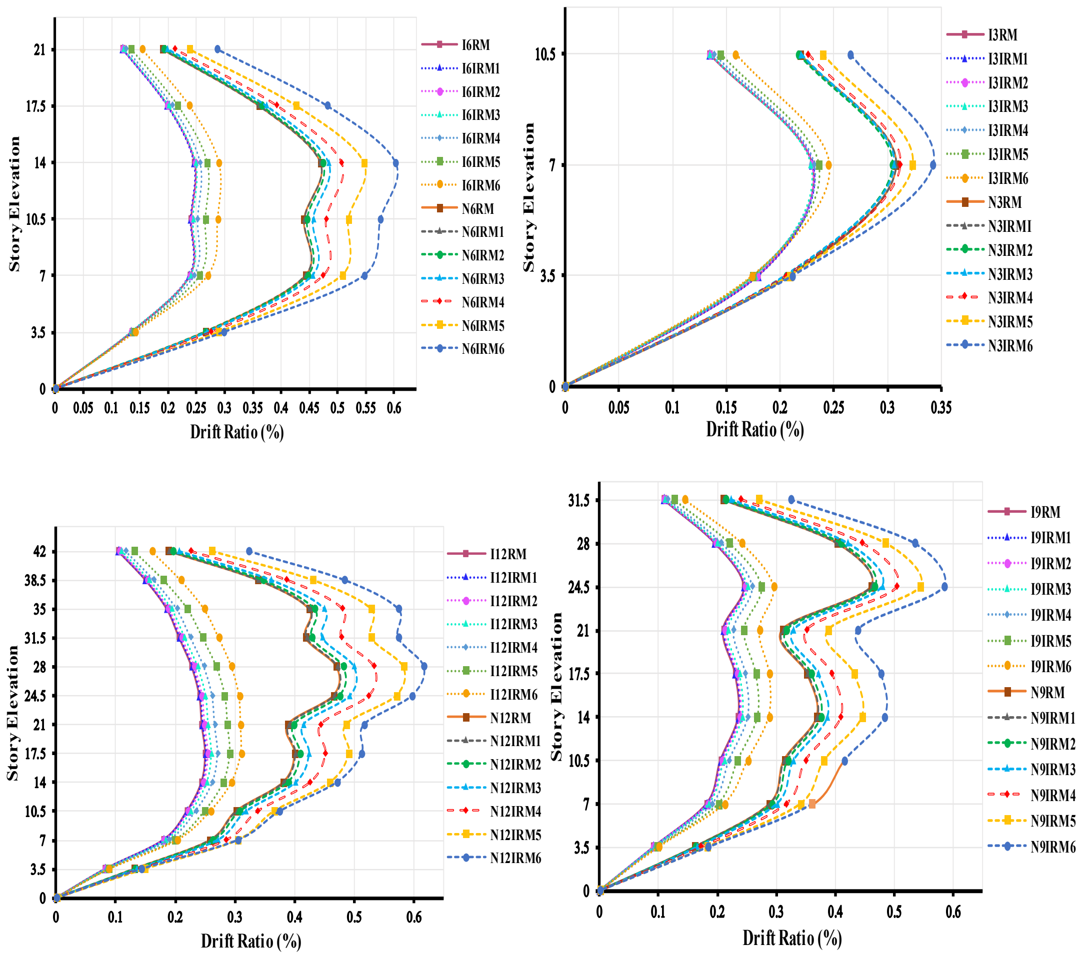

Figure 8: Drift Ratio

4. Conclusion

From the response spectrum analysis it was found that, the values of the story displacement, torsional irregularity ratio and drift ratio, increased with increase in planar irregularity (i.e I6RM to I6IRM6 and N6RM to N6IRM6). But values of the time period, base shear, story stiffness and story shear, decreased with increase in planar irregularity. This indicates that the irregular models have higher seismic vulnerability as compared to regular models, which was due to increase in torsion and discontinuous load path in irregular models, demanding careful dynamic analysis and additional strengthening measures. However the overall comparison between NBC and IS models showed the higher values for the NBC models than IS models that might be due to difference in codal provisions, response reduction factor, seismic zone coefficient, soil type and importance factor. This indicates the conservative design of structure using NBC than IS code. From the study, irregular models were found to be more seismically vulnerable than irregular models. So, irregularity in structure should be avoided as afar as possible. Otherwise, more careful analysis of irregular models should be performed as well as sufficient strengthening measures should be adopted.

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AI as a Global Equalizer: How NEP 2020 Can Leverage Artificial Intelligence to Bridge Educational Disparities

Sudan Jha[1*], Niraj K.C.[2], Sanjiv Regmi[3], Prakash Gupta[3]

[1] Department of Computer Science and Engineering, School of Engineering, Kathmandu University, Nepal

[2] Institute of Engineering and Information Technology, Lumbini Technological University, Banke, Nepal

[3] Institute of Engineering and Information Technology, Lumbini Technological University, Banke, Nepal

*Corresponding Email: sudan.jha@ku.edu.np

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Abstract

This paper examines the potential of the National Education Policy (NEP) 2020 to transform South Asia's educational landscape by integrating Artificial Intelligence (AI) to address systemic inequities. Despite rising literacy rates, the region faces deep seated structural divides rooted in geography, gender, and socio-economic status that traditional, "one-size-fits-all" teaching models fail to resolve. The study argues that AI can operationalize the core pillars of NEP 2020 such as universal foundational literacy, multilingualism, and inclusive education for Socio-Economic Disadvantaged Groups (SEDGs) through technologies like adaptive learning platforms, Natural Language Processing for mother-tongue instruction, and predictive analytics for early intervention. By proposing a phased implementation roadmap (2025-2030), the authors emphasize a "human-in-the-loop" approach that prioritizes bridging the digital divide and mitigating algorithmic bias, ultimately positioning AI as a scalable tool to democratize quality education and foster social transformation.

Keywords: *Artificial Intelligence, Educational Equity, Adaptive Learning, Digital Transformation, Socio-Economic.*

1. Introduction

1.1 The Twin Revolutions in Education

1.1.1 The Persistent Challenge of Educational Disparity

The education system in South Asia is among the world's largest, serving over 340 million learners across many unevenly distributed social and geographic systems. Some very positive trends can be found in the latest indicators. For example, the 2023 - 24 PLFS Report indicates that the National Literacy Rate has risen from 74% in 2011 to 80.9% today. The rise in this aggregate number of literate people is encouraging; however, it masks a complicated and fractured education system based upon multiple factors: region, gender and economic status. The real challenge is structural; the system remains dominated by a traditional, uniform education model despite operating in a region of the world with the highest degree of diversity. As a result, learners arrive to classrooms from very different linguistical and cultural backgrounds, come from many different home environments, and learn at very different speeds. Yet the system treats all learners equally. As a result, many of these learners will likely fall behind in the class and not be able to achieve their full academic potential. While student enrollment has increased, learning outcomes remain% very low and a significant percentage of students fail to develop foundational skills.

The disparities manifest in several critical areas:

a. Urban–Rural Divide: Urban areas show a literacy rate of 88.9 percent, while rural areas report only a literacy rate of 77.5 percent, representing a difference of more than 11 percentage points. The difference between urban and rural literacy rates is not simply a statistical anomaly; instead, it shows the persistent disparities in access to qualified educators, educational facilities and internet access that have historically been provided at greater rates to urban centres than to rural areas.

b. Gender Gap: The percentage of males who are literate (87.2%) is significantly higher than the percentage of females who are literate (74.6%) in India, with a difference of 12.6 percentage points. However, in some states, i.e. Rajasthan, this gap increases to an alarming 20.1%. These social norms and expectations regarding women's roles in the household, together with concerns about safety, early marriage, etc., have kept girls from participating equally with boys in education even with formalized policies supporting gender parity.

c. Regional Disparities: The performance of states varies greatly in terms of educational attainment. Mizoram has one of the highest literacy rates of any state in India (98.2%); whereas Bihar remains one of the lowest (74.3%). These differences illustrate two key findings: i) in parts of northeastern India where there are higher levels of educational attainment, there are many examples of effective community engagement and strong local government; and (ii) that policy decisions alone cannot produce strong educational attainment without institutional capacity and social cohesion.

Table 1: Literacy Rate Disparities in South Asia (PLFS 2023-24)*

Indicator	National Average	Top Performer	Bottom Performer
Overall Literacy (Age 7+)	80.9%	Mizoram (98.2%)	Bihar (74.3%)
Male Literacy	87.2%	Mizoram (99.2%)	Bihar (82.3%)
Female Literacy	74.6%	Mizoram (97.0%)	Bihar (66.1%)
Urban Literacy	88.9%	Likely high-performing states/UTs like Chandigarh and Kerala	--
Rural Literacy	77.5%	--	--

The combination of these disparities combined with the above-mentioned two reinforcing constraints is exacerbated by a lack of qualified teachers and poorly developed infrastructure in rural and underserved areas. Compounding these issues, the digital divide created additional barriers to formal education for many students during the COVID-19 pandemic. A lack of access to reliable internet service or personal devices effectively rendered students without both, unable to participate in formal learning, pushing already vulnerable groups even further to the margins.

1.1.2 A Paradigm Shift: The National Education Policy 2020

The National Education Policy (NEP) 2020 is an attempt to create significant reform to South Asia's education system based on the social and economic inequality that exists in this part of the world at the time of writing. Developed under Dr. K. Kasturirangan's direction, the NEP proposes to create a cohesive vision for the future of education within South Asia, including elevating this region to the status of a "knowledge society," which is equitable and vibrant.

While NEP 2020 has a far-reaching scope, the real distinction between it and previous educational reform initiatives is its fundamental philosophical change. Instead of traditional curriculum systems designed around fixed pathways and rote memorization, the NEP establishes a new framework for education that emphasizes flexible, holistic, and interdisciplinary learning environments. Equity is embedded into the design of the policy rather than being viewed as an additional component to an existing educational framework.

Five interrelated goals anchor this shift:

a. Access: Quality education; specifically, consideration of students from Socio-Economic Disadvantaged Groups (SEDGs).

b. Equity: Using research-based strategies to close the long-standing achievement gap and access to higher-learning institutions through targeted, evidence-based intervention strategies.

c. Quality: Developing critical thinking, creativity, and character rather than emphasizing rote memorization.

d. Affordability: Reducing the financial barriers to education and all levels of education.

e. Accountability: Providing comprehensive means to measure Learning Outcomes and Performance of Educational Institutions.

The fifth anniversary of NEP 2020, from a policy perspective, will be viewed as a time when policymakers refer to their position as being on a “path of strength, rootedness and stability” with continued focus on establishing foundational systems supporting future growth. There are some initial visible initiatives having been developed, including the establishment of the Academic Bank of Credits, creation of flexible entry/exit opportunities and formal incorporation of the South Asian Knowledge System (IKS) into higher education in India. However, scale will continue to present a significant challenge.

1.1.3 The Emergence of a Powerful Tool: Artificial Intelligence

Using these technologies, educators have the capability of creating dynamic systems, which allow for learner reactions based on individual learning behaviours instead of responding to learners' behaviours uniformly. For example, AI-powered platforms for education can create personalized learning experiences by observing student performance in real time and adapting content equitably to those students simultaneously.

Intelligent adaptive tutoring systems can give a high percentage of one-on-one support to students, even in places where teachers are not available. Moreover, the ability to have automation in the administrative process will save educators significant time regarding grading and scheduling, allowing their attention to be focused on instructional and student mentorship. Accessibility tools will include the ability for translation in real-time, providing text-to-speech capabilities and various other tools, and expand the opportunities for learners with disabilities and also to learners who come from linguistically diverse backgrounds.

It is important to note that rather than replacing teachers, AI will enhance teachers' ability to guide their students by providing teachers with data to support their professional judgement. This will give the educator the power to address issues sooner, to teach more accurately, and to better support their learner(s). "Human-in-the-loop" training emphasizes that there are many ways for a teacher to provide support to their learners. It is impossible for an algorithm to provide a learner with mentorship, motivation and emotional support. As such, these roles will always be part of the education process.

1.1.4 Thesis Statement

The chapter presents an argument for how South Asia can leverage AI, through NEP 2020, to overcome previous limitations, by creating a more accessible, customized and competitive system of education. AI is no longer just a technical enhancement, but as we align AI with policies centered on equity, it becomes a platform for social transformation.

Table 2: Synergistic Framework of NEP 2020 and AI in Education

NEP 2020 Goal	Corresponding AI Application	Potential Impact
Personalized Learning	Adaptive Learning Platforms	Tailors education to individual student's pace and style.
Equity & Inclusion	AI-powered Translation & Accessibility Tools	Breaks down language and disability barriers.
Teacher Empowerment	Automation of Administrative Tasks	Frees up teacher time for instruction and mentorship.
Competency-Based Assessment	AI-Driven Analytics and Feedback	Provides real-time, targeted feedback on student understanding.
Lifelong Learning	AI-Enabled Skill Development Platforms	Offers personalized reskilling and upskilling pathways.

This type of systemic change means that a new model does not only address the inequities within the education systems in South Asia; rather, it provides a framework that can easily be adjusted by other countries experiencing similar size, diversity and inequities to their respective education systems, as well as an opportunity for continuous improvement.

2. The NEP 2020 Framework: A Blueprint for Equitable Transformation

Instead of viewing the National Education Policy 2020 as simply another update to an existing policy, we should instead view it as a complete re-imagining of the education system in South Asia. The idea behind the National Education Policy (NEP) 2020 is that the educational disadvantage faced by certain groups is not due to the individual's lack of ability or intelligence, but rather a result of the inequitable nature of our existing systems that produce such inequalities through both design and lack of resources. Therefore, since inequities are produced by these systems, these systems need to be completely redesigned and rebuilt to eliminate any potential sources of inequity.

The NEP 2020 accomplishes this goal through the establishment of extensive and interrelated pillars which are designed specifically to identify and eliminate the major sources of inequality for students: Early Learning, Language, Rigid Curricula, Teacher Professionalism, and Access to Opportunity. In addition, each of these pillars can also serve as a point where Artificial Intelligence can be utilized to take advantage of the power of AI in order to provide maximum benefit to the student population and educational system beyond the capabilities of traditional administrative processes.

2.1 Key Pillars Relevant to Bridging Disparities

2.1.1 Universal Foundational Literacy and Numeracy: The Critical First Step

The Policy expresses the position that Foundational Literacy and Numeracy (FLN) should not only be a long term expectation but also is the priority of the policy. In fact, the NEP 2020 specifically identifies FLN as being "an urgent and necessary prerequisite for all learning" (MHRD 2020). The NEP 2020 recognizes that FLN is the foundation upon which all subsequent interventions occur, and this commitment is demonstrated through the NIPUN Bharat (National Initiative for Proficiency in Reading with Understanding and Numeracy) Mission.

The need for urgency in FLN is supported by data. For example, the ASER 2023 report indicates that, as early as Grade 5, only 42.8% of students are able to read at the level of a Grade 2 student (ASER Centre 2023). The inability to exhibit FLN is not just a curriculum concern, it is a systemic alarm. The presence of weak FLN skills creates an environment in which the focus of instructional delivery is on coverage, rather than a focus on the actual instruction of students, making it more about learning than teaching.

The shift from content-based instruction to competency-based education is a core theme of the NEP 2020 and provides an inherent expectation of continual or fine-tuned assessment and monitoring of student achievement for every learner in every classroom. In the current structure of classroom assessment as a basis for institutional accountability across the nation, this increase in expectation would simply overwhelm traditional forms of student assessment and for the purposes of remediation. However, AI driven adaptive learning platforms address this dilemma and the need for increased capacity to both diagnose students' diagnostic gaps/needs with respect to Reading with Understanding and Numeracy, and subsequently deliver additional targeted practice for real-time remediation, allowing mastery based progression to go from rhetoric to practice (Baker & Inventado, 2014).

2.1.2 Flexible and Multidisciplinary Learning: Moving Away from Rigid Streams

The Policy revamps the educational system, drastically changing from legacy structural systems by replacing the rigid 10+2 model with a flexible 5+3+3+4 curricular framework, which allows for the delaying of early academic streaming and allows for the opportunity for the multidisciplinary exploration of a subject by not limiting learners to the rigid educational framework and allowing for Physics to be part of the same curricular framework as Music or History to be part of the same curricular framework as Computer Science. This flexible conceptual approach to the curriculum is aligned with the contemporary understandings of Cognition, Creativity, and Employability.

However, this new curricular framework introduces greater complexity for learners, as they will have to navigate through an expanded choice space for courses; schools will need to maintain multiple types of pathways for learners; and, the assessments will need to account for the non-linear progression of learners through their curricular pathway.

The use of AI-powered recommendation systems to provide learners with the best course combinations for their individual learning paths is essential, not simply a convenience. Through the analysis of student aptitude, interest, and changing labor market information, AI-powered recommendation systems will provide guidance for learners to put together the best subject combinations to take for their career interests. The recommendations provided by AI recommendation systems could be transformative for students from marginalized populations who may not have access to professional career guidance.

2.1.3. Multilingualism and the Power of Language: Education in the Mother Tongue

The NEP 2020 has placed a focus on language as an important part of equity. The policy has stated that instruction, when possible, will be conducted in a student's home language or mother tongue through Grade 5, and in the native tongue, ideally through Grade 8 and beyond (MHRD, 2020). This initiative was taken in response to decades of evidence showing the negative cognitive impacts placed on first-time generations in a language that is not their mother tongue.

The reason for establishing this policy is to address the lack of high-quality curricular content, training for teachers and assessment materials that exists in many South Asian languages, which will provide the same challenges for instructional support and implementation.

AI—specifically NLP and generative AI—can quickly and easily provide organizations with value by allowing them to create large quantities of instructional content in many local languages through the use of translation, transcreation and generation capabilities associated with these technologies (UNESCO, 2021). In addition, speech recognition tools will support early readers by providing immediate feedback regarding the pronunciation of words in their mother tongue, thereby allowing them to improve fluency, as well as comprehension. AI, therefore, does not just enable multilingual education - it puts in place support systems for multilingual education to become operational.

2.1.4. Equitable and Inclusive Education: Focus on SEDGs

The National Education Policy (NEP) 2020's approach to equity does not consider equity as merely an abstract idea. The NEP has made a clear identification of the various Socio-Economically Disadvantaged Groups (SEDGs). SEDGs include: (i) girls; (ii) children or youths living in rural economies; (iii) children with disabilities; and (iv) children from impoverished households and families; and requires specific and targeted forms of support such as Gender Inclusion Funds and Special Education Zones to address the systematic barriers to participation faced by many SEDGs within the country (MHRD, 2020).

Despite the use of technology, the identification of the at-risk population traditionally has been reliant on lagging indicator data, meaning that it has often been able to identify the risk of disengagement/Aid (at times, after the fact). With the advent of Artificial Intelligence (AI)-enabled predictive analytics technologies, there are now methods to predict this risk sooner. Predictive analytics can be used to recognise patterns in learner attendance, engagement and assessment data, and when specific behaviours might signify the likelihood of disengagement (Baker & Inventado, 2014). Additionally, AI-powered assistive technology solutions such as speech-to-text tools, text-to-speech readers, and sign language avatars have the potential to change the means of providing classroom access for learners with disabilities from a model of accommodation to one of full classroom equity (Bhattacharjee, 2024).

2.1.5. Lifelong Learning (LLL) and Vocational Integration

According to NEP 2020, the two-decade timeline of initial education theory and practice is being shifted because of rapid technological change and the fact that skills have a very short shelf life today. As such, Lifelong Learning (LLL) is thought of as a necessary element and part of a more extensive education process as opposed to being just a new educational policy element. By including vocational education beginning at middle school age, the intent is to incorporate a LLL approach into the overall educational system.

AI is being utilized as an enabling component that is scaling the way in which LLL can be achieved. AI-based platforms will allow users to identify and track existing competencies and skills that are missing, along with recommended learning pathways for continuing education based upon the future employment demands identified by labor market projection sources, such as the World Economic Forum.

2.1.6. Robust Digital Infrastructure: The Role of DIKSHA and NETF

Smart technology is at the heart of this policy and includes DIKSHA (Digital Infrastructure for Knowledge Sharing) opportunities, as well as the proposed National Educational Technology Forum (NETF) (MHRD, 2020) DIKSHA serves as a central location for all forms of content, assessment, and teacher resources.

While intelligent systems can help support and direct growth, without them, the scale becomes only useless sound. With the advent of Artificial Intelligence (AI), DIKSHA could evolve from a passive archive to a dynamic feedback-loop-based learning ecosystem featuring appropriate recommendation systems, and providing tutoring and analytics capabilities built into the learning experience. NETF would provide the basis for an ethical approach to the development and use of intelligent systems aligned with the principles of equity, privacy, and accountability, as well as other frameworks designed to govern ethical AI development (Nguyen et al., 2023 and UNESCO, 2021).

3. AI in Action: Strategic Applications to Fulfil NEP 2020's Vision

While AI is an Operational tool for the NEP 2020 as a Policy Directive, the operational effectiveness of AI cannot be evaluated based solely on its application to Education. Instead, as regards to Education, the effective application of AI technology will require a concerted effort to identify specific applications that will effectively address South Asia's persistent, underlying Educational Failures. In the following section, we will review AI applications that fit directly with NEP 2020's goals, which will provide tangible mechanisms by which NEP 2020 policies can be translated into action.

3.1 Personalized and Adaptive Learning Pathways

Problem: Conventional classrooms are structured based on the belief that every student is an average learner; however, this is not true. Each student learns at different rates, develops a different grasp of concepts, and reacts to varying signals from their teachers in diverse ways. The one-size-fits-all model punishes both groups of students: the slower learners lose interest, while the quicker learners remain stagnant.

AI Solution & NEP Alignment: Adaptive Learning Technology addresses the issue at the source by employing machine-learning algorithms trained on the student interaction data to create and manage levels of content difficulty, sequencing, and pace of individual students based on their performance. If a student is having trouble with fractions, the solution is not to give them a reduced score; instead, the system provides support through visual explanations, additional practice or prerequisite concepts associated with fractions. Likewise, if the student has mastered the content through demonstrated performance, the system should offer an opportunity for acceleration rather than forcing the student to go back over the material they have already demonstrated competency in.

a. This directly achieves NEP 2020's goal of foundational literacy and numeracy by ensuring each child builds core competencies at their own pace.
b. It embodies the policy's vision for student-centric, flexible learning that recognizes and nurtures the unique capabilities of each student.

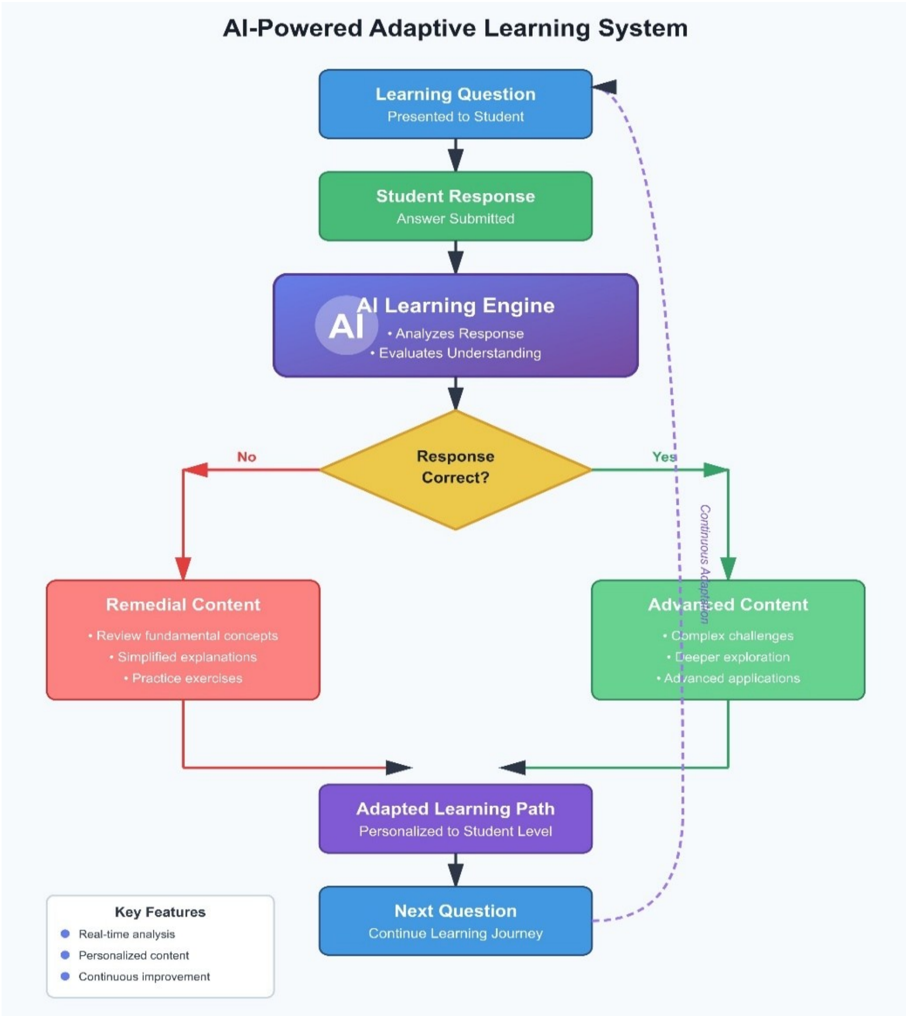

Figure 1: Adaptive Learning Flowchart

3.2 Breaking Language Barriers

Problem: In South Asia, the language is very underappreciated in terms of how it influences education; there appears to be a mismatch between how it has been formulated in policies with its actual implementation in schools. The lack of good quality local language learning materials and well-trained teaching professionals hinders students' understanding, especially in the first few years of their education.

AI Solution & NEP Alignment: AI-Based Translators and Natural Language Processors Provide Scalability While Traditional Methods Fail to Scale. Using AI-based Real-Time Translation, Textbooks, Lectures, and Assessments Can Be Instantly Translated into Multiple Languages Throughout South Asia Eliminating Many of the Existing Constraints Associated with Centralized Content Production. Learners Will Be Able to Interact with Digital Systems Using Their Mother Tongue Using NLP Interfaces Thus Reducing the Cognitive Load on Learners and Enhancing Engagement.

Speech Recognition Technology Takes This A Step Further by Giving Users Immediate Feedback on Their Pronunciations. Using AI to Provide Immediate Pronunciation Feedback for Local Languages Will Help Students in Their Early Reading Development and This Intervention Is Directly Aligned with the NEP 2020 Mandate on Mother-Tongue Instruction.

Overall, the Combination of these Technologies Not Only Supports Multilingual Education but Also Establishes the Structural Capability for Linguistic Inclusivity.

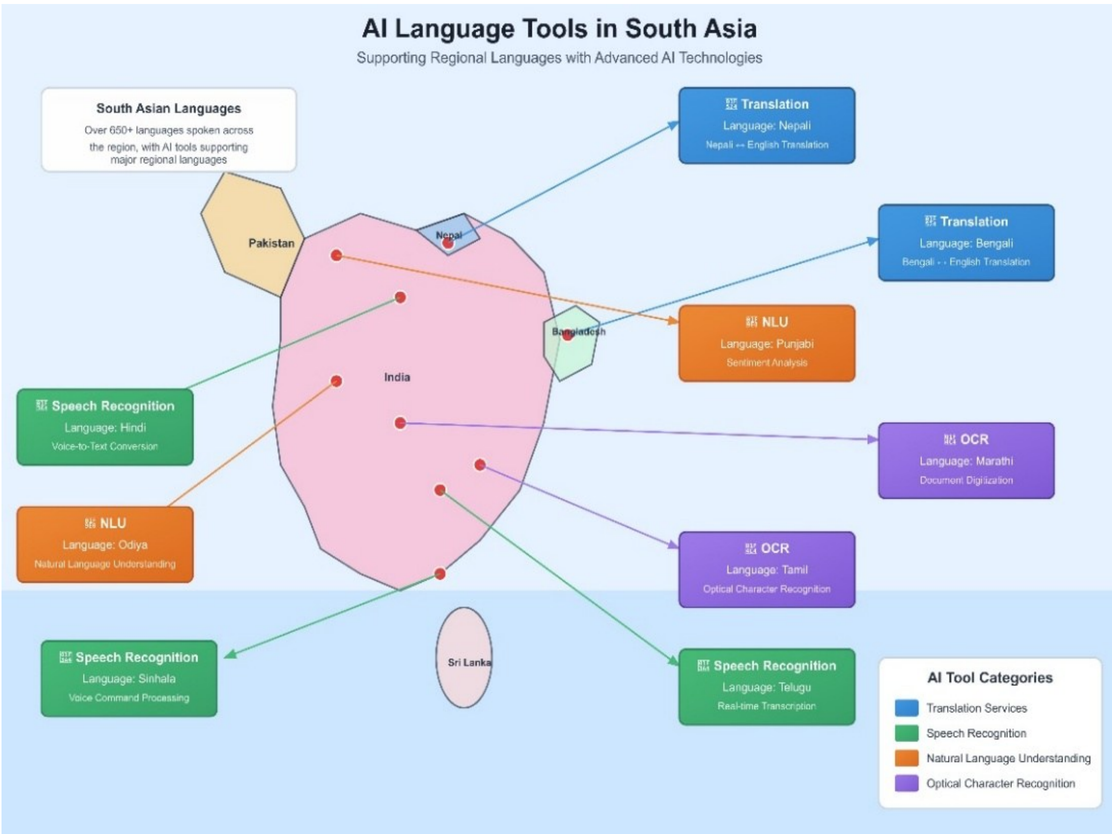

Figure 2: South Asia AI Map

3.3 Intelligent Tutoring and Scaffolding Support

Problem: A high student-teacher ratio, especially in rural or under-served areas, results in little individualized attention except for a few cases. Students frequently experience difficulties with their studies when outside of class but receive little or no assistance. These students often build up their learning gaps without any noticeable signs or clues.

AI Solution & NEP Alignment: Chatbots and other AI advancements can serve as on-demand tutors for students. Students can get immediate feedback, guidance and assistance on conceptual questions, and all in a timely manner by using these tools.

Chatbots and other AI systems should not be seen as replacements for the teacher, but rather a way to absorb a lot of the lower-level repetitive instruction that takes up significant amounts of time for teachers.

Therefore, because of this redistribution of instruction, all students will receive academic assistance consistently, no matter where they live or what their socioeconomic status is, while teachers will be able to devote their time to more complex instructional activities, such as developing concepts, mentoring, and organizing the classroom settings. Thus, when developed properly, an AI tutor will serve as a multiplier for teachers, supporting and enhancing the goals of NEP 2020 for equitable access for all students, without increasing the teacher's workload or the number of human resources necessary to perform the tutoring function.

Table 3: AI Tutoring vs. Traditional Support

Feature	Traditional After-School Support	AI-Powered Intelligent Tutoring System
Availability	Limited hours	24/7, on-demand
Scalability	Limited by human resource availability	Virtually unlimited, can serve millions simultaneously
Personalization	Generic, group-focused	Highly personalized based on individual learning gaps
Cost	Can be prohibitively expensive for many families	Highly cost-effective at scale
Consistency	Varies by tutor	Consistent, standardized quality of instruction

3.4. Democratizing Access to Expert Teachers and Content

Problem: Access to quality education continues to be determined by geographic location. The availability of specialized subjects, experienced teachers, and access to enriched teaching and learning resources continues to be concentrated in urban areas, which reinforces the traditional gap between urban and rural areas.

AI Solution & NEP Alignment: Platforms such as DIKSHA (Digital Infrastructure for Knowledge Sharing) develop recommendation algorithms by analyzing the content available through their systems and identifying curated, high-quality content that meets the specific requirements of each learner's course of study, learning level and specific history of previous learning. Instead of searching through a huge, potentially overwhelming amount of material manually, students and educators receive resources like videos, simulations, modules to practice what they learned and so on that will help them complete their current teaching.

Through this process, digital platforms are able to transition from passive, "dumb" repositories of information to intelligent distribution systems which provide access to expertise based on connectivity rather than geographical location. This supports the principle of access and equity outlined in the NEP 2020.

3.5. Data-Driven Insights for Early Intervention and System Management

Problem: Historically, a reactive approach has been utilized in educational systems. As learning failures are often recognized only after they become evident (e.g., dropouts), it is usually too late, making remediation both costly and frequently ineffective. Furthermore, administrator access to updated insight on systemic weaknesses is limited. Instead, they rely upon fragmented indicators developed by individual teachers.

AI Solution & NEP Alignment: The application of predictive analytics will change how we intervene with students based on their behaviour over time. By examining student attendance, engagement, and performance over time, AI predictive models provide early identification of at-risk students who would benefit from targeted support. On a broader scale, predictive analytics identify the common areas where curriculum development has been stymied, consistent student misunderstandings, and the areas in need of teacher professional development support.

With this new capability, the accountability component of NEP 2020 is enhanced, enabling data-informed decision-making across all levels of classroom, school and administrative.

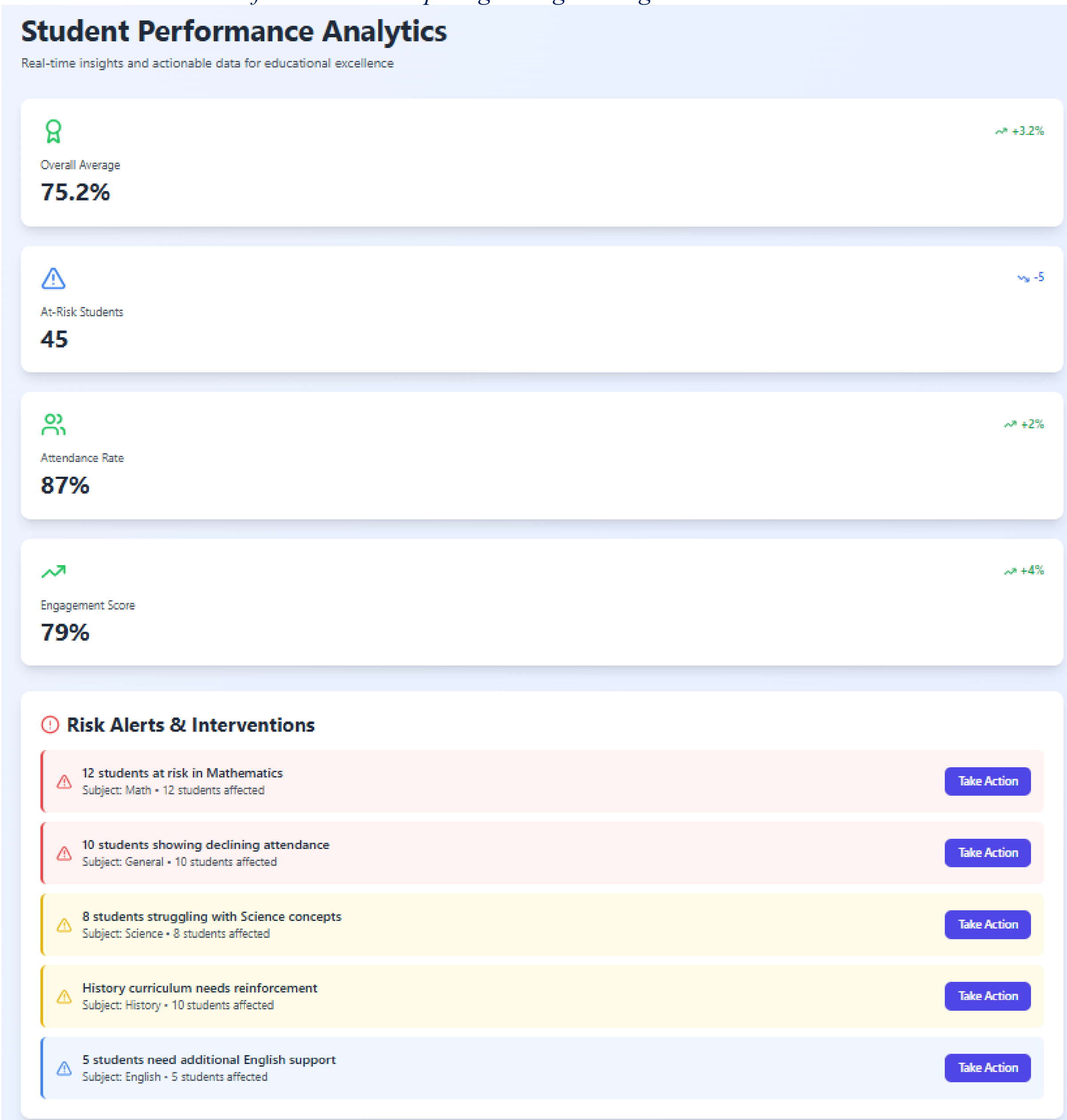

Figure 3: Sample Student Performance Dashboard

3.6. Revolutionizing Vocational Education and Skill Development

Problem: There continues to be a significant gap between what employers need in terms of workforce readiness and what education provides. Graduates tend to be qualified but not sufficiently skilled for the current, rapidly changing technological landscape.

AI Solution & NEP Alignment: AI-based platforms for developing skills are designed to solve this convergence problem. With data from current employment trends, AI can provide recommendations for pathways towards a vocation that is tailored to a specific skill set and will meet the future's employment demands. In addition to identifying possible career choices based on skill sets, AI also offers interest-based, aptitude tests, and the opportunity to explore high growth areas of employment, such as AI, data analytics, and mechatronics.

The use of AI to provide vocational training opportunities is a direct result of the NEP 2020 focus on vocational integration and the idea that employability should be integrated throughout the entire education process, not just treated as an issue to be addressed after a student graduates.

4. Navigating the Chasm: Challenges and Ethical Imperatives

Artificial Intelligence (AI) can deliver benefits to education; however, those benefits will not be automatic and will not happen unless appropriate safeguards are established. Without careful deployment of AI, we risk exacerbating pre-existing inequalities. In South Asia, where deep-seated structural inequities exist, the risks associated with these developments are real and immediate. Therefore, engaging with these challenges vigorously is not just an option; it is essential to successfully implement credible AI-enabled educational reforms in accordance with the goals established under the National Education Policy (NEP) 2020.

4.1. The Digital Divide: The Foundational Fault Line

The most fundamental constraint facing the integration of AI technology lies in the uncertainty of power supply and internet connectivity, as both are required for AI to operate to its fullest potential. In many regions of South Asia, there is no solid infrastructure for reliable access to electricity or high-speed internet service; therefore, many areas lack a reliable technology foundation upon which to build an AI-enabled education system.

For example, in many rural areas, access to the internet is sporadic, if not completely absent. The ASER 2023 report on foundational learning in rural areas highlights how the need for access to digital learning tools must be met within the context of the existing inequity in the educational system. Thus, without investment focused on addressing existing inequities, AI-enabled education will perpetuate and deepen, rather than reduce, disparities between urban and rural areas.

Access to technology is another major challenge to implementing AI technology in education. Even in areas where access to the internet is available, most households can only afford to purchase one smartphone per household, resulting in fragmented and limited access to learning opportunities. As such, even the most sophisticated AI tutoring system cannot compensate for the lack of available technology resources or the absence of consistent access to digital learning tools. When the implementation of technology is not accompanied by the investment needed to ensure continuous access and an affordable technology, success will be very limited and the impact of technology will vary widely across regions and demographics.

Table 4: Dimensions of the Digital Divide in South Asian Education

Dimension	Urban/Affluent Context	Rural / Underserved Context	Impact on AI in Education
Connectivity	High-speed, reliable broadband	Intermittent or no internet; reliance on mobile data	Disrupts streaming, real-time interaction with AI platforms, and data syncing.
Device Access	Multiple devices per household; personal laptops/tablets	Shared family smartphone; often outdated models	Limits exposure to complex educational software; makes learning intermittent and fragmented.
Digital Literacy	Higher familiarity with digital interfaces and navigation	Lower comfort levels; may view technology with skepticism	Creates a usability barrier; students struggle to interact with the platform itself.

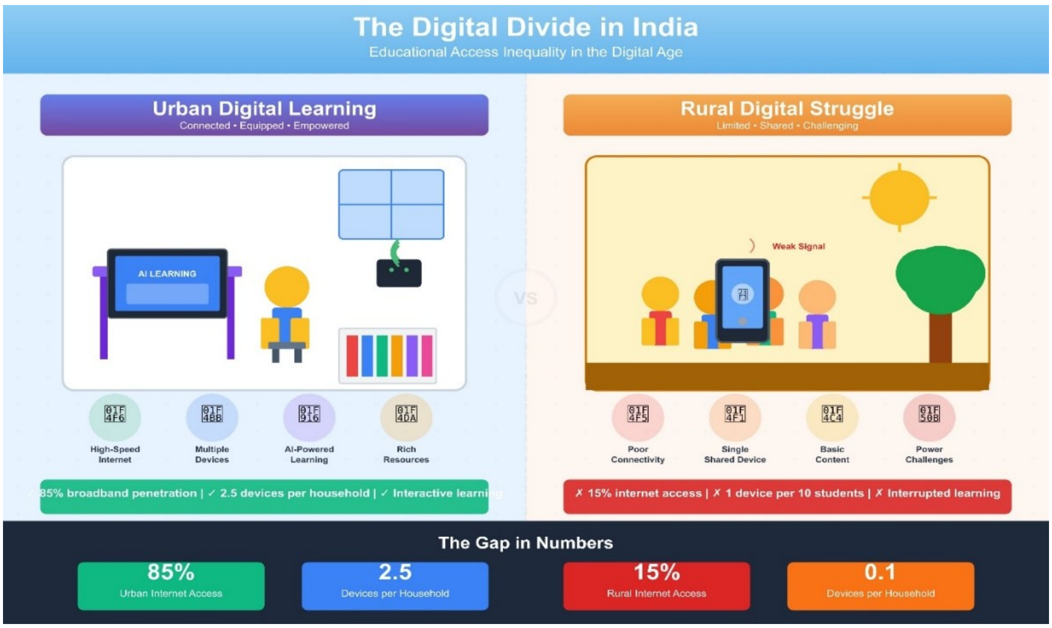

Figure 4: Digital Divide Infographic

4.2. Algorithmic Bias: The Perpetuation of Inequality

The assumptions embedded within AI training data are inherited by the created system. Therefore, when a model uses data that reflects historical inequalities, social prejudices, or culture-non-specific viewpoints, the model creates a more extensive version of such respective prejudice or discrimination (i.e., it creates scaling).

Large AI systems are mainly built from English-speaking (and, Western-centric) based datasets. Thus, when they are utilized in South Asia, they may misinterpret the environment and be incapable of appreciating and properly interpreting knowledge systems, as well as equating their output to the lives of the South Asians.

For example, if a young woman with an educational background based in a rural society were to logically create a premise based on her experiences and actions, the algorithms would not be able to measure it correctly, which could cause an implicit penalty for her rationale because it is not based on urban norms.

Bias can lead to truly detrimental outcomes in applications that have substantial risk exposure, such as in the area of guiding careers. In situations where AI systems are trained using data from historical records of enlisting students or hiring employees, there may be subtle biases that may encourage girls away from STEM fields. Additionally, there may be additional subtle recommendations towards students who belong to lower income demographics away from elite careers. Ultimately, we can conclude that the results produced from the systems create a serious contradiction to the ethical guideline of Justice, which dictates that any AI-created systems need to actively work against and/or combat structural injustice and oppression rather than replicate it.

4.3. Data Privacy and Security: Protecting the Student

The use of AI in education relies heavily on the continued collection of data; performance metrics, behaviours towards learning, errors made in class and the history of engagement. In essence, when all of these elements are aggregated together they form one of the most comprehensive datasets concerning children and young adults that has ever been created. However, with the aggregation of sensitive information such as this comes risk.

Centralised repositories of information become high-value targets for cybercriminals seeking to steal personal information and potentially have devastating effects on the life of the student if the sensitive information falls into the wrong hands. Beyond the risk of a data breach, there are many unanswered questions regarding ownership of that data and the consent needed to access it. Who owns the data about the student learning process? How long does that organisation keep the data? When, and under what circumstances, can that organisation share the data?

With the introduction of the proposed Digital Personal Data Protection Act in South Asia – which represents a step in the right direction in terms of privacy, protection of the individual and accountability – there remains a significant lack of clarity regarding how to enforce this legislation within the context of education and educational technology. Ethical AI Frameworks universally identify Privacy, Data Protection and Transparency as essential elements of any ethical AI Framework and a lack of credible protections and enforcement will result in a loss of faith (the world's most valuable commodity) in large-scale educational reform

4.4. The Teacher-AI Symbiosis: Redefining Roles, Not Replacing Them

The fear of being displaced is one of the most highly emotional responses to AI technologies in education. However, the real issue surrounding AI's impact on education is not about being replaced by AI but rather realigning how we think about education.

Many educators lack the necessary knowledge and experience to effectively work with AI. They do not have enough experience with AI tools, are not adequately trained in how to effectively implement them into their classrooms, and do not have a clear understanding of what is expected of them when using AI tools in their classrooms. This lack of experience, training, and understanding creates more technophobia than it does to promote techno philia or the adoption of AI tools.

When AI tools are introduced into a teacher's classroom without being integrated with best pedagogical practice, teachers feel as though technology is complicating their lives rather than assisting their instructional strategies.

According to the NEP 2020, there must be a fundamental shift in the role of the teacher—the traditional role of the teacher as an expert providing knowledge to the classroom. AI tools will automate many administrative tasks, provide constant and continuous feedback about student progress, and assist educators in delivering individualized instruction, but the functions of AI cannot replace the functions of human judgment, empathy, mentorship, and all of those other human characteristics that we associate with quality teaching.

Ultimately, the integration of AI into education, and more broadly, into the fabric of our society, cannot be achieved unless we promote continued professional development for educators.

4.5. Cost and Implementation Logistics: The Question of Scalability

The implementation of AI systems is not as simple as developing a piece of software to address an identified need. The total cost of AI systems goes far beyond the software development phase, including the purchase of hardware or devices; obtaining connection subsidies to allow individuals to access the Internet of Things (IoT); translating all content into multiple languages; establishing a network of servers to enable AI systems; ongoing maintenance and operation of AI systems; and so on.

Assuming that costs are incurred at the national level, the cost of deploying AI systems at this level would be significant. Therefore, public funding alone may not be sufficient and, consequently, many countries may have to rely on Public-Private

Partnerships (PPPs) to fund this initiative. However, these partnerships must be structured carefully, ensuring that commercial motivations do not overrule educational goals, and that student data cannot be sold for profit.

The experience of companies like Vedantu and Eruditus provides insight into the potential and limitations of the private sector's ability to scale; while initial operational experiences can inform the development of efficient and effective educational models via AI, it would be inappropriate to insert profit-driven models into public school systems without consideration for equity.

5. A Proposed Roadmap for Integration

To close the gap between educational technology aspirations and the realities of education, many things are required beyond being excited about technology. Countries need to sequence actions carefully and limit themselves, while at the same time learn from institutions that have gone before them. Rushing the deployment of any type of technology can create inequity; however, taking a slow yet thoughtful approach makes it possible to correct issues prior to scaling. Therefore, it is imperative that the introduction of AI takes place in accordance with a phased implementation plan within the NEP 2020, and focuses on developing the same Technical Capacity, Institutional Trust, and Human Readiness concurrently.

5.1. Phase 1: Foundation and Piloting (Short-Term: 2025–2027)

Phase One's aim is to create a stable foundation rather than one that can be expanded upon later --- there are steps that must be taken to establish the infrastructure, ethics and institutions needed for the responsible use of AI.

5.1.1. Strengthen Digital Infrastructure in Partnership with States.

The most important requirement prior to any form of ICTC (Information Communication Technology Connectivity) implementation, is connectivity. Therefore, it is crucial to collaborate with state governments in order to connect all secondary and higher secondary schools in their respective areas to the BharatNet Optical Fiber Network. In addition, block Level Digital Hubs must be established in order to facilitate access outside of regular school hours, especially in the underserved parts of the community. Finally, targeted device subsidy programs for students who come from socio-economically disadvantaged groups (SEDGs) should also be implemented in order to ensure that simple access does not remain a theoretical phenomenon, but instead becomes a practical reality.

5.1.2. Initiate Localized Pilot Projects.

Instead of introducing one-size-fits-all AI products throughout the country, Phase 1 of AI for Learning focuses on implementing localised pilots that allow for testing FlN (Foundational Literacy & Numeracy) solutions in very different linguistic/geographic areas. For instance, piloting a speech-enabled reading tool in Tamil in Tamil Nadu would make sense, whereas doing so with the same tool in Hindi would fit better in an area such as Uttar Pradesh. In addition to gauging the pilot project's success in terms of improved student performance, each pilot will likely also require evaluation for its usability to teachers, adoption by teachers, and cost/effectiveness within the scaled system.

5.1.3. Develop Robust Data Privacy and Ethical AI Guidelines.

In this stage, the NETF plays a pivotal part. NETF will put into action a National Framework of Ethics and Responsibility with the help of the Global Standards as presented by EDUCAUSE's AI guidelines and the recommendations from UNESCO. This framework will fit the unique cultural context of South Asia. As a given, Legitimate use of AI requires the completion of a variety of Algorithmic Audits, appropriate data ownership protocol, and open communication on grievance and dispute resolution methods all come together in creating an effective ethical framework.

Table 5 : Phase 1 - Foundation and Piloting (2025-2027)*

Key Action	Primary Stakeholders	Success Metrics
Strengthen Infrastructure	Central & State Govts, BSNL, Private Telecom	50,000 schools connected with high-speed internet; 1 million devices distributed under subsidy schemes.
Launch FLN Pilots	NETF, DIKSHA, State SCERTs, EdTech Partners	Improved FLN scores by 15% in pilot districts; development of effective implementation playbooks for 5 South Asian languages.
Establish Ethical Framework	NETF, Ministry of Education, Legal Experts, Child Rights Bodies	Publication and formal adoption of the "National Framework for Ethical AI in Education"; establishment of an audit and grievance-redressal mechanism.

5.2. Phase 2: Scaling and Capacity Building (Medium-Term: 2028-2030)

Once basic systems are tested and found to be successful, the second phase begins to look at expanded scope and human capability.

5.2.1. Integrate Proven AI Tools into National Platforms.

Pilot tools that have demonstrated success must be integrated directly into DIKSHA; for example, Adaptive Learning Modules, AI-Translation engines and Predictive Analytics Dashboards all of these pilot tools will eventually become widely used beyond the pilot phase. By integrating these tools into DIKSHA, DIKSHA will become a single source to access multiple systems, which prevents the creation of disparate and vendor-specific platforms for each type of tool.

5.2.2. Launch Massive Teacher Training Programs.

The failure to develop human capacity rather than assuming its existence is one reason that technology initiation fails. A nationwide initiative to support teachers in the area of "AI-Augmented Teaching" should be focused on ongoing professional development rather than one-off event style workshops. The use of a blended delivery method, using both online modules via DIKSHA and in-person master trainer programs, will assist teachers in using AI-generated insights to provide evidence-based instruction in meaningful contexts in their classrooms.

5.2.3. Foster Public–Private Partnerships for Innovation.

To grow equitable AI solutions, continual development is necessary. Dedicated funding to develop innovation, together with sponsorship by government and Corporate Social Responsibility (CSR), will allow new start-ups and research teams to create affordable and offline-first vernacular AI that takes advantage of the region's tech talent and ties into the educational goals of the populace and the businesses that operate in that region.

5.3. Phase 3: Systemic Transformation and Global Leadership (Long-Term: 2031 and Beyond)

Finally, the vision for the tertiary institution is that AI will not be seen as something extra; rather, AI will form an integral part of education during its entirety.

5.3.1. Full Integration of AI-Driven, Personalized Pathways.

From early childhood through vocational training and lifelong learning, learning pathways will continue to adapt, with AI systems supporting individual transitions, reskilling and credential accumulation. The vision of NEP 2020 is to create a flexible, learner-centric ecosystem that will provide for both individual ambition and societal need.

5.3.2. Establish South Asia as a Global Leader in Equitable, Low-Cost EdTech.

South Asia can use the approach of facing the challenges of scale, diversity and equity for themselves, instead of utilizing only the education technology produced from other countries, and instead develop their own educational technologies as producers of educational technologies. Solutions designed for low-bandwidth environments and diverse languages can then be used throughout the Global South and help South Asia to transform their reform efforts into global leadership.

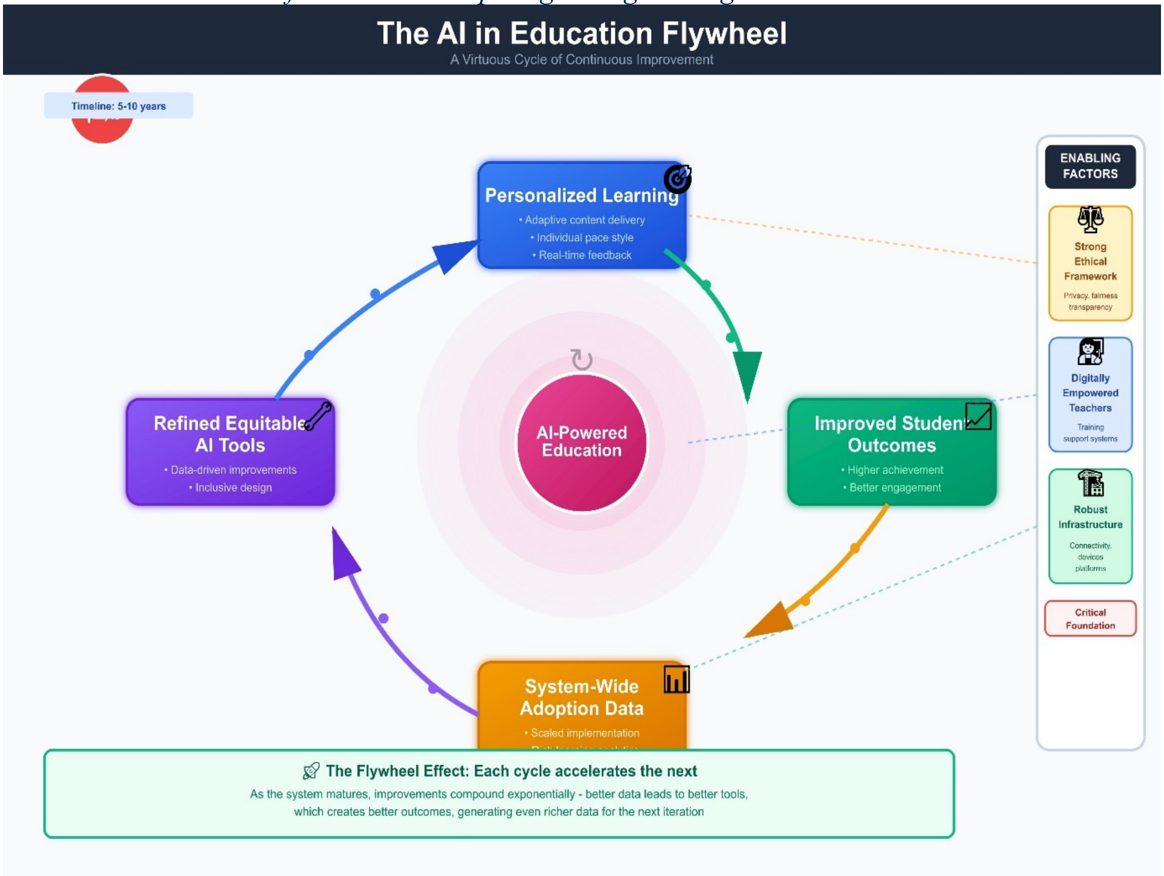

Figure 5: AI Education Flywheel

6. Conclusion: Towards an Equitable Educational Future

6.1. Recapitulation: A Synergistic Blueprint for Transformation

This chapter outlined a convergence that has occurred and is consequential to both the current time frame and to education in South Asia: the Education Equity Vision of the NEP 2020 Committee and the Capability of Artificial Intelligence. The National Education Policy 2020 has provided the foundational architecture for educational equity and has identified and corrected the previous structural barriers and historical exclusions that have shaped South Asia's education system with an emphasis on access, equity, quality, affordability, and accountability (MHRD, 2020). However, the National Education Policy 2020 does not provide an implementation mechanism with the capability to be implemented on the scale and diversity that is warranted by the policy.

AI does not replace education policy; rather, AI provides an enabling capability to the education policy. Adaptive learning platforms enable the translation of the personalized education aspiration into practical application. The use of Natural Language Processing (NLP) tools facilitates the movement of multilingualism from a pedagogical ideal to the ability to implement multilinguism at scale. Digital Platforms like DIKSHA equip teachers and educators with expert instructional materials, and the use of predictive analytics adds timeliness and accuracy to interventions and governance actions(Baker & Inventado, 2014, UNESCO, 2021, Bhattacharjee, 2024 and LearnQoch 2024). This does not result in technological determinism; rather, it is the result of the use of computational intelligence to enhance the implementation of education policy

6.3. A Global Model: South Asia's Blueprint for the World

The influence of this merger (technology and education) will be global in nature. Countries in the Global South have to deal with similar issues as South Asia: a large number of persons living in the area, many languages, great differences in how rich or poor people are throughout the region, and a limited amount of money to spend on education.

There are three main points to take away from this merger. First, technology must be connected to strong and fair policies in order for it to work effectively; the NEP 2020 will ensure that A.I.(Artificial Intelligence) is used for the right reasons and not just for profit. Second, the fact that A.I. has been created for the low-end, local language, and offline markets will fill a void that currently exists in the worldwide market for education products, many of which are designed for use in wealthy markets (South AsiaAI 2024). Third, by continuing to discuss ethical issues such as bias, privacy, and transparency as the technology scales, South Asia has set an example for others; there is no need for scale to be achieved at the cost of doing what is right (Nguyen et al., 2023 and UNESCO, 2021).

By using this method, the South Asian education community is able to move from being a consumer of Western Education Technology to becoming a producer of education technology that is scalable and contextualized for the Global South. In so doing, the South Asian Education Community has created a new way to think about the ancient idea of "Vasudhaiva Kutumbakam" — that the world is one big family.

6.4. A Final Vision: Education as the Great Equalizer

Integrating Artificial Intelligence (AI) in the New Education Policy (NEP) 2020 isn't just seen as a technical challenge; it is a moral responsibility. Integrating AI into education reaffirms that all students, regardless of their origin (e.g., birthplace, language, gender, income), have an equal opportunity to reach their potential.

Imagine two students starting their day: one female student living in Odisha's remote village and one male student attending an elite school in New Delhi. Each is using a personalized learning dashboard and receiving adaptive learning content based on previous academic performance from the artificial intelligence (AI) system.

While both students have access to the same national knowledge database (DIKSHA), translated and contextualized according to their needs, the female student is receiving foundational numeracy support in her native language of Odia; the male student is using advanced scientific simulations. The AI-generated insights provided to the teachers of both students enable these professionals to make timely, informed decisions where human judgment is critical.

Although the students are not starting off on a completely level playing field, the difference is that they both have access to the same tools that will allow them to achieve academic success.

The potential of Artificial Intelligence (AI) to level the playing field worldwide is great. With good governance, ethical restrictions, and a focus on human-centered pedagogy, AI will allow education systems to view all learners as individuals rather than averages of learners. With the right policies and leveling the playing field with a focus on the above-mentioned developments, South Asia can turn the scale of its population into an asset rather than a hindrance and can move toward an education system that is not only bigger but is also a more equitable and smarter and genuinely inclusive system.

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Youth Voice, Economic Growth and Gen Z Empowerment in Lumbini Province

Nahakul KC[1*]

[1] Independent Policy Analyst and former Vice Chairman of Lumbini Provincial Planning Commission, Nepal

*Corresponding Email: nahakulkc@gmail.com

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Abstract

Lumbini Province of Nepal faces a dual challenge of harnessing the demographic dividend of a large youth population while addressing persistent youth unemployment and outward labor migration. Drawing on the FY 2082/83 provincial budget priorities and recent policy initiatives, this paper examines how structured youth voice and policy dialogue can strengthen economic governance and youth-responsive development outcomes. It situates youth employment, entrepreneurship, and digital economy opportunities within the province's broader growth strategy and highlights the role of institutionalized dialogue mechanisms linking young people with provincial decision-makers. The paper also reflects on the contribution of development partners, particularly the UK's Foreign, Commonwealth and Development Office (FCDO) through the British Embassy Kathmandu and The Asia Foundation (TAF), in advancing collaborative governance and evidence-based policymaking at the subnational level. The paper concludes with policy recommendations aimed at translating youth participation into tangible economic outcomes in federal Nepal.

Keywords: *Youth employment; Gen Z; provincial governance; policy dialogue; economic development; Nepal*

1. Introduction

Lumbini Province stands at a critical juncture in its development trajectory. With a young and dynamic population, increasing pressures of youth out-migration, and an evolving federal governance structure, the province faces both significant challenges and unprecedented opportunities. The Fiscal Year 2082/83 provincial budget and the Second Periodic Plan articulate an ambitious vision of rapid, inclusive, and employment-oriented economic growth anchored in agriculture, industry, tourism, and infrastructure. At the same time, these policy instruments recognize that without meaningful engagement of young people—particularly the digitally connected and innovation-driven Generation Z, the promise of prosperity will remain incomplete. In this context, youth voice and structured policy dialogue are not peripheral concerns; they are central to building a responsive, future-ready provincial economy.

This article examines the intersection of youth participation, economic growth, and policy dialogue in Lumbini Province. Drawing on provincial budget priorities and the proposed Youth Voice and Policy Dialogue for Gen Z Economic Empowerment (YVPD–GenZ) initiative, it argues that institutionalizing youth engagement can significantly enhance the effectiveness, inclusiveness, and sustainability of economic policies. It further explores how targeted investments in entrepreneurship, skills, and the digital economy—combined with platforms for dialogue between youth, government, and the private sector—can transform Lumbini's demographic advantage into a durable development dividend.

2. Economic Growth Priorities and the Youth Dimension

The development strategy of Lumbini Province is guided by the vision of "Prosperous Lumbini, Happy Citizens," with agriculture, industry, tourism, and infrastructure identified as the main pillars of growth. The FY 2082/83 budget reflects a strong commitment to increasing production, productivity, and employment through modernization of agriculture, expansion of infrastructure, promotion of tourism, and facilitation of private investment. These priorities are inherently youth-relevant. Agriculture modernization requires energetic and skilled young farmers and Agri entrepreneurs; industrial growth depends on a technically competent workforce; tourism thrives on service innovation and cultural entrepreneurship; and infrastructure development generates both immediate jobs and long-term economic multipliers.

Despite these opportunities, a persistent gap remains between policy intent and youth experience. Many young people perceive limited pathways to influence economic decision-making, and employment creation has not kept pace with aspirations. Youth out-migration, particularly for foreign employment, continues to drain productive labor from the province, even as local industries report skill shortages. This paradox highlights the need for policies that are not only youth-targeted but also youth-informed. Incorporating youth perspectives into economic planning can improve policy relevance, foster ownership, and increase the likelihood that programs translate into tangible outcomes.

3. Youth Employment, Entrepreneurship, and Skills Development

Employment generation and entrepreneurship promotion are at the core of Lumbini's economic agenda. The provincial budget prioritizes self-employment, startup development, and skill-based training as strategies to retain youth and create domestic opportunities. Flagship programs include youth skill development and technology transfer initiatives, entrepreneurship promotion with a specific focus on Gen Z, support for returnee migrant workers, and innovative internship schemes that integrate learning with earning.

These initiatives represent an important shift from traditional welfare-oriented youth programs toward productivity- and enterprise-based approaches. By emphasizing practical skills, innovation, and access to capital, the province aims to cultivate a new generation of entrepreneurs in agriculture, services, technology, and creative industries. However, the effectiveness of these programs depends on their design and implementation. Young people are more likely to engage when programs align with market realities, offer mentorship and networks in addition to training, and provide credible pathways to finance and markets. Structured dialogue with youth entrepreneurs and aspiring workers can help policymakers refine program modalities and ensure that public investments respond to real constraints on the ground.

4. Private Sector Engagement and Investment Climate

The provincial government increasingly recognizes the private sector as a partner in development. Policies to attract domestic and foreign investment, improve infrastructure, and promote public–private collaboration signal a commitment to investment-led growth. For youth, a vibrant private sector is the primary source of employment and innovation. Startups, small and medium enterprises, cooperatives, and larger industries all play a role in absorbing young talent and translating skills into income.

Yet private sector–youth–government linkages remain fragmented. Young entrepreneurs often struggle to navigate regulatory processes, access credit, or connect with markets, while policymakers lack systematic feedback on how regulations and incentives affect youth-led enterprises. Platforms for policy dialogue that bring together youth networks, business associations, and provincial authorities can bridge this gap. Such platforms can help identify bottlenecks in the investment climate, co-create solutions, and build trust among stakeholders. By embedding youth voices within broader economic governance structures, Lumbini can foster a more inclusive and responsive investment ecosystem.

5. Tourism, Culture, and Youth Innovation

Tourism is a flagship sector for Lumbini Province, anchored by its global religious and cultural significance as the birthplace of Buddha and complemented by rich natural and cultural diversity. Substantial budget allocations for tourism infrastructure, heritage conservation, and destination promotion underscore its importance for income generation and employment. Youth have a particularly critical role to play in this sector, bringing creativity, digital skills, and service orientation.

Youth-led tourism enterprises—ranging from eco-tourism and agro-tourism to digital marketing of destinations and cultural products—can diversify the tourism economy and extend benefits to rural areas. However, realizing this potential requires more than funding for infrastructure. It calls for targeted capacity building, incubation of tourism startups, and inclusion of young innovators in tourism planning processes. Policy dialogue forums that foreground youth perspectives can help ensure that tourism strategies reflect changing visitor preferences, leverage digital platforms, and promote sustainable and community-based models.

6. The Digital and Gig Economy: An Emerging Frontier

One of the most promising avenues for youth employment in Lumbini is the digital and gig economy. With expanding internet access and the proliferation of online platforms, young people can increasingly access national and global labor markets without migrating. Opportunities exist in freelancing, digital content creation, online services, e-commerce, and remote work. These pathways are particularly attractive to Gen Z, whose digital literacy and adaptability position them well for platform-based work.

At the same time, the digital economy presents new challenges. Digital divides persist between urban and rural areas, training ecosystems remain underdeveloped, and gig workers often lack social protection and regulatory clarity. Provincial policy has begun to acknowledge the importance of innovation and IT-driven entrepreneurship, but more deliberate action is needed. Youth-informed dialogue can play a crucial role in shaping policies that support digital skills development, innovation hubs, affordable connectivity, and fair working conditions in the gig economy. By proactively engaging young digital workers and entrepreneurs, Lumbini can position itself as a hub for inclusive digital growth.

7. Institutionalizing Youth Voice through Policy Dialogue

While sectoral programs are important, their impact is amplified when embedded within strong institutional mechanisms for participation and coordination. The proposed Youth Voice and Policy Dialogue for Gen Z Economic Empowerment (YVPD–GenZ) initiative offers a practical model for institutionalizing youth engagement in Lumbini Province. By facilitating structured policy dialogue between youth representatives, the Ministry of Youth and Sports, and the Economic Development Committee of the Provincial Assembly, the initiative seeks to bridge the gap between youth aspirations and policy processes.

This initiative builds directly on the Collaborative Governance Programme supported by the UK's Foreign, Commonwealth and Development Office (FCDO), through the

British Embassy Kathmandu (BEK), and implemented in partnership with The Asia Foundation (TAF). FCDO/BEK's strategic emphasis on accountable institutions, inclusive governance, and locally led development has enabled provincial assemblies and ministries in Nepal to experiment with new forms of evidence-based dialogue and oversight. TAF's long-standing technical engagement has further strengthened legislative committees' analytical capacity, policy research, and convening power. Together, these partnerships have created an enabling environment in which youth engagement can move beyond consultation toward institutionalized influence.

High-level policy dialogue forums, orientation sessions for policymakers, and the production of evidence-based policy briefs—supported through FCDO and TAF technical assistance—can create channels for sustained engagement. Importantly, such mechanisms move beyond ad hoc consultations toward regularized interaction, enabling youth perspectives to inform agenda-setting, policy formulation, and monitoring. When youth participation is embedded in the operating procedures of ministries and legislative committees, it becomes a routine part of governance rather than a symbolic gesture.

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8. Evidence, Advocacy, and Accountability

Effective youth engagement must be grounded in evidence. Generating and disseminating policy-relevant research on youth employment, entrepreneurship, and innovation can strengthen advocacy and improve decision-making. Policy briefs that synthesize youth priorities in key sectors such as agriculture, ICT, and tourism can provide actionable recommendations to policymakers. Similarly, dialogue reports that document commitments and follow-up actions can enhance accountability.

Civil society organizations with strong policy engagement experience play a vital intermediary role in this process. By convening stakeholders, facilitating research, and supporting dialogue, they help translate youth voices into policy influence. At the same time, collaboration with government institutions ensures that recommendations are aligned with planning cycles and legislative mandates. Such partnerships are essential for moving from consultation to impact.

9. Inclusiveness and Equity in Youth Empowerment

Youth are not a homogeneous group. Gender, geography, caste, ethnicity, disability, and socio-economic status shape access to opportunities and voice. Inclusive youth empowerment requires deliberate efforts to engage marginalized and underrepresented groups, including young women, rural youth, returnee migrants, and those from disadvantaged communities. Provincial programs already include targeted measures for some of these groups, but participation gaps remain.

Policy dialogue mechanisms should therefore be designed with inclusiveness in mind, ensuring diverse representation and safe spaces for participation. Monitoring and evaluation systems that track who benefits from youth programs can further enhance equity. By centering inclusiveness, Lumbini can ensure that youth-driven growth does not reproduce existing inequalities but instead contributes to broader social transformation.

10. Conclusion:

10.1 Toward a Youth-Responsive Growth Model

Lumbini Province has articulated a clear vision for economic growth, employment generation, and inclusive development. The challenge now lies in translating this vision into outcomes that resonate with the lived realities of young people. Youth voice and policy dialogue are not add-ons to this agenda; they are foundational elements of effective economic governance in a youthful society.

By institutionalizing platforms for Gen Z engagement, aligning youth entrepreneurship and skills programs with market needs, leveraging the digital economy, and strengthening collaboration between government, the private sector, and civil society, Lumbini can harness the full potential of its young population. Such an approach promises not only to reduce youth unemployment and out-migration but also to cultivate a generation of engaged citizens and innovators who see their future within the province. In doing so, Lumbini can move closer to realizing its aspiration of shared prosperity and happy citizens, grounded in inclusive, youth-responsive development.

10.2 Concluding Policy Recommendations: Translating Youth Voice into Economic Outcomes

To consolidate recent policy commitments and respond to emerging economic realities, the following policy recommendations are proposed for Lumbini Province. These recommendations are grounded in current provincial budget priorities, recent implementation experiences, and evolving youth labor-market trends, and are intended for policymakers, development partners, and academic and policy audiences.

First, Lumbini Province should institutionalize youth policy dialogue within formal governance structures, building on the collaborative governance architecture supported by FCDO/BEK and TAF. Regular, calendar-based policy dialogue forums between youth representatives, the Ministry of Youth and Sports, and the Economic Development Committee of the Provincial Assembly should be embedded within annual work plans and committee operating procedures. Evidence from the FY 2082/83 budget cycle shows that while youth-focused allocations exist—such as NPR 4.65 crore for youth skill development and dedicated funding for Gen Z–focused entrepreneurship—the absence of structured feedback mechanisms limits policy learning and adaptive implementation.

Second, youth employment and entrepreneurship programs should be scaled up and strategically co-financed through public, private, and development partner resources. Despite a reported decline in provincial unemployment to around 8 percent, youth out-migration remains high, indicating a mismatch between available jobs and youth aspirations. Development partners such as FCDO and TAF can play a catalytic role by supporting pilot models, innovation funds, and learning platforms that inform provincial scaling decisions. Entrepreneurship support should integrate finance, mentorship, incubation, and market access rather than relying on stand-alone training interventions.

Third, agriculture and tourism policies should be deliberately redesigned to attract and retain young entrepreneurs. Targeted incentives for youth-led agribusinesses, including preferential access to subsidized loans, agri-tech incubation, and guaranteed market linkages, can help reverse declining youth engagement in agriculture. Similarly, the province's allocation of approximately NPR 80 crore for tourism development provides a strategic opportunity to integrate youth-led innovation in eco-tourism, cultural enterprises, and digital destination promotion. Development partners can support applied research, policy pilots, and public–private dialogue to strengthen youth inclusion in these sectors.

Fourth, the digital and gig economy should be recognized as a strategic pillar of youth employment policy. With a digitally literate Gen Z population and expanding connectivity, platform-based work and online entrepreneurship offer viable livelihood pathways without physical migration. Provincial policy should prioritize digital skills training, local innovation hubs, and affordable broadband access, particularly in secondary towns and rural municipalities. Support from partners such as FCDO and TAF in regulatory analysis, skills ecosystem development, and inclusion frameworks can help ensure that digital employment is both productive and decent.

Fifth, implementation capacity and results-based monitoring must be strengthened. Past experience across provinces highlights that weak execution can undermine well-designed programs. Lumbini should invest in outcome-focused monitoring systems that track youth employment, enterprise creation, and income effects, with transparent reporting to the Provincial Assembly. Technical assistance from development partners can support the design of such systems and strengthen the analytical capacity of legislative committees.

Finally, inclusiveness should remain central to youth economic empowerment strategies. Young women, marginalized caste and ethnic groups, rural youth, and returnee migrants face distinct barriers to participation. Targeted outreach, simplified procedures, and gender- and equity-responsive design—areas where FCDO and TAF have demonstrated comparative strengths—are essential to ensure that youth-focused growth contributes to broader social inclusion.

Taken together, these recommendations point toward a youth-responsive growth model that is participatory, evidence-based, and institutionally grounded. By leveraging provincial leadership alongside strategic support from development partners such as FCDO/BEK and The Asia Foundation, Lumbini Province can convert youth voice into sustained economic transformation within Nepal's federal system.

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Predicting Sustainable Construction Practices: A Critical Review of Traditional Tharu Mud House Techniques in Kanchanpur, Nepal

Santosh Raj Bhatt[1], Kishan Datta Bhatta[2], Birendra Kumar Bohara[3]*

[1] School of Engineering, Far Western University, Nepal

[2] Professor, School of Engineering, Far Western University, Nepal

[3] Assistant Professor, School of Engineering, Far Western University, Nepal

*Corresponding Email: birendra.bohara@fwu.edu.np

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Abstract

A prime example of utilizing traditional mud-based housing systems is to gain knowledge on sustainable, climate-sensitive, and culturally inclined ways of constructing houses. The paper includes a critical examination of the ancient methods of Tharu mud houses in Kanchanpur, Nepal, in terms of their applicability on the global and national systems of vernacular architecture and sustainable building. Based on the global research on earthen construction technologies, e.g., adobe, cob, rammed earth and wattle-and-daub, and various Nepalese traditions, the review appraises Tharu houses within the framework of the essential sustainability indicators, e.g., environmental footprint, thermal comfort, cost/efficiency, and socio-cultural meaning. Tharu mud houses consist of locally available materials, including mud, bamboo, straw, and timber which indicate that they have low embodied energy, carbon footprint, and also effective passive design strategies that can fit the hot-humid Terai climate. Thick earthen walls, shaded verandas, and natural ventilation are among the features that promote the achievement of stable indoor thermal conditions without involving the consumption of mechanical energy. Nevertheless, the available literature gives huge gaps in quantitative evaluation, especially to the methods of thermal performance, lifetime cost evaluation, and structural behavior during environmental risks. The proposal identifies that a multi-dimensional assessment is most effective and possibly that the combination of indigenous Tharu construction expertise and modern sustainability systems would generate resilient and low-carbon residential approaches to housing in the rural and peri-urban areas of Nepal.

Keywords: *sustainable construction, mud house, vernacular architecture, thermal comfort, passive design*

1. Introduction

Traditional building systems form an essential part of Nepal's architectural heritage, offering valuable insights into sustainable, climate-responsive, and community-driven construction practices. Among these, the Tharu mud houses of Kanchanpur represent a remarkable example of indigenous knowledge that has evolved through generations in response to local environmental, cultural, and socioeconomic conditions. Constructed primarily from natural materials such as mud, bamboo, timber, and thatch, these dwellings have historically provided comfortable living environments in the hot and humid climate of the western Terai. Their low carbon footprint, low embodied energy, and reliance on locally available materials align closely with modern concepts of sustainability and green construction. As global attention increasingly turns toward environmentally responsible and culturally appropriate construction methods, understanding traditional practices becomes essential (Mehra et al., 2021). In recent decades, the rapid growth of the construction industry has contributed significantly to environmental degradation, including excessive energy consumption, depletion of natural resources, and rising carbon emissions. Modern construction materials particularly cement, steel, and synthetic composites, though structurally efficient, often come at the cost of environmental sustainability and cultural heritage (Mehra et al., 2021).

To organize this review systematically, the chapter is divided into some thematic sections. It begins with a global overview of traditional mud construction, examining techniques such as adobe, cob, rammed earth, and wattle and daub. These methods have been utilized for centuries across diverse climatic and geographic zones and offer valuable insight into natural building systems that remain relevant today. This section discusses the advantages of these systems such as low environmental impact and high thermal performance while also addressing their common limitations, including vulnerability to water damage and limited structural capacity, which are often cited as reasons for their decline.

2. Global Overview of Mud Construction Techniques

Earthen construction methods such as adobe, cob, rammed earth, and wattle and daub have been used for centuries across various climatic and cultural contexts, offering environmentally sustainable alternatives to industrialized building systems (Abdulrahman Maghrabi, 1994; El-Sawalhi & Ajwa, 2013; Ibrahim & Osman Ibrahim, 2021). Adobe, composed of sun-dried mud bricks, is widely used in Latin America, the Middle East, and parts of Asia for its thermal mass and low cost. Cob, a mixture of earth, straw, and water molded by hand, is prevalent in the UK, sub-Saharan

Africa, and New Zealand, known for its sculptural flexibility and resilience (Rashid et al., 2025; Sesay et al., 2025). Rammed earth, where moistened soil is compacted into forms, has been revived in countries like China, Australia, and parts of Europe for its high compressive strength and striking aesthetics (EKSI AKBULUT & ALİBEYOĞLU, 2025; Maniatidis et al., 2003; Sesay et al., 2025). Meanwhile, wattle and daub—a lattice of sticks smeared with clay or mud—is still seen in parts of Africa and Southeast Asia due to its simplicity and use of fully renewable materials. Despite their benefits, these techniques face challenges such as poor resistance to heavy rainfall, seismic vulnerability, and social perceptions associating them with poverty or backwardness (Houben & Guillaud, 1994). However, recent innovations in stabilization (e.g., lime or cement additives), proper detailing, and hybrid construction have improved durability and broadened acceptance (Easton et al., 2007; Osman Ibrahim, 2021; Rashid et al., 2025; Sadat, 2021a). These global traditions underscore the potential of earth-based construction to inform sustainable housing in resource-constrained regions like rural Nepal.

3. Vernacular Architecture in Nepal

Nepal's diverse topography, from the lowland Terai to the mid-hill regions and the high Himalayas has shaped a wide range of vernacular architectural traditions. Each region has evolved construction techniques that respond to its unique climate, material availability, and socio-cultural context. In the Terai region, homes built by ethnic groups like the Tharu and Rajbanshi are typically made using mud, straw, bamboo, and timber (Liang et al., 2025; Raj et al., 2019). These materials, which are locally sourced and low in embodied energy, help regulate indoor temperatures in the region's hot and humid climate (Raj et al., 2019). The traditional Tharu mud houses, in particular, use thick earthen walls, thatched or tiled roofs, and shaded verandas to enhance thermal comfort without relying on mechanical systems.

In the mid-hills, communities such as the Gurung, Magar and others have developed stone masonry structures with timber elements (Amit Kumar, 2002; Asmita Dahal, 2019; Prakash Shah et al., 2024). These houses are compact, often built in terraced patterns along the contours of hills, helping to prevent soil erosion and manage monsoonal runoff. Roofs are typically made from stone slates or corrugated metal sheets in more recent adaptations (Pant et al., 2023). Houses are oriented to maximize solar gain and protect against prevailing winds, showing strong climatic responsiveness as shown in Figure 1. Traditional Gurung houses also use central courtyards and inward-sloping roofs to collect water and control internal microclimates. These buildings reflect generations of adaptation to the hilly terrain, harsh winters, and seismic activity.

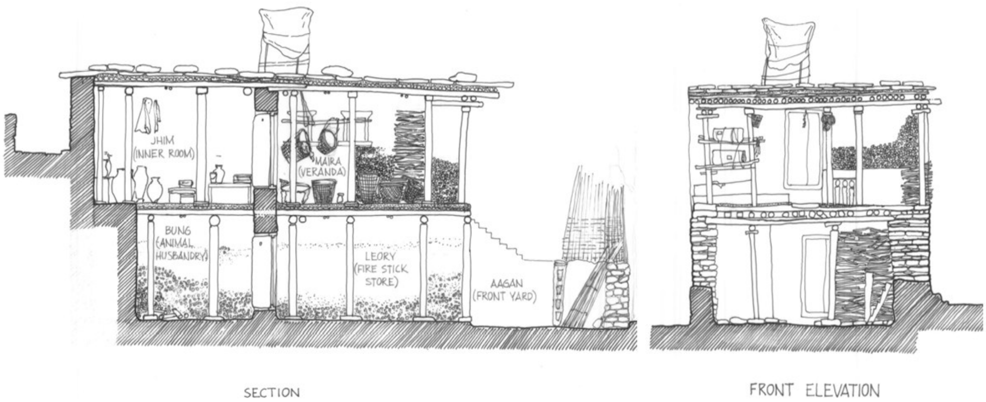

Figure 1: Magar house views (Pant et al., 2023)

In the high Himalayan region, such as in Mustang, vernacular architecture has evolved in response to arid conditions, high wind exposure, and freezing temperatures (Prasad Gyanwali, 2025). As Asmita Dahal's (Dahal, 2019) study in Marpha illustrates, the traditional homes are made from stacked stone walls, mud mortar, and flat roofs used for drying crops or stacking wood. The buildings are clustered to reduce heat loss and to shield from wind, as shown in Figure 2. Settlements like Marpha are laid out in compact formations, creating wind breaks and conserving thermal energy during long winters. Dahal's research also emphasizes the role of solar orientation, thermal mass, and passive solar heating as key elements of sustainability in mountain architecture.

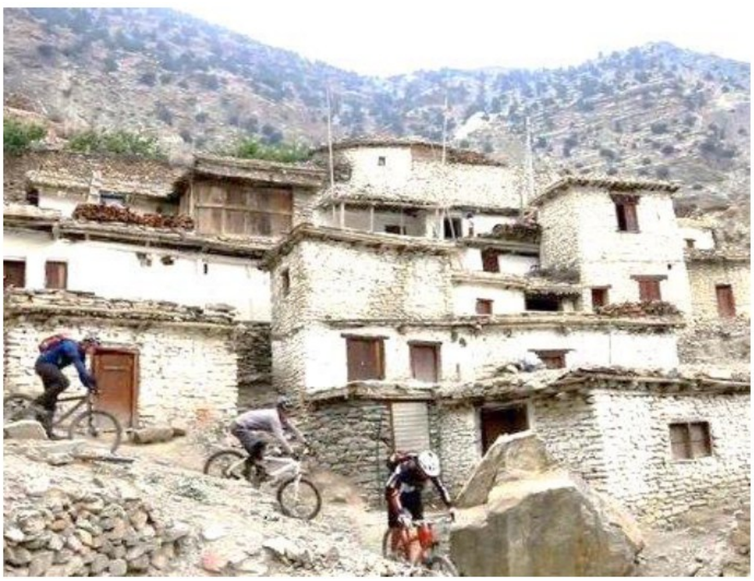

Figure 2: Vernacular Architecture Mustang (Dahal, 2019)

Vernacular architecture across Nepal has demonstrated remarkable disaster resilience, particularly in terms of responding to earthquakes, floods, and extreme weather

(Poudel & Chaulagain, 2024). After the 2015 Gorkha earthquake, studies found that traditional buildings performed better or worse depending on material condition and maintenance, but many mud, stone, and timber structures withstood the initial shocks due to their flexibility and lightweight roofing (See Figure 3). For example, Gurung houses built with timber tie-beams and small openings were observed to perform better than rigid RCC structures with poor detailing (Gautam & Chaulagain, 2016). In flood-prone Terai, the elevated plinths and natural drainage patterns surrounding Tharu and Rajbanshi homes reduce water damage and allow structures to quickly dry after inundation. Such resilience, embedded in centuries of indigenous knowledge, highlights the potential for integrating vernacular features into modern, disaster-resistant building practices (Adhikary, 2016).

Figure 3: Completely Collapsed dry Stone Masonry Houses

Material availability and economic considerations are core to vernacular design across the country. In all three regions, construction relies heavily on locally available materials soil, stone, timber, bamboo, and thatch which reduce transportation costs and support local economies. The cost-effectiveness of these materials makes vernacular architecture accessible to low-income communities while fostering low-carbon construction (Hu, 2023). Additionally, many traditional techniques require communal labor, reinforcing social cohesion and knowledge transfer. In contrast to modern buildings that often rely on imported cement and steel, vernacular structures are biodegradable, repairable, and highly adaptable to local environmental and cultural contexts.

In summary, in Table 1, Nepal's vernacular architecture offers region-specific solutions to climatic adaptation, economic sustainability, and cultural identity. From the mud-based homes of the Terai, the stone and timber dwellings of the Hills, to the climate-responsive courtyard houses of Mustang, these building traditions provide valuable lessons in low-impact, resilient design. As both your research and Dahal's study affirm, documenting and modernizing these approaches can contribute meaningfully to sustainable construction and disaster risk reduction in Nepal's rural and peri-urban areas.

Table 1: Literature Review on Vernacular Architecture and Sustainable Building Practices in Nepal.

Author (s)	Title / Year	Focus Area	Key Findings	Relevance to Nepal
(Bodach et al., 2014)	Climate Responsive Building Design Strategies of Vernacular Architecture in Nepal	Bioclimatic design	Traditional houses align with solar passive strategies using local materials; suited to regional climates.	Highlights thermal efficiency of mud-based design in different climate zones.
(Tiwari et al., 2004)	Cultures in Development: Conservation of Vernacular Architecture	Conservati on & policy	Vernacular architecture is dynamic; loss due to globalization and lack of protection threatens identity.	Supports policy-driven preservation of local materials and techniques.
(Gautam et al., 2016)	Disaster Resilient Vernacular Housing Technology in Nepal	Earthquake & flood resilience	Rajbanshi, Gurung, Magar houses show disaster resilience with mud masonry and timber framing.	Validates mud and timber-based housing for disaster-prone rural areas.
(K.C. et al., 2025)	Role of Vernacular Architecture in Enhancing Environmental Sustainability	Life Cycle Assessment (LCA)	Traditional buildings emit less CO_2 and use less energy; biogenic materials enable carbon sequestration.	Endorses mud as low-carbon option in Nepal's hydropower-rich context.
(Prakash Shah et al., 2024)	Study of Changes in Vernacular Architecture of Baitadi	Spatial transformat ion	Architecture adapted to geography and climate; cultural shift threatens traditional identity.	Encourages adapting hill region vernacular features in new designs.

(Sakar Shrestha, 2025)	Newari Heritage, Commoner to Luxury	Identity & urbanization	Newari mud-brick architecture eroded by urbanization and modernization after 2015 earthquake.	Advocates holistic heritage conservation including mud-brick common houses.
(Anupama, 2024)	Greener Materials in Vernacular Architecture	Sustainable materials	Greener materials like adobe and bamboo combined with modern tech for scalable solutions.	Demonstrates integration potential for mud-based methods and green tech.
(Khoja, 2025)	From Vernacular to Verno mimicry: Vernacular Design Principles for Resilient Communities	Climate adaptation	Vernacular strategies offer climate adaptation via simplicity, local resources, and community.	Promotes vernacular-based climate adaptation in Nepal's urban planning.
(Hu, 2023)	Exploring Low-Carbon Design & Construction Techniques	Circular economy & materials	Bio-based materials support circular construction; vernacular principles suit sustainable design.	Reinforces viability of mud for low-impact, modular construction in Nepal.

4. Existing Studies on Tharu/Rana Mud Houses

The traditional mud houses built by the Tharu and Rana communities in Nepal's Terai region represent a culturally rich and environmentally responsive form of vernacular architecture. These houses are deeply embedded in the socio-cultural identity of the Tharu people, reflecting their customs, seasonal rhythms, and community-based construction practices (Bhatta et al., 2023). According to ethnographic and anthropological literature, these structures are more than just dwellings they serve as multifunctional spaces for cooking, storing grains, sheltering livestock, and conducting rituals. Built through communal labor systems, their design reflects social cohesion and indigenous knowledge systems passed down across generations (Bhatta et al., 2023; Mary, 2025; Raj et al., 2019).

From an environmental perspective, Tharu/Rana mud houses utilize readily available materials such as mud, straw, bamboo, thatch, and timber, which have low embodied energy and are biodegradable (Bhatta et al., 2023; Kalauni, 2025). Their thick mud walls provide excellent thermal mass, keeping interiors cool in summer and warm in winter—critical for the hot and humid climate of the Terai. The traditional use of natural ventilation, shaded verandas, and overhanging roofs further contributes to indoor thermal comfort without mechanical energy input. These features align with contemporary sustainable design principles, yet remain underappreciated or undocumented in mainstream architectural discourse (Kalauni, 2025; Lam, 2012; Liang et al., 2025; Sharma et al., 2021).

Despite these strengths, existing studies on Tharu and Rana mud houses are limited and fragmented. Much of the current literature focuses on cultural or historical narratives, with minimal technical or quantitative analysis (Chamorro et al., 2025; Kalauni, 2025; Lam, 2012; Liang et al., 2025; Shrestha, 2022). For example, few studies have investigated the structural behavior of mud walls under lateral loads, despite the Terai's increasing vulnerability to floods and windstorms. There is also a noticeable lack of cost-benefit comparisons between traditional Tharu mud houses and modern masonry or RCC structures, especially when considering lifecycle costs, repair frequency, and embodied energy. Similarly, thermal performance data including indoor temperature, humidity control, and energy savings remain largely anecdotal or based on observation rather than scientific measurement.

This lack of comprehensive, multi-dimensional evaluation represents a critical gap in current knowledge. While the cultural and symbolic value of these homes is well acknowledged, their technical performance, economic viability, and environmental sustainability remain under-researched. Your thesis addresses this void by conducting a structured comparative analysis of Tharu mud houses with RCC and masonry buildings in Kanchanpur, using thermal comfort evaluation, construction cost assessment, and environmental impact analysis as core criteria. In doing so, it bridges the divide between tradition and technology, offering insights that can inform both policy-making and community-based sustainable housing initiatives.

5. Sustainability in Construction: Principles and Traditional Practices

Sustainability in construction involves designing, building, and managing the built environment in a way that fulfills current needs without compromising the ability of future generations to meet their own (Dhanchha, 2024a; Madhumathi et al., 2014; Mavi et al., 2021; Yılmaz & Bakış, 2015). It is evaluated through three core pillars: environmental sustainability, which focuses on efficient use of resources, reducing carbon emissions, and minimizing ecological harm; economic sustainability, which emphasizes affordability, local job creation, and long-term cost efficiency; and social sustainability, which ensures that buildings are culturally relevant, inclusive, and promote the well-being of their occupants (Barbhuiya et al., 2025; Madhumathi et al., 2014; Opoku et al., 2019). These principles have been widely adopted into global sustainability frameworks such as the United Nations Sustainable Development Goals

(SDGs)—notably SDG 11: Sustainable Cities and Communities—and are operationalized through green building certification systems like LEED (Leadership in Energy and Environmental Design) and BREEAM. These systems evaluate construction based on energy performance, material use, indoor environmental quality, and the overall carbon footprint, aiming to merge ecological responsibility with functional and resilient architecture.

6. Traditional Tharu Mud Houses and Sustainability Indicators

Traditional Tharu mud houses in Nepal's Terai region inherently fulfill many of these sustainability criteria, despite not being formally recognized by green rating systems (Dhanchha, 2024b). These structures are built using locally sourced and renewable materials such as mud, straw, bamboo, and timber, minimizing the environmental cost of material processing and transportation (Rijal, 2018; Sadat, 2021b; Yu, 2024). Sustainability indicators in construction assess environmental, economic, and social performance, including energy efficiency, carbon footprint, lifecycle cost, cultural relevance, and community participation. These metrics help evaluate how well a building minimizes environmental impact, supports local economies, and enhances occupant well-being, aligning with global frameworks like LEED and the UN SDGs (Gebara et al., 2024; Guan et al., 2024).

7. Thermal Comfort and Passive Design

One of the key sustainability features of Tharu mud houses is their ability to provide thermal comfort without relying on mechanical systems like fans or air conditioning (Arsad et al., 2023; Liang et al., 2025; Mitra, 2022). The high thermal mass of mud walls enables them to absorb heat during the day and release it slowly at night, stabilizing indoor temperatures(Ashraf & Nisar, 2025). Roof overhangs, verandas, and small window openings help reduce solar gain and facilitate cross-ventilation—core principles of passive design (Arsad et al., 2023; Madhumathi et al., 2014).

To quantitatively assess thermal performance, studies often use R-values (thermal resistance) and U-values (thermal transmittance) (Tyagi et al., 2024). Mud walls, especially when built thick (often 300–450 mm), exhibit R-values of 0.4–0.6 $m^2 \cdot K/W$ and U-values around 2.0–2.5 $W/m^2 \cdot K$, which, though not as insulating as modern materials, perform well in combination with passive strategies (Lars Vedder, 2025). These values reflect moderate insulation compared to materials like fiberglass insulation, which can have R-values of 2.5 to 4.0 per inch (Lars Vedder, 2025). However, mud walls have a high thermal mass, meaning they can absorb heat during the day and slowly release it at night, naturally stabilizing indoor temperatures. Mud houses are known for their excellent thermal regulation due to the natural properties of earth materials. The key thermal performance indicators for building envelopes are the R-value and U-value. The R-value measures a material's resistance to heat flow.

The higher the R-value, the better the insulation. In contrast, the U-value indicates the rate of heat transfer through a material. The lower the U-value, the better the material prevents heat loss (Madding, 2008).

To calculate the R-value of a wall, divide the thickness of the material (in meters) by its thermal conductivity (W/m·K) (Madding, 2008). For example, a 0.4 m thick mud wall with thermal conductivity of 1.0 W/m·K would have an R-value of 0.4. The U-value is simply the inverse of the R-value (U = 1/R), making it easy to interpret (Madding, 2008). Compared to modern materials, mud walls may not provide high insulation, but they excel in maintaining thermal comfort through delayed heat transfer. This makes them particularly beneficial for rural and traditional homes where energy consumption is low and natural cooling is essential. Overall, mud construction remains a sustainable and thermally responsive option when designed with proper detailing and orientation (IS 3792, 1978; Madding, 2008; Modi et al., 2024; Wang et al., 2023).

A bioclimatic chart, also known as a bio-thermal comfort chart, is a graphical tool used in architecture and environmental design to assess human thermal comfort in relation to climate conditions such as temperature, humidity, solar radiation, and wind speed (Asmita Dahal, 2019). It helps architects and engineers determine what passive design strategies (like natural ventilation, shading, or thermal mass) are suitable for a building in a specific climate.

Sita Bhusal's (Bhusal, 2021) focuses on the significance of thermal comfort in school buildings, especially in Nepal's Terai region, where rising temperatures negatively affect students' learning. Drawing on ASHRAE standards, the review emphasizes optimal indoor temperature and humidity ranges for human comfort and explores adaptive thermal comfort models, such as Fanger's PMV-PPD framework, which link physiological responses to environmental conditions. It discusses how building envelopes, materials, and passive design strategies significantly influence indoor thermal performance. Previous studies on Nepalese schools highlight that many are naturally ventilated, poorly insulated, and exceed recommended comfort limits, underscoring the need for sustainable, energy-efficient designs. Overall, Bhusal argues that understanding and improving classroom thermal environments through climate-responsive design is essential for enhancing student well-being and academic performance

8. Conclusion

The reviewed literature highlights that traditional mud-based architecture, especially Tharu mud houses in Nepal's Terai, embodies an effective synthesis of environmental responsiveness, cultural identity, and economic viability. Globally, earthen techniques like adobe, cob, and rammed earth demonstrate the potential for low-carbon, affordable construction, while Nepal's vernacular systems exhibit centuries of adaptation to varied topographies and climates. Despite these strengths, critical research gaps remain: quantitative data on thermal comfort, lifecycle costs, and structural resilience are sparse, and the socio-cultural value of such architecture is often overlooked in modern construction discourse. Addressing these gaps is vital to repositioning vernacular mud housing as a sustainable, climate-adaptive solution for rural communities. This thesis, therefore, builds on existing knowledge by providing a multi-dimensional evaluation of Tharu mud houses, comparing them with modern RCC and masonry systems, and identifying pathways to integrate indigenous techniques with contemporary sustainability frameworks.

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Performance Analysis of Loan Classification for Commercial Banks in Neural Network

Narendra Bahadur Shahi[1*], Pratik Chand[2], Prakash Gupta[2]

[1]Institute of Engineering and IT, Lumbini Technological University, Nepalgunj, Nepal

[2]Institute of Engineering and IT, Lumbini Technological University, Nepalgunj, Nepal

*Corresponding Email: narendra.shahi@ltu.edu.

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Abstract

With the rapid growth in banking services, there has been a tremendous increase in the number of individuals and businesses applying for loans. It is therefore getting tougher and tougher for banks to make correct and consistent decisions regarding loan approval. In this regard, Neural Networks (NN) can play an important role in financial institutions for such tasks of loan classification and making decisions about loan sanctions. This study develops more accurate Multilayer perceptron (MLP) as an enabling tool to support loan decisions in commercial banks analyzing different features of loan applicant. The dataset consists of different representative cases of loan applications that were considered or rejected based on the guidelines of banks, to train and validate the neural network model. The proposed study shows the effectiveness of the neural networks under balanced datasets which can play an important role to understand the impact of quality of dataset as well. It illustrates the ability of neural network model to predict the creditworthiness of an application accurately and precisely preventing the bank and its officials from making erroneous decisions with regard to loan approvals. The proposal aims to shed light on the exploration of the available datasets, selection of the appropriate neural network and using them for making correct and consistent loan decisions. The main goal is to create an accurate deep neural network that will take into consideration all independent variables and based on that will predict if the applicant is going to get loan approval or not. Also working of the proposed model will also be compared with other classifiers such as KNN (K Nearest Neighbor) Classifier and SVM (Support Vector Machine) classifier in terms of accuracy, sensitivity and F_1-scores.

Keywords: *Loan Classification, Bank dataset, Deep Neural Network, Accuracy, F1-score, balanced and unbalanced data set.*

1. Introduction

The banking sector is one of the most well-established industries globally. However, despite its long history and structured systems, it continues to face significant challenges related to security threats, risk management complexities, and operational inefficiencies, all of which can negatively affect the overall performance and stability of banks. Recently, Artificial Intelligence (AI) has been proposed as a promising solution to address these challenges. Additionally, banks today operate in a highly competitive environment, where survival and growth depend on adopting the latest technologies and ensuring high accuracy. Therefore, banking systems must make precise decisions to minimize cases of loan defaults. Over time, banks have grown increasingly dependent on information systems and Artificial Intelligence to manage banking transactions efficiently and to offer personalized services and products to their customers. AI provides significant benefits to core banking by addressing challenges that threaten the sector's sustainability. It improves credit risk assessment, detects fraud, reduces cyber-attacks, and lowers operational costs. Additionally, AI can predict financial crises, bankruptcies, and exchange rate fluctuations, enhancing overall profitability. One of the key areas of banks is making loan related decisions. Conventionally, loan officers have been involved in making such loan related decisions however things are gradually changing and even decision-making jobs are being done by artificially intelligent technologies. The switch is needed also because studies have shown that the decisions made by loan officers are subjective, inefficient, and inconsistent. This is the reason why this study attempts to come with multilayer Perceptron that can play an important role in making loan decisions precisely.

2. Methodology

2.1 Model Development

A proper model is built, which consists of a series of steps to solve the problem. The general architecture of a framework is shown below. It consists of a data acquisition process for extracting the required dataset, data preprocessing for cleaning the data, finding missing values and outliers, finding and analyzing the appropriate attributes, oversampling the dataset to achieve balanced dataset, and then developing a neural network model for training and a classifier for making final decision of accepting or rejecting the loan.

2.2 Dataset Collection

The dataset to be used here is publicly available dataset, which is then pre-processed and then used for evaluation of the neural network. Data has been collected from open source data (kaggle.com)and these are related to universal bank, it consists of a total of 5000 records and 14 attributes. Here 4520 are rejected loans and 480 are accepted loans. Attribute selection includes numeric and integer attributes along with some factor attributes relevant to the research problem. Dataset consists of a combination of variables as follows:

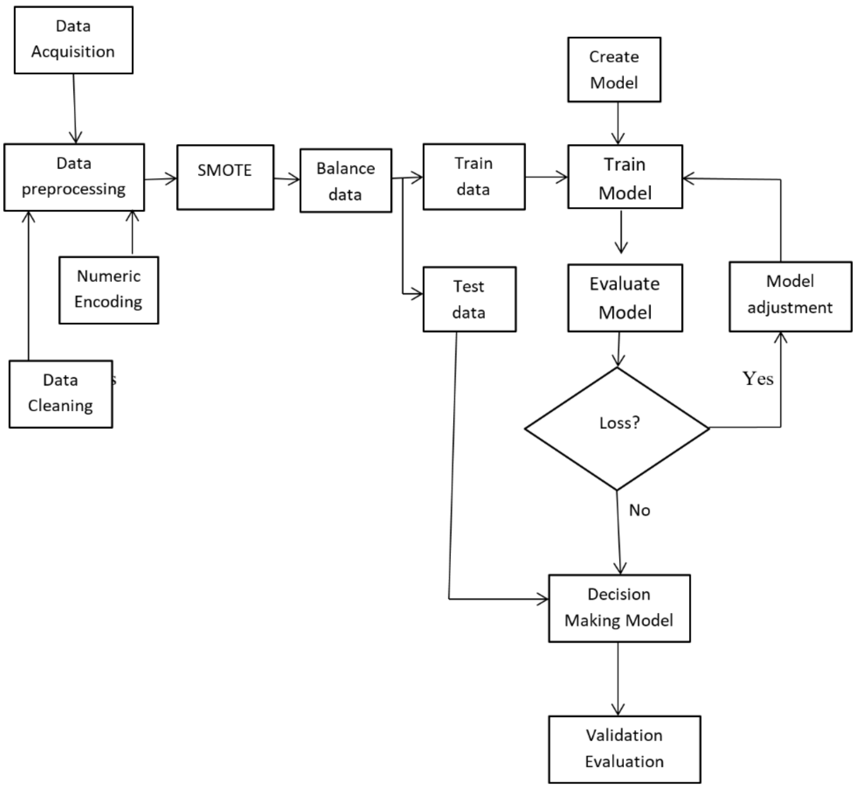

Figure 1: Methodology for loan classification

2.2.1 Dependent Variable

loan decision (0 and 1), this paper aims to predict whether the applicant should be approved for personal loan or not. In this context, if the applicant has good economic status and other supporting attributes, he will be approved of loan and the applicant will be deprived of loan if he is not supported by his attributes. So, to differentiate in a neural network 0 indicates that the personal loan will not be approved and 1 indicates that the applicant will succeed in getting a loan.

2.2.2 Independent Variable

Following variables are considered as an independent variable:

a. ID: Customer ID

b. Age: Age of the Customer

c. Experience: The amount of work experience in years

d. Income: the amount of annual income (in thousands)

e. Zip Code: Zip Code where customer lives

f. Family: Number of family members

g. CCA vg: Average monthly credit card spending

h. Education: Education level (1: Bachelor, 2: Master, 3: Advanced Degree)

i. Mortgage: Mortgage of house (in thousands)

j. Securities Account: Boolean of whether customer has a securities account

k. CD Account: Boolean of whether customer has Certificate of Deposit account

l. Online: Boolean of whether customer uses online banking

m. Credit Card: Does the customer use a credit card issued by the bank?

2.3 Dataset Collection

Once the required data is collected, it is tailor made for neural network with the help of data preprocessing. It is only after this step that the data is fed to the neural network. This phase mainly involves exploratory data analyzing, data cleaning and augmentation, finding and replacing missing values, and data normalization. It also involves visualization of major attributes to observe their distribution pattern. The process also includes observing the co-relation coefficient through heat map to learn about the relation and impact of different attributes. Outliners should be removed from the dataset and Missing value should be either delete or place with values with the help of mean, median etc. dataset can be split into training and testing set (70 and 30). Following steps are done in data preprocessing:

a. Importing libraries.

b. Importing the data set.

c. Finding the missing values.

d. Encoding categorical data.

e. Splitting data into training and testing set.

2.4 SMOTE

In this for synthetic minority oversampling technique and used to oversample the minority class. In this process, first selection a minority class instance at a random and find its K nearest minority class neighbors. Then synthetic instance is created by choosing and synthetic instances are generated as a convex combination of the two chosen instances a and b. It can be represented in an example as below shown in figure 2

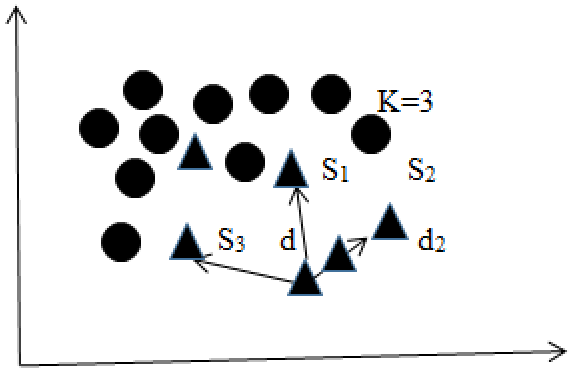

Figure 2: SMOTE

Here, SMOTE(sampling_strategy is auto, random_State is None, K_neighbours is 5, n_jobs is none) is library function. n_jobs represents no of CPU cores to do cross validation. We generally set none, it means single processor. k_neighbours represents no of instances for neighborhood. Default value is 5. Random_state is like a seed used by the random number generator. Default value is None. Sampling_strategy represents sampling information to resample the data. Default value is auto. The main steps are as below:

a. Identify feature vectors and it's the nearest neighbor.
b. Takes a differences between the two.
c. Multiple differences with random number between 0 and 1.
d. Identify the new point on the line segment by adding the random number to feature vector.
e. Repeat this process for identified features vector.

2.5 Back Propagation Algorithm

The back propagation algorithm has two passes, which are forward pass and backward pass. In forward pass, the calculation and storage of the intermediate variables (including outputs) is done for neural network in order from input layer to output layer. In the backward pass, it traverses in the reverse order. It is computed the output error and then go backward into the network and update the weights using gradient descent. This algorithm can be summarized in following steps:

Step 1: Firstly initialize all the weights, parameters by some random values.

Step 2: The network takes a training data as input, goes through the forward propagation step and finds the output probabilities for each class.

Step 3: Now we calculate binary cross entropy for loss calculation for batch as

$$L = -\frac{1}{m}\sum_{i=1}^{m} yi.\log(\overline{yi}) + (1-y_i).\log(1-\overline{yi}) \qquad \text{Eq 1}$$

Where y is actual label and $\overline{yi}$ is classifier's output.

Step 4: After obtaining the predicted output from the forward pass, the next objective is to minimize the error by adjusting the network parameters. This is achieved through backpropagation followed by stochastic gradient descent.

Step 5: Repeats step two to four with all dataset in the training set.

2.6 Back Propagation Algorithm

Gradient descent algorithm is used to minimize a cost function J(W) parameterized by model parameters W.

Algorithm:

a. Randomly initialize the weights W.

b. Determine the gradient G of the cost function in relation to the W parameters.

c. Update the weights.

$W_{new} = W_{old} - n * G$

W_{new} = new weights

W_{old} = old weights

n=Learning Rate

G=Gradient

d. Continue until the cost J(W) stops decreasing or unless other predetermined termination requirements are satisfied.

2.7 Back Propagation Algorithm

Now the model is trained using the training data. The batch size is set to 32 and a total of 100 iterations are involved on each epoch. During model compilation, we set the loss function to Binary Cross Entropy because this is a binary classification task. This loss function is:

$$\text{Loss}= -\frac{1}{N}\sum_{i=1}^{N} yi * log\big(p(yi)\big) + (1-yi) * \log(1-p(yi)) \qquad \text{Eq 2}$$

where y is the label and p(y) is the probability of y

In order to minimize the above loss function, Adam optimizer was used and the learning rate was assigned to 0.1.During the model training, the validation set was also fed to the model.

2.7 Model Evaluation and Testing

The performance matrix is used to evaluate the accuracy of our model. There should be minimum loss in order to get the accurate model. The minimum loss of a classification task is typically measured by accuracy and F1 score.

A true positive (TP) is an outcome where the model correctly predicts the positive class. Similarly, a true negative (TN) is an outcome where the model correctly predicts the negative class.

A false positive (FP) is an outcome where the model incorrectly predicts the positive class. And a false negative (FP) is an outcome where the model incorrectly predicts the negative class.

Accuracy is one metric for evaluating classification models. Informally, accuracy is the fraction of predictions our model got right. Formally, accuracy has the following definition:

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \qquad \text{Eq 3}$$

If accuracy comes out to 0.91, or 91% means 91 correct predictions out of 100 total examples.

This F-score is way of the combining the precision and the recall of this model, and this is defined as harmonic mean of model's precision and the recall.

Precision is the fraction of true positive examples among the examples that the model classified as positive. In other words the number of true positives divided by the number of false positives plus true positives.

Recall is the fraction of examples classified as positive, among the total number of positive examples. In other words the number of true positives divided by the number of true positives plus false negatives. These metrics are calculated as:

$$Precision = \frac{TP}{TP+FP} \qquad \text{Eq 4}$$

$$Recall = \frac{TP}{TP+FN} \qquad \text{Eq 5}$$

$$F1 = 2 * \frac{Precision * Recall}{Precision+Recall} \qquad \text{Eq 6}$$

AUC-ROC Curve: It is an evaluation metric which can be used to evaluate the performance evaluation of binary classifiers. Here TPR is plotted along the y-axis and FPR is plotted along the x-axis. Through this curve, the performance of a classifier can be analyzed.

2.8 Comparative Study

The methodology above describes a binary classifier using MLP. This classifier is finely tuned and hence its performance is also compared with other models like SVM and KNN on the given dataset and hence conclusion will be derived accordingly. The comparison is to be done on metrics such as AUC-ROC curve, precision, recall and f1-score.

3. Results and Discussion

3.1 Model Training Analysis

The model was trained on the training data sets that consist of a total of 5000 records and 14 attributes. Here 4520 are rejected loans and 480 are accepted loans. Attribute selection includes numeric and integer attributes along with some factor attributes relevant to the research problem. Some of the major attributes are depicted as follows:

3.2 Data attributes

The data has 14 attributes, thirteen are independent variables and one is dependent variables. Value of personal loan depends on the remaining thirteen attributes. Some attributes have high contribution on loan decision and some attributes have less contribution. Education, mortgage, income plays an important role regarding loan decision so these are explained detail below. Following attributes are present on data:

Table 1: Distribution of data in Imbalanced dataset

	ID	Age	Experience	Income	ZIP Code	Family	CCAvg	Education	Mortgage	Personal Loan	Securities Account	CD Account	Online	CreditCard
0	1	25	1	49	91107	4	1.6	1	0	0	1	0	0	0
1	2	45	19	34	90089	3	1.5	1	0	0	1	0	0	0
2	3	39	15	11	94720	1	1.0	1	0	0	0	0	0	0
3	4	35	9	100	94112	1	2.7	2	0	0	0	0	0	0
4	5	35	8	45	91330	4	1.0	2	0	0	0	0	0	1

Firstly, the data set is highly imbalanced only 10 percentage of loan is accepted and remaining 90 percentage of loan is rejected. Some of the attributes have high role on loan decision. These attributes are shown in figure. The imbalanced dataset are visualized in following Figures.

Figure 3 below shows the count of personal loan approvals (target class) and education of applicants respectively. On the left, 0 represents the number of applicants whose loan has not been approved and 1 represents the count of applicants whose loan is approved. The figure in the rights shows the education level of applicants 1 for bachelors, 2 for masters and 3 for more advanced degrees.

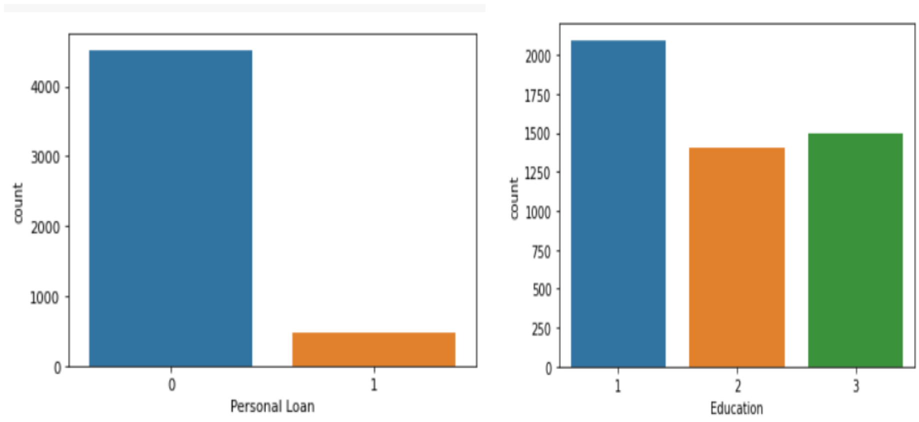

Figure 3: Personal loan and Education Count (imbalanced dataset)

In above figure, most of loans are rejected. Accepted loans are below 500 and remaining loan decisions are rejected. About half of applicants are done bachelor degree and total applicants who are done master are about thirteen hundred and fifteen hundred applicants are done advanced degree so these data are highly imbalanced regarding education.

Fig 4 below shows the distribution of income (in thousands) of the applicants. The average income of the applicants comes out to be 73 thousand hence the density is high on the left. Most of applicants have income less than hundred and very less applicants have income more than two hundred and fifty. It is highly imbalanced data as more applicants are under hundred. Bell curve is used to represent the distribution of income. Y axis represents in density instead of count as it is continuous data.

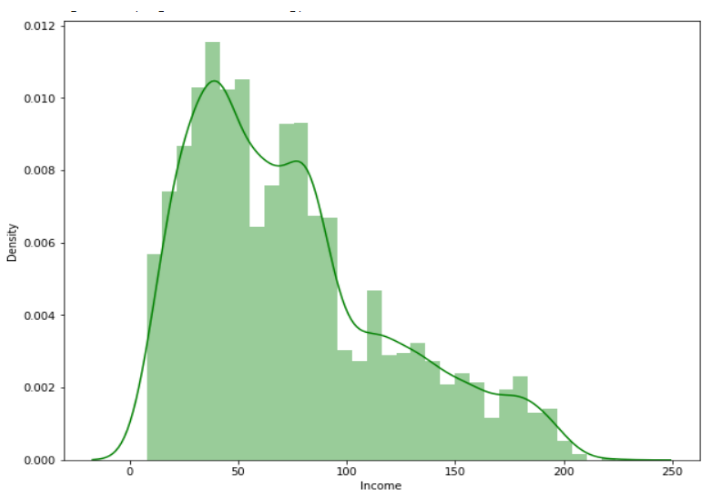

Figure 4: Income distribution (imbalanced dataset)

Figure 5 below shows the distribution of mortgages of the houses (in thousands) of applicants. As seen from the figure a significant number of the applicants have not taken out a mortgage facility. From the figure it represents that most of applicants do not have mortgage and some have mortgage and very less applicants have good mortgage facility.

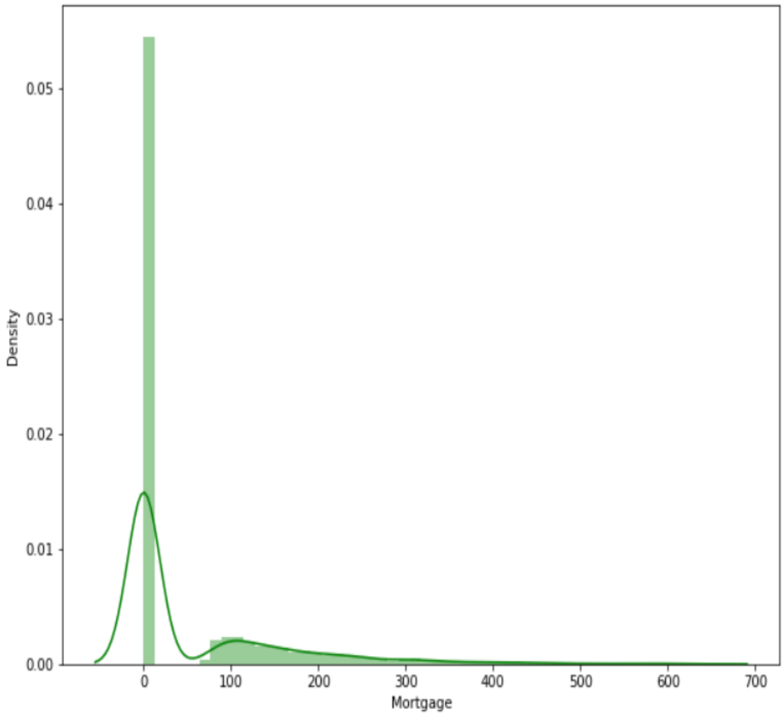

Figure 5: Mortgage distribution (imbalanced dataset)

Bell curve is used to represent the distribution of mortgage. Y axis represents in density instead of count as it is continuous data and average mortgage facility is 56.6 thousand.

3.3 Distributed of data in balanced dataset

The imbalanced dataset is not a healthy one to train the neural network as it causes over-fitting and makes the network biased. Therefore, an attempt has been made to balance the dataset using smote algorithm. Some of the attributes under the balanced dataset are visualized in following figures. Fig 6 below shows the count of personal loan approvals (target class) and education of applicants respectively. On the left, 0 represents the number of applicants whose loan has not been approved and 1 represents the count of applicants whose loan is approved. In this case, the number of applicants with and without personal loan is equal hence the balanced dataset. After oversampling the rejected applicants are increased and became equal to the accepted applicants and now data is quite balanced.

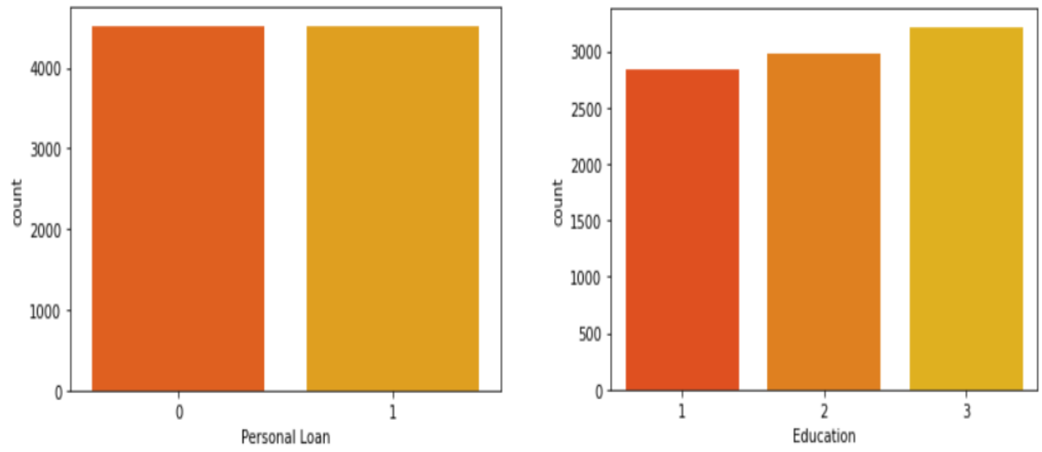

Figure 6: Personal loan and Education Count (balanced data)

The figure in the rights shows the education level of applicants 1 for bachelors, 2 for masters and 3 for more advanced degrees. Quite interestingly, the counts here are different from the former case. The number of applicants with masters and higher studies has increased as they are more likely to get personal loan approvals.

Figure 7 below shows the distribution of income (in thousands) of the applicants. As seen from the distribution plot, the income of the applicants in this case is more uniformly distributed with average around the middle and comes out to be 105 thousand.

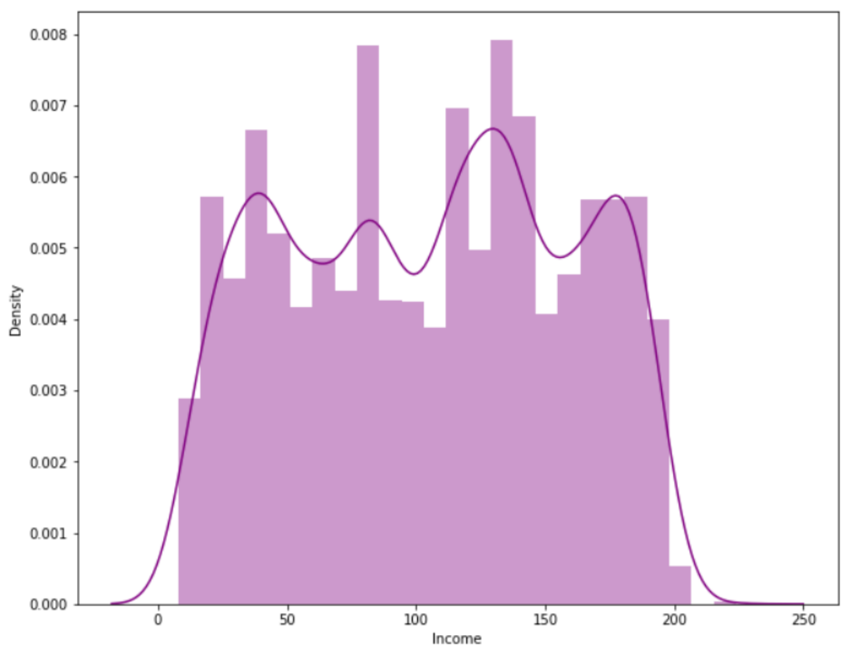

Figure 7: Income distribution (balanced dataset)

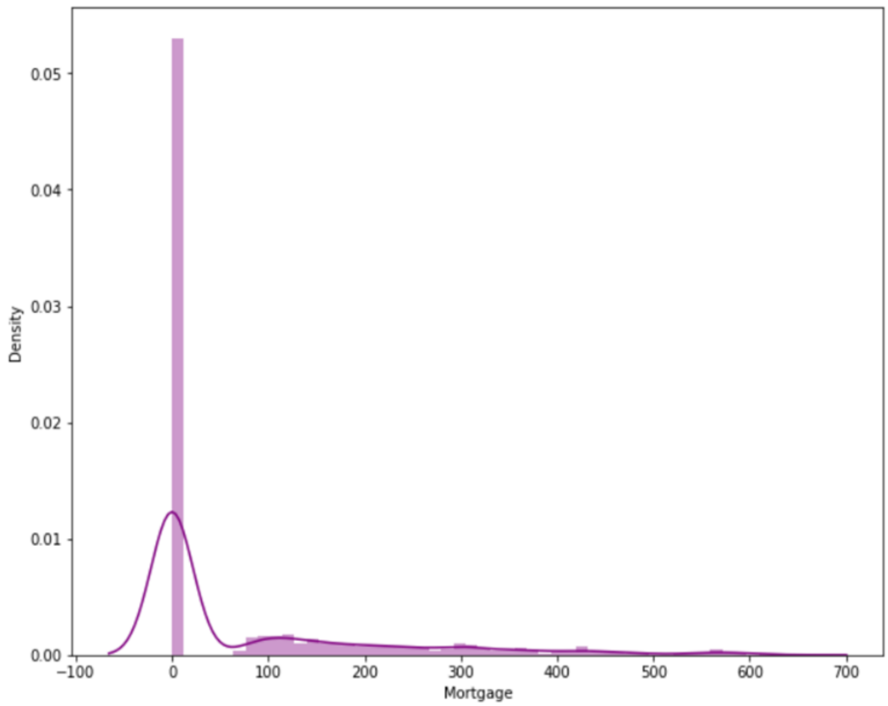

Figure 8: Mortgage distribution (balanced dataset)

Also, Figure 9 below shows the distribution of mortgages of the houses (in thousands) of the applicants. As seen from the figure a significant number of the applicants have not taken out a mortgage facility. The average amount of mortgage here comes out to be 77.7 thousand compared to 56.5 thousand in the previous case.

The visual representation of applicants getting loan approval versus the applicants not getting the loan approvals against their income can be depicted in the figure below. It shows the range of income of applicants that are likely to be approved and rejected for loans. In other words, it shows the distribution of two income groups. One with the people who got loan approval versus the second group that did not get loan approval. At the same time, it also depicts the cases in which the decisions may fall in either of the categories.

The visual representation of applicants getting loan approval versus the applicants not getting the loan approvals against their CCAvg can be depicted in the figure below. It shows the range of CCAvg of applicants that are likely to be approved and rejected for loans. In other words, it shows the distribution of two income groups. One with the people who got loan approval versus the second group that did not get loan approval. At the same time, it also depicts the cases in which the decisions may fall in either of the categories.

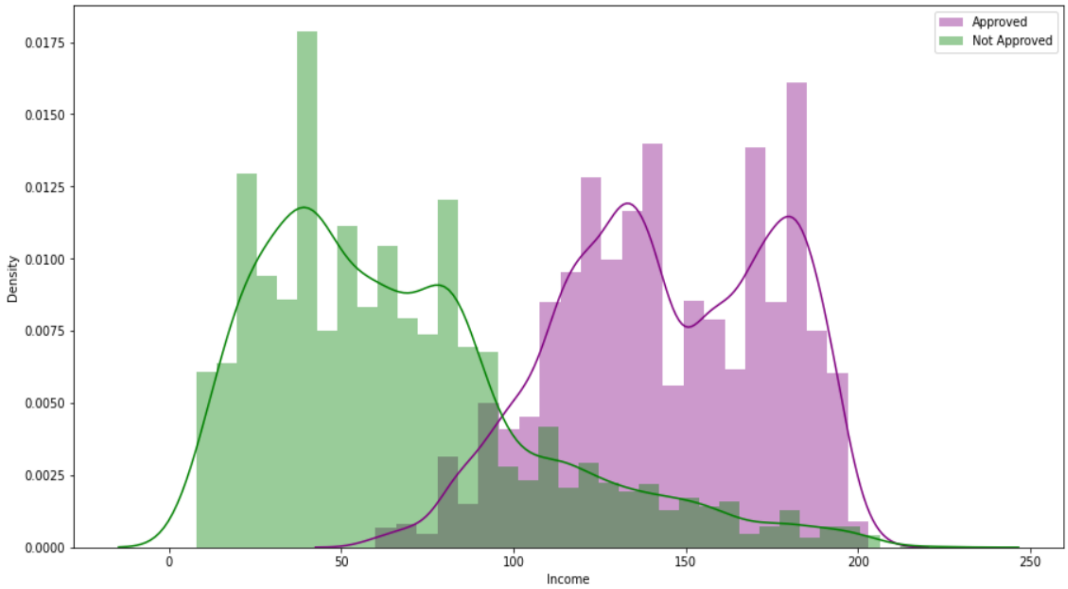

Figure 9: Loan approvals vs income (balanced dataset)

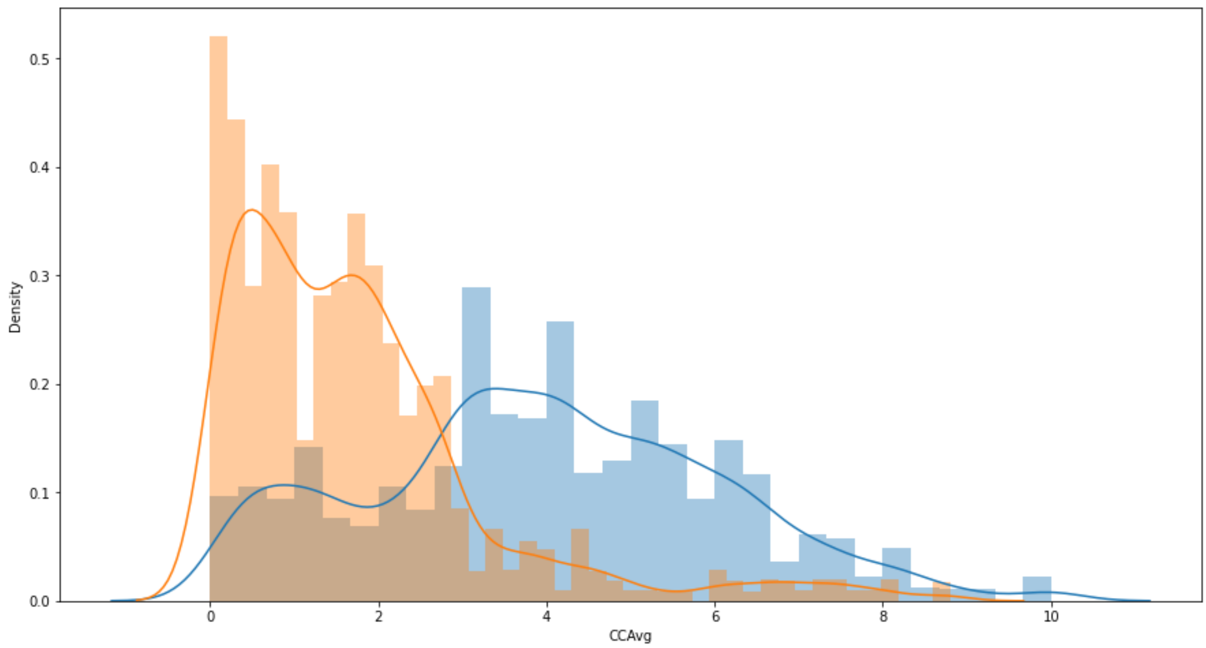

Figure 10: Loan approvals vs CCAvg (balanced dataset)

Figure 11 below shows correlation between various features. For example, it can be seen how experience and age have high correlation. As people grow older, they gain more work experience and vice versa. It is found how different features are related to personal loan feature. It shows the degree or amount of influence each attribute can have on decision making.

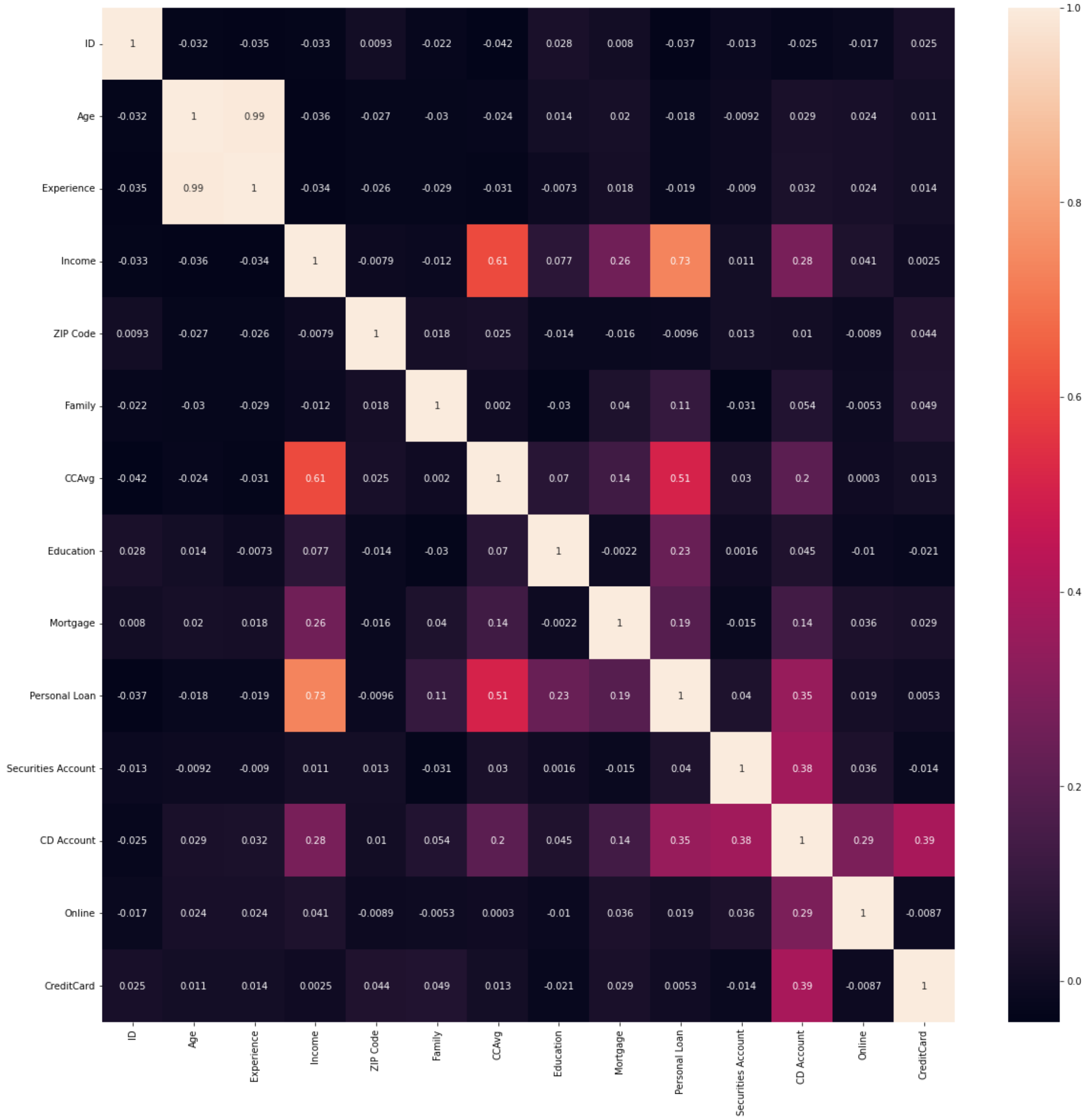

Figure 11: Correlation matrix

The main aim of the project is to apply an MLP on the datasets to find whether loan should be approved or not. The paper uses machine learning libraries including Scikit-learn, pandas, numpy, matplotlib and seaborn from Python 3.9. Furthermore, it uses keras and tensorflow for building MLP with appropriate input size, loss function, optimizer and learning rate. We have used a cross validation technique for splitting the dataset into training and testing data. Different performance metrics have been evaluated to figure out the effectiveness of the neural network.

In preprocessing of that data, the algorithm further divided this dataset into the training and the testing sets. That the process consists of the two phases, phase first is training phase where model is trained with training dataset. Each training data consist of X-train and Y-train data which store independent and the dependent features respectively. In our case, we used 10% of the data for testing and the other 90% for training. The training and testing data were then normalized using standard scales. This is followed by building the model, discussed below, then training the model through appropriate number of epochs. This is followed by testing phase where the model is first tested by using X_test and Y-test datasets to evaluate the accuracy and correctness of the model using other performance metrics described below. The model thus trained and tested is all set for prediction where we can predict the class of a new transaction data such that y_pred = model (X_new). This allows us to find how effective and consistent the model has been in making loan decisions.

3.4 Network Model

In this study, a multilayer perceptron has been used. Here, MLP classifier from sklearn module has been used for creating the model and GridSearch has been used to find the optimal parameter for the model. The optimal parameters for the model are as follows:

{'activation': 'tanh', 'alpha': 0.0001, 'hidden_layer_sizes': (150, 100), 'learning_rate': 'constant', 'max_iter': 100, 'solver': 'sgd'}

The classifier thus developed is trained using the X_train and the Y_train for 100 epochs. The process of the training can be observed from below data.

```
Iteration 1, loss = 0.55019050
Iteration 2, loss = 0.34125560
Iteration 3, loss = 0.27606763
Iteration 4, loss = 0.25993781
Iteration 5, loss = 0.23615281
Iteration 6, loss = 0.21687573
Iteration 7, loss = 0.20543686
Iteration 8, loss = 0.19532038
Iteration 9, loss = 0.18216090
Iteration 10, loss = 0.16983400
Iteration 11, loss = 0.16216931
Iteration 12, loss = 0.14660711
Iteration 13, loss = 0.14017379
Iteration 14, loss = 0.13367704
Iteration 15, loss = 0.12295981
Iteration 16, loss = 0.11442916
Iteration 17, loss = 0.11003679
Iteration 18, loss = 0.10741663
Iteration 19, loss = 0.10330445
Iteration 20, loss = 0.09332315
```

The MLP consists total 13 input variables, 1 hidden layer and the output layer with two neurons that represents that classifier. The hidden layers are using 'tanh' as activation function and learning rate given by 'alpha'. The network is trained by using supervised learning. The algorithm optimizes the neuron weights using the 'sgd' optimizer to minimize the error between actual and desired output. As a result of this the loss which is initially 0.55 goes on decreasing to become 0.003 in the 100th epoch. At the end of 100 epochs, the model has provided with following classification report.

	precision	recall	f1-score	support
0	0.98	0.96	0.97	442
1	0.97	0.98	0.97	462
micro avg	0.97	0.97	0.97	904
macro avg	0.97	0.97	0.97	904
weighted avg	0.97	0.97	0.97	904
samples avg	0.97	0.97	0.97	904

The loss curve for the model is as follows:

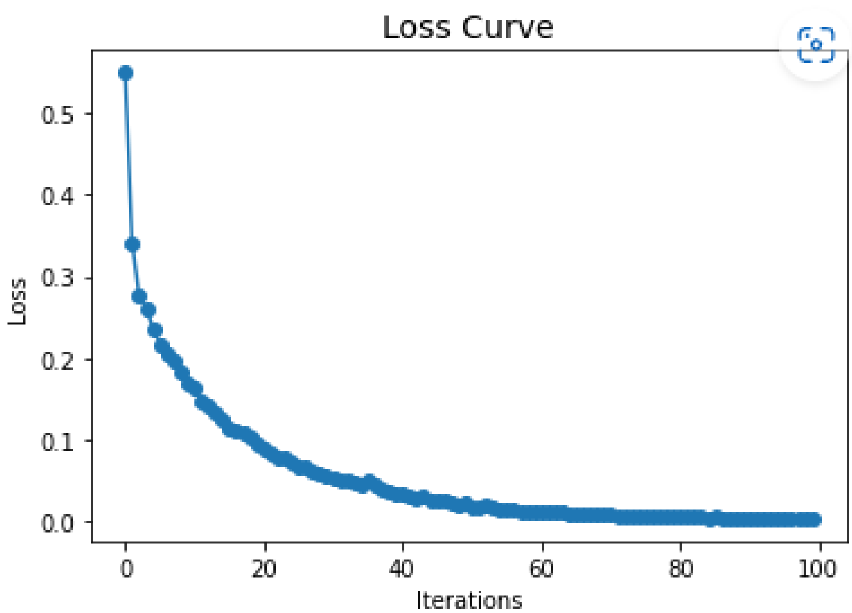

Figure 12: loss curve vs iteration

From the above figure the result of this the loss which is initially 0.55 goes on decreasing to become 0.003 in the 100^{th} epoch. After 80^{th} iterations the loss is almost constant and no need to iteration after 100^{th} epoch.

3.5 Model Performance Analysis

The performance of model is analyzed in terms of the metrics such as AUC-ROC curve, precision, recall and f1-score. Confusion Matrix is generated for the MLP model which is as shown in below

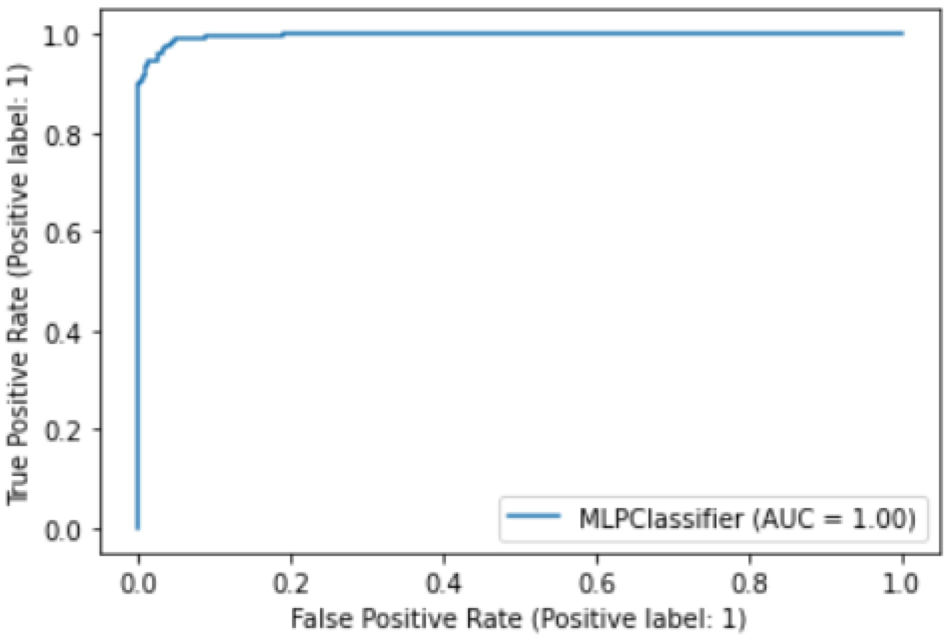

Figure 13: AUC and ROC curve

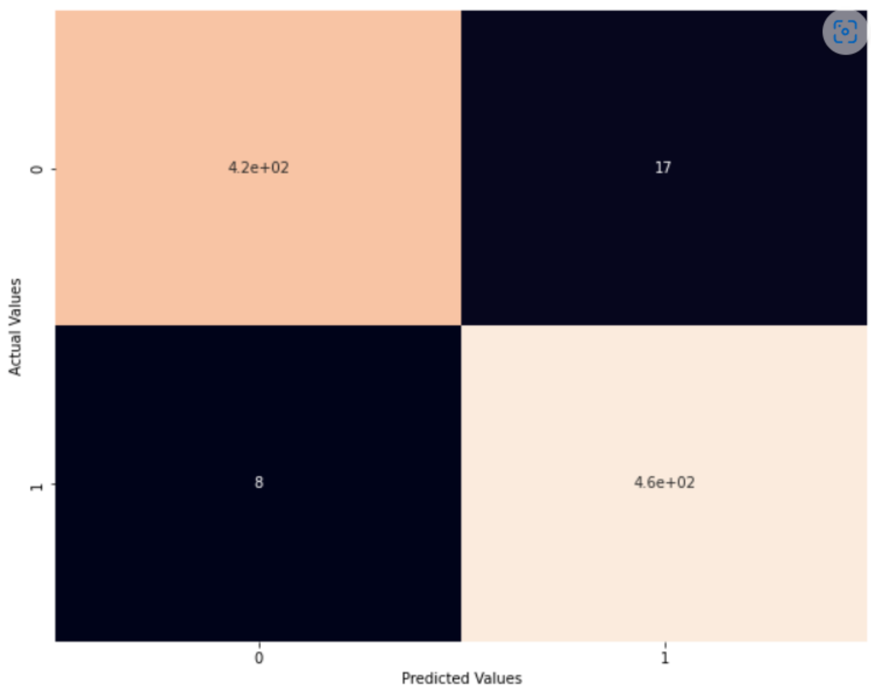

Figure 14: Confusion Matrix for MLP

From the above figure, true positive (TP) is $4.6x10^2 = 460$, FN = 8, FP = 17 and TN = $4.2x\ 10^2 = 420$.

Performance metrics and its value are as below:

Table 2: Performance Metrics and its Values on MPL

SN	Metrics	Values
1	AUC value	0.999
2	Precision Score	0.975
3	Recall Score	0.970
4	F1-Score	0.970

3.6 Overall comparison

The individual performance analysis of each model can be now compared with each other. The comparison shows that MLP shows betterment in evaluation metrics compared to other model KNN and RF. The validation process also requires many comparisons between predicted result and training result. The techniques that are based on decision were looked into. These include precision, recall, accuracy and F1 score.

The validation process also requires many comparisons between predicted result and training result. The techniques that are also based on decisions were also looked into. These include precision, recall, accuracy and F1 Score. which is shown in table below.

Table 3: Overall Comparisons

SN	Metrics	Values for KNN Model	Values for RF Model	Values for MLP Model
1	AUC value	0.9535	0.9259	0.999
2	Precision Score	0.9333	0.9509	0.975
3	Recall Score	0.9809	0.9045	0.970
4	F1-Score	0.9565	0.9272	0.970

There is no threshold for a good precision value so the result of 0.97 can be considered to be good for an loan classification. Similarly perfect recall score is considered to be 1 and the result of this model is 0.97 which is close.

As a F1 score of 1 is generally said to be that of a perfect model, this project has the F1 score of 0.97 which is very close to 1 which is a good result. Although it might have helped to make a comparison of Precision, Accuracy, Recall and F1 score between this model and other ones mentioned above, the fact that the proposed models' metrics are already high means that a direct comparison may not be needed but it has been mentioned in above table

reason to be rejected, it can be refer the attribute that should improve to get loan. It is used medium-size date, data can be increased too.

4. Conclusion

The development of machine learning-based Quantitative Structure-Activity Relationship (QSAR) models for predicting the toxicity of herbal and synthetic organic compounds marks a significant advancement in computational toxicology. Our study demonstrates that Logistic Regression, Random Forest, and Support Vector Machines (SVM) can achieve high accuracy (>90%) in predicting hepatotoxicity, neurotoxicity, and general acute toxicity. Random Forest slightly outperformed the others, with an accuracy of 92.78%, precision of 98.73%, recall of 86.67%, and F1 score of 92.31%. SVM exhibited perfect recall (100%) but lower precision (87%), making it particularly suitable for applications where missing toxic compounds is critical, even at the cost of some false positives.

Feature importance analysis provided valuable insights into the structural determinants of toxicity. For Random Forest, key features included molecular fingerprints corresponding to substructures such as aromatic rings, nitro groups, and tertiary amines, which are well-known for their association with toxic effects. Logistic Regression and SVM highlighted the significance of molecular weight and lipophilicity (logP), consistent with established toxicological principles. These findings not only validate the models' predictive capabilities but also offer actionable insights for designing safer compounds by identifying structural features that contribute to toxicity.

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Preparation of Poly- Herbal Mouthwash and Evaluation of Antimicrobial Activity Against Common Oral Pathogens

Madan Kumar Singh[1], Jay Kant Chaudhary[1], Karan Kumar Chaudhary[1], Suvash Shah[1], Ram Shrestha[1], Pratik Khanal[2*]

[1] Modern Technical College Lalitpur, Nepal

[2] Crimson College of Technology, Butwal, Nepal

*Corresponding Email: Pratikkhanal18@gmail.com

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Abstract

Polyherbal mouthwash is an oral preparation formulated with extracts of natural ingredients such as leaves of Neem, the pericarp of Barro, the Betel plant, and the rhizome of Turmeric, along with specific antibacterial agents that show antimicrobial properties. It is applied to maintain oral hygiene, prevent bad breath, and prevent dental and periodontal disease. Polyherbal mouthwash prepared from these plants is used to study their antimicrobial effect against oral pathogens like Staphylococcus aureus, Candida albicans, Escherichia coli, Enterococcus, and Klebsiella, which are commonly found in the oral cavity. The formulation of the polyherbal mouthwash was done by the hydroalcoholic extraction method using a ratio of 1:5 of pulverized powder and solvent (70% alcohol). After the extraction, the mother liquor was evaporated using a water bath at 50°C, and the powder of the active extract of the plant was collected and stored in an airtight container at 2–8 °C. The polyherbal mouthwash was formulated in four different formulations: F1, F2, F3, and F4, in increasing concentrations, respectively. The evaluation of the antimicrobial activity of the formulated polyherbal mouthwash was done by the agar well diffusion method and compared to a commercially available mouthwash (chlorhexidine) as a standard. The zone of inhibition of bacterial growth was measured and compared to the standard. Among the four formulations, F4 had the most effective zone of inhibition: Enterococcus, C. albicans, and S. aureus were 24mm, 26mm, and 18mm, respectively, compared to the standard (chlorhexidine), which were 20mm, 26mm, and 20mm. However, the hydroalcoholic preparation of the polyherbal mouthwash was resistant to E. coli and K. pneumoniae, while the standard was effective toward these bacteria. The formulated mouthwash's physical properties (color, consistency, odor, pH, density, and viscosity) were also evaluated. The results of this study will provide *valuable information on the potential benefits of using a polyherbal mouthwash as part of a daily oral care routine*

Keywords: *Azadirachta indica, Terminalia bellirica, Piper betle, Curcuma longa, Antimicrobial, S. aureus, C. albicans, E. coli, Enterococcus, K. pneumonia*

1. Introduction

Herbal medicines use plant parts for healing and disease treatment. Historically, they have been widely used, with the World Health Organization reporting that about 80% of people use them for primary healthcare. Over 35,000 plant species are utilized globally for medical purposes, some having antimicrobial, antidiabetic, antiviral, anticancer, and antifungal properties. Oral infections, such as dental caries, affect enamel and dentine and can lead to tooth loss if untreated. Imbalance in the mouth's normal flora, typically non-pathogenic bacteria, can cause infections and tooth decay (Shukla & Kumari, 2019).

Polyherbal mouthwash means that two or more plants have beneficial effects towards oral hygiene. Each plant used in the formulation of herbal mouthwash has been used traditionally value for centuries as a natural remedy for oral care in many cultures. In many societies cultural use of Neem (*Azadirachta indica*), Barro (*Terminalia bellirica),* Betel plants (*Piper betle*) and Turmeric (Curcuma longa) these plants are rich in antibacterial agent, anti-inflammatory agents, anti-oxidant and mouth freshener properties.

Periodontal diseases can destroy ligaments, cementum, gingiva, and alveolar bone. Plaque causes gingival inflammation, and its control can be achieved with instant herbal mouthwashes. These mouthwashes deliver therapeutic ingredients to combat oral organisms. Chlorhexidine (0.1%-0.2%) is a gold standard but has notable side effects, including tooth staining, contact dermatitis, and IgE-mediated hypersensitivity (Singgih et al., n.d.).

Junk foods significantly impact oral health, particularly candies, chocolates, jellies, and jams, which have high sugar content. These sugars contain insoluble glucan that adheres to tooth enamel, leading to cavities. Carbonated drinks also damage enamel, causing erosion, potential dentine exposure, and tooth discoloration. Mouthwashes are recommended to quickly remove food particles (Banu & Gayathri, 2016).

Herbal mouthwash is in high demand for its quick pain relief, effectiveness against oral pathogens, and fewer side effects. Chemical mouthwashes with hydrogen peroxide and chlorhexidine whiten, sterilize, and relieve pain but may discolor teeth and cause side effects, despite being economical. Chlorhexidine is not ideal for long-term use due to staining, but this can be managed with proper oral hygiene. Herbal mouthwashes are suitable for prolonged use to address various dental issues (Namdeo et al., n.d.).

Azadirachta indica (Neem) has been extensively used in Ayurveda, Unani and homoeopathic medicine and has become a wonder tree of modern medicine. It has been used traditionally for the treatment of inflammation, infections, fever, skin diseases and dental problems. *Neem* twigs are used as oral deodorant, toothache reliever and for cleaning teeth. *Neem* bark possesses antibacterial and deodorant activity (Vinod et al., 2018).

The phytochemical constituents present in *neem* are nimbidin, nimbin, nimbolide, Azadirachtin, gallic acid, epicatechin, catechin, and margolone which exhibit potent antibacterial activity. The chief active constituent of *neem* is azadirachtin, which is an effective antimicrobial agent (Chaudhary et al., 2023).

Ethanolic and aqueous extract of *Neem* leaf showed significant anti-candidial effects against *C. albicans* (Kumar et al., 2022). A clinical study demonstrated the effects of the leaf aqueous extract from *Azadirachta indica* (*Neem*) on adhesion, cell surface hydrophobicity and biofilm formation, which may affect the colonization by *Candida albicans*. The results suggest that *Neem* leaves have a potential anti-adhesive effect on the sample studied *in vitro* (Hoque et al., 2012).

The Piper betel plant (Piper betle Linn.) is a native plant of Southeast Asia. Leaves of the piper betel plant contain several active compounds such as eugenol and its isomers, chavibetol, hydroxychavicol, pentatriacontanol, piperol, piperbetol, Hydroxychavicol has been examined as an antimicrobial ingredient, and it is promising for several applications. The possibility of using hydroxychavicol was evaluated from piper betel as an oral care agent and found that its antimicrobial profiles are well suited as an active ingredient for oral care products (Das & De, 2011).

Antifungal activities of hydroxychavicol from *Piper betel* extract demonstrated fungicidal effects against all the fungal species tested including *Candida* species, *Aspergillus* species, and dermatophytes including *Trichophyton rubrum* (Khosla et al., 2000).

Terminalia bellirica (Barro) is a medicinal plant which has a wide range of pharmacological activity. The major ingredients of *T. bellirica* are ellagic and gallic acid and acid derivatives including epigallocatechin gallate. Tannic acid is found to be the major constituent of the ripe fruit (Athavale, 1999). They have large phenolic groups that provide them with unique binding properties causing them to bind to mucosal and tooth surfaces and this results in the prolonged action of the extract (Khosla et al., 2000).

The ethnobotanical use of *T. bellirica,* the fruit decoction is used as a gargle in oral ulcers and sore throats. Its powder is a good astringent dentifrice in loose gums, bleeding and ulceration in gums.

The aim is to prepare Anti-microbial polyherbal Mouthwash from the hydroalcoholic extracts of 4 different leaves namely *Azadirachta indica*(Neem), leaves of *Piper betle* (Betel plant), the fruit of *Terminalia bellirica* (Barro) and rhizomes of *Curcuma longa* (Turmeric) that acts against the common oral pathogens- *Staphylococcus aureus, Candida albicans, Enterococcus spp, Klebsiella pneumoniae and Escherchia coli* and to evaluate the Anti-microbial activity by using Agar well diffusion method.

2. Materials and Method

2.1 Test Organisms

Test organisms used in this study were collected from the pathology lab of Star Hospital, Sanepa-2, Lalitpur, Nepal. The organisms included *Candida albicans*, *Staphylococcus aureus*, *Escherichia coli*(both resistant and sensitive strains), *Enterococcus faecalis*, and *Klebsiella pneumoniae*.

2.2 Collection of Plants

The plant materials were collected from various locations in Nepal. The leaves of Neem (*Azadirachta indica*) and the Betel plant (*Piper betel*) were obtained from Lahan Municipality-9, Siraha, Nepal, on 26th Ashadh 2080 (Nepali calendar). The fruits of Barro (*Terminalia bellirica*) and the rhizome of Turmeric (*Curcuma longa*) were acquired from Ram Pharma Supplier. These plant parts were carefully selected to ensure freshness and authenticity for the study

2.3 Preparation of Plant Extract

The collected plant materials were washed with sterile water and then collected plant materials were shadow-dried at room temperature for 3-5 days. The dried plant materials were pulverized and stored in air-tight containers separately. The hydro-alcoholic solution was prepared by mixing 70% v/v of ethyl alcohol and water. Then powder of each ingredient was added to the hydroalcoholic solution in a ratio of 1:5 (Pankaj et al., 2011).

Each plant material was prepared by soaking the powdered plant parts in a prepared solution and macerating them at room temperature for 72 hours. The macerated solution was first filtered by sterilized muslin cloths for coarse residue and filtered using sterilized Whatmann filter paper (no.1), Whatman filter paper was sterilized by using an autoclave at 121^0C and 15 psi for 30 min and measured and kept in an airtight amber-coloured container (Biswas et al., 2002; Pankaj et al., 2011). Marc was washed with 10 ml of distilled water and pressed. After being concentrated by evaporation by using a water bath at 50°C for complete drying of extract and then the powder was collected and stored in an airtight container

2.4 Formulation of Herbal mouthwash

Formulation of polyherbal mouthwash was prepared by using the following procedure as shown in Fig. 1 (Banu & Gayathri, 2016)

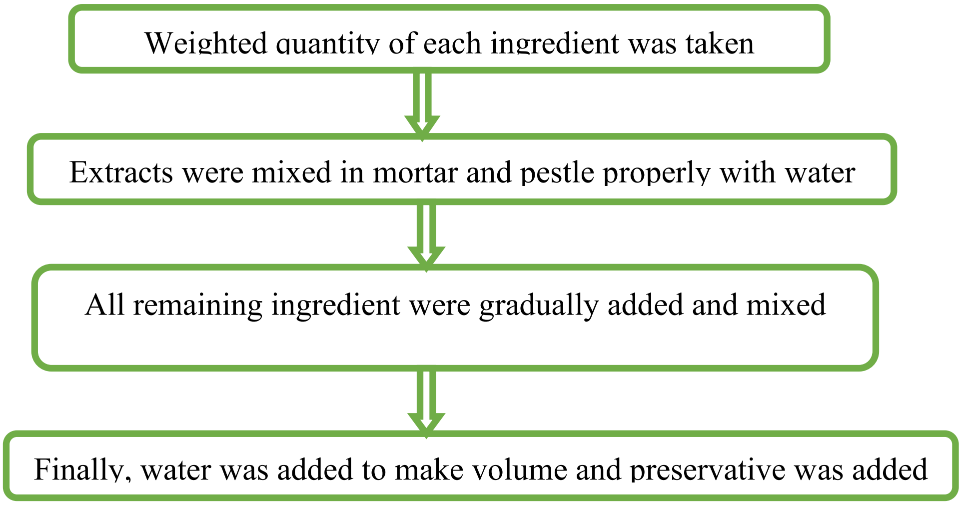

Figure 1: Flowchart of the polyherbal Mouthwash Formulation

Table 1: Formulation of Herbal Mouthwash

SN.	Ingredients	Botanical name/ Company name	Plant parts	Function	Formulation in four different quantities			
					F1	F2	F3	F4
1.	Neem	*Azadirachta indica*	Leaves	Antimicrobial	100 mg	200 mg	400 mg	800 mg
2.	Barro	*Terminalia bellirica*	Pericarp	Antimicrobial	100 mg	200 mg	400 mg	800 mg
3.	Betel plant	*Piper betle*	Leaves	Antimicrobial	100 mg	200 mg	400 mg	800 mg

4.	Turmeric	*Curcuma longa*	Rhizome	Antimicrobial	100 mg	200 mg	400 mg	800 mg
5.	Clove oil	*Eugenia caryophyllus*	Flower bud	Flavor, Analgesic	0.1 ml	0.15 ml	0.20 ml	0.25 ml
6.	Saccharine	CDH(030034)	N/A	Sweetener	0.1 mg	0.1 mg	0.1 mg	0.1 mg
7.	PEG 40	HIMEDIA	N/A	Surfactant	6 g	6 g	6 g	6 g
8.	Glycerol	HIMEDIA (GRM 081)	N/A	Co-surfactant	6.5 ml	6.5 ml	6.5 ml	6.5 ml
9.	Ethyl alcohol	CHFC Co. Ltd	N/A	Preservative	2 ml	2 ml	2 ml	2 ml
10.	Distilled water	MARECH Pvt. Ltd.	N/A	Solvent	q.s.	q.s.	q.s.	q.s.

Table No. 1 F_1, F_2, F_3, and F_4 represent formulations containing 100 mg, 200 mg, 400 mg and 800 mg extract respectively (Abbreviation: q.s. = quantity sufficient, PEG = Poly Ethylene Glycol)

2.5 Evaluation of Prepared Herbal Mouthwash

2.5.1 Physical Evaluation

Colour, Odour and Consistency were examined by using the visual examination of prepared herbal mouthwash.

Colour: Light- Orange

Odour: pleasant aromatic odour

Consistency: homogenous solution

a. pH: A digital pH meter was used to measure the pH of the prepared herbal mouthwash and careful reading should be taken and recorded in the notebook. It was repeated for three times and the average reading should be calculated properly. The average calculated pH of the prepared herbal mouthwash was slightly acidic in nature (Sunitha et al., 2009).

b. Relative Density: It is the ratio of the density of the substance to the density of pure water. it is also known as the specific gravity. the density of water is essential at room temperature. Thus, the relative density of the substance is very nearly equal to its density and it has no unit. Density was measured by using a pycnometer which represents mass per unit volume in the unit's g/ml or g/cm^3. Firstly, we were washed the pycnometer and dried it in the hot air oven for complete drying of the apparatus and then left it for cooling and then only used it for the measurement of the density of the water and prepared herbal mouthwash (Basir et al., 2023; Viana, 2002).

$$\text{Relative density}(\rho) = \frac{\text{Mass of liquid}(W3 - W1)}{\text{Mass of equal volume of water}(W2 - W1)} \quad \text{Eq 1}$$

c. Viscosity: Viscosity was measured by using Ostwald's viscometer, Firstly water was passed through it and time was recorded and reading was recorded in the notebook. After that prepared herbal mouthwash was passed through the same Ostwald viscometer, which was repeated three times and their average time should be calculated carefully.

According to Ostwald's viscosity of the sample could be calculated as the following formula (Beaulieu et al., 2017).

$$\text{Viscosity sample } (\eta_2) = \frac{\rho 2 * t2}{\rho 1 * t1} * \eta_1 \quad \text{Eq 2}$$

Where,

η_1=Viscosity of water

η_2=Viscosity of sample

ρ_1=Relative density of distilled water

ρ_2=Relative density of the sample

t_1=Time of water pass A to B mark of Ostwald Viscometer.

t_2=Time of the sample pass A to B mark of Ostwald Viscometer.

2.5.2 Preparation of Agar Media

Mueller Hinton Agar (MHA) was used to prepare the agar media to provide the nutrition for the growth of bacteria. It was prepared by using sterile distilled water in the conical flask, all the required apparatus was washed properly and dried in the hot air oven. Suspend 38 gm of the medium in one-litre distilled water and the prepared solution was heated with frequent stirring and boiled for one minute to completely dissolve the medium. The prepared MHA solution was sterilized in the autoclave at 121^{o}C and pressure was adjusted to 15lb and sterilized for 15 minutes, the solution was left to cool the solution at room temperature. A sterilized petri plate was taken. The prepared solution of MHA was poured into the plate inside the laminar airflow to maintain the aseptic technique and was left to solidify the prepared media completely and the prepared plate was stored in the refrigerator by adjusting the temperature between 2^0C - 8^0C (Shanthi & Radha, 2020).

2.5.3 Antibacterial Sensitivity Test (Agar Well Diffusion Method)

An antibacterial activity test was performed on the isolated colonies of bacteria which were taken from the microbiology lab of the Star Hospital. The agar well diffusion method was used to determine the zone of inhibition. The prepared MHA media agar plate was taken and an aseptic environment was created by burning of burner at four different corners of the working table, The working area should be free of microbes. The isolated bacteria were handled carefully and the code of the bacteria should be noted properly. After being created in an aseptic area bacteria were inoculated on the Petri plate by using the streaking method to distribute the bacteria equally in the plate, After the completion of the distribution of bacteria, a well was formed at six different places in the plate carefully calculating the distance between each well, by using the agar well cutter the well was formed properly and then the well was loaded 100µl with the help of micropipette of prepared herbal mouthwash which was prepared in the different concentration F_1, F_2, F_3, F_4, blank and standard at the coded well of plate respectively. After the completion of loading of the well, the plate was left 1 hour undisturbed for the passive diffusion of the herbal mouthwash into the culture media. The loaded culture media plate was incubated at 37ºC for 24 hours and a triplicate method was used & The experiment was repeated three times and the zone of inhibition was measured & and calculated, noted in the notebook careful (Namdeo et al., n.d.).

2.5.4 Statistical Data Analysis

The experiments were repeated three times and the values were expressed as mean ± standard deviation. Data were analyzed using one-way ANOVA using IBM SPSS Statistics version 29.0.1.0(171) and a significance value of $P<0.05$.

3. Result

The pH of the different formulations is slightly acidic F_1, F_2, F_3, and F_4 are 5.6, 5.6, 5.7, and 5.7 as compared to Chlorhexidine mouthwash pH was 5.9 as shown below in Table 2. Hence, the pH values for different formulations (F_1, F_2, F_3, and F_4) were slightly acidic, ranging from 5.6 to 5.7. In comparison, the Chlorhexidine mouthwash had a pH of 5.9. The results suggest that the prepared mouthwashes are within the suitable pH range for oral use

3.1 Evaluation of relative density of different formulations

The evaluation of the relative density of different quantities of formulation is represented in sample Blank, F_1, F_2, F_3, F_4 and Chlorhexidine. Where W_1 represent the weight of an empty specific gravity Pycnometer, W_2 represent the weight of a specific gravity Pycnometer + Distilled water and W_3 represent the weight of a specific gravity Pycnometer + Sample. According to the method, relative density of quantities formulation were measured and noted in the table as shown below in Table No.3. The relative density of the formulations (F_1, F_2, F_3, F_4) and Chlorhexidine ranged around 1.03 to 1.04, indicating that the formulations are slightly denser than water. This density is considered appropriate for oral formulations

Table 2: Result and Evaluation of pH of different formulation

S.N	Sample	pH_1	pH_2	pH_3	Mean pH
1.	Blank	5.4	5.7	5.5	5.5±0.12
2.	F_1	5.4	5.6	5.8	5.6±0.16
3.	F_2	5.9	5.6	5.5	5.6±0.18
4.	F_3	5.8	5.6	5.9	5.7±0.08
5.	F_4	5.6	5.9	5.7	5.7±0.12
6.	Chlorhexidine	6.1	5.8	5.9	5.9±0.12

The evaluation result of pH is expressed in the mean ± standard deviation.

Table 3: Evaluation of relative density of different formulations

S.N	Sample	W_1(gm)	W_2 (gm)	W_2-W_1	W_3 (gm)	W_3-W_1	Relative Density(ρ)
1.	Blank	26.74	80.47	53.73	82.37	55.63	1.03
2.	F_1	28.05	77.73	49.68	79.93	51.88	1.04
3.	F_2	30.15	81.52	51.37	83.04	53.09	1.03
4.	F_3	26.27	71.69	53.42	81.82	55.55	1.03
5.	F_4	29.77	79.82	50.05	81.67	51.90	1.03
6.	Chlorhexidine	27.57	81.43	53.86	82.64	55.07	1.02

3.2 Evaluation of Viscosity of the different Formulations

The viscosity of different formulations were measured and noted as shown below in Table no. 4. Where T_1, T_2, and T_3 represent the times to repeat the experiment and the average value of these values were calculated.

Table 4: Evaluation of viscosity of the different formulations

S.N	Sample	Time (sec)			Mean Time (sec)	Relative Density of Sample ρ(g/cc)	Viscosity(η)in mPa.
		T_1	T_2	T_3			
1.	Water	1.34	1.32	1.35	1.33	1.00	1.00
2.	Blank	1.52	1.42	1.43	1.45	1.03	1.12
3.	F_1	1.42	1.45	1.41	1.42	1.04	1.11
4.	F_2	1.43	1.39	1.45	1.42	1.03	1.09
5.	F_3	1.42	1.41	1.46	1.43	1.03	1.10
6.	F_4	1.43	1.45	1.47	1.45	1.03	1.12
7.	Chlorhexidine	1.23	1.43	1.39	1.35	1.02	1.03

3.3 Result of Agar Well Diffusion Antimicrobial Test of F_1

The evaluation of the agar well diffusion antimicrobial test of formulation F_1 for isolated micro-organism are shown below Table No.5 . Where X_1, X_2, and X_3 represent the repeated times of average triplicate data respectively

Table 5: Result of Agar Well Diffusion Antimicrobial Test of formulation F_1

SN.	Organism	Zone of Inhibition (mm)				
		Blank	F_1			Mean ± Standard Deviation
			X_1	X_2	X_3	
1.	*C. albicans*	0	18	19	21	19.00±1.24
2.	*S. aureus*	0	12	11	14	12.34±1.24
5.	*E. feacalis*	0	13	15	11	13.00±1.6
3.	*E. coli* (resistant)	0	0	0	0	0±0
4.	*E.coli* (sensitive)	0	0	0	0	0±0

6.	*Klebsiella pneumoniae*	0	0	0	0	0±0

The zone of inhibition of F_1 on growth agar media expressed in mean ± standard deviation.Where, X_1, X_2 and X_3 are respective times to represent the experiment respectively.

Table 6: Result of Agar Well Diffusion Antimicrobial Test of F_2

SN.	Organism	Zone of Inhibition (mm)				
		Blank	F_2			Mean ± Standard Deviation
			X_1	X_2	X_3	
1.	*C. albicans*	0	21	23	19	21.00±1.6
2.	*S. aureus*	0	14	17	15	15.34±1.24
3.	*Enterococcus*	0	13	14	17	14.67±1.69
4.	*E. coli* (resistant)	0	0	0	0	0
5.	*E.coli* (sensitive)	0	0	0	0	0±0
6.	*Klebsiella pneumoniae*	0	0	0	0	0±0

Where, X_1, X_2 and X_3 are respective times to represent the experiment respectively. Note: The zone of inhibition of F_2 on growth agar media expressed in mean and standard deviation

Table 7: Result of Agar Well Diffusion Antimicrobial Test of F_3

SN.	Organism	Zone of Inhibition (mm)				
		Blank	F_3			Mean ± Standard Deviation
			X_1	X_2	X_3	
1.	*C. albicans*	0	22	25	27	24.67±2.04
2.	*S. aureus*	0	18	15	17	16.66±1.24
3.	*Enterococcus*	0	21	19	23	21.00±1.66
4.	*E. coli* (resistant)	0	0	0	0	0±0
5.	*E.coli* (sensitive)	0	0	0	0	0±0
6.	*Klebsiella pneumoniae*	0	0	0	0	0±0

Note: The zone of inhibition of F_2 on growth agar media. Where, X_1, X_2 and X_3 are respective times to represent the experiment respectively.

The zone of inhibition of F_3 on growth agar media expressed in mean ± standard deviation.

Table 8: Result of Agar Well Diffusion Antimicrobial Test of F_4

S.N	Organism	Zone of Inhibition (mm)				
		Blank	**F_4**			**Mean ± Standard Deviation**
			X_1	**X_2**	**X_3**	
1.	*C. albicans*	0	27	24	28	26.33±1.63
2.	*S. aureus*	0	22	19	21	20.66±1.23
3.	*Enterococcus*	0	22	20	25	21.66±2.35
4.	*E. coli* (resistant)	0	0	0	0	0±0
5.	*E.coli* (sensitive)	0	0	0	0	0±0
6.	*Klebsiella pneumoniae*	0	0	0	0	0±0

Note: Where, X_1, X_2 and X_3 are respective times to represent the experiment respectively.

Table 9: Result of Agar Well Diffusion Antimicrobial Test of Standard

SN.	**Organism**	**Zone of Inhibition (mm)**				
		Blank	**Standard (Chlorhexidine)**			**Mean ± Standard Deviation**
			X_1	**X_2**	**X_3**	
1.	*C. albicans*	0	27	24	26	25.66±1.24
2.	*S. aureus*	0	21	22	19	20.66±1.24
3.	*Enterococcus*	0	19	23	21	21.00±1.6
4.	*E. coli* (resistant)	0	17	20	19	18.66±1.49
5.	*E.coli* (sensitive)	0	15	18	17	16.66±1.24

6.	*Klebsiella pneumoniae*	0	13	15	16	14.66±1.24

Where, X_1, X_2 and X_3 are respective times to represent the experiment respectively.

Table 10: Result of Agar Well Diffusion Antimicrobial Test

S.N	**Organism**	**Zone of Inhibition (mm)**					
		Blank	**F_1**	**F_2**	**F_3**	**F_4**	**Standard (Chlorhexidine)**
1.	*C. albicans*	0	19.00 ±1.24	21.00± 1.6	24.67±2.04	26.33±1.63	25.66±1.24
2.	*S. aureus*	0	12.34 ±1.24	15.34± 1.24	16.66±1.24	20.66±1.23	20.66±1.24
3.	*Enterococcus*	0	13.00 ±1.6	14.67± 1.69	21.00±1.66	21.66±2.35	21.00±1.6
4.	*E. coli* (resistant)	0	0±0	0	0±0	0±0	18.66±1.49
5.	*E.coli* (sensitive)	0	0±0	0±0	0±0	0±0	16.66±1.24
6.	*Klebsiella pneumoniae*	0	0±0	0±0	0±0	0±0	14.66±1.24

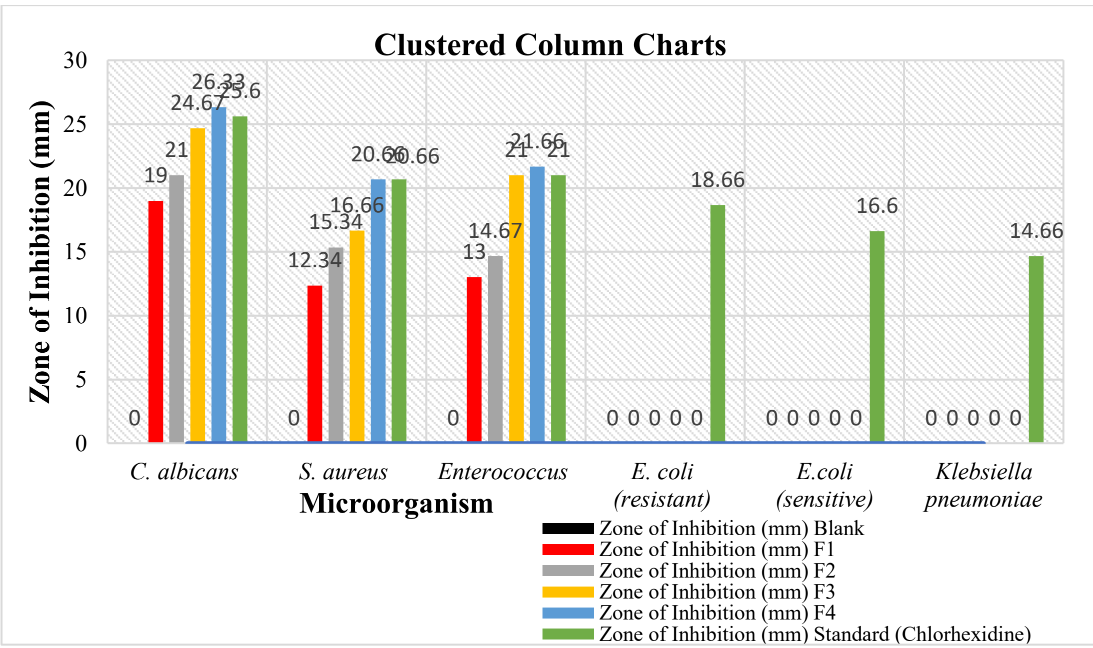

Figure 2: Result of Agar Well Diffusion Antimicrobial Test of microorganism.

The collective summary across all formulations (F1, F2, F3, F4) demonstrated varying degrees of antimicrobial activity against tested microorganisms. The standard Chlorhexidine also showed comparable effectiveness.

Table 11: Formulation showing significance with standard

Organism	Zone of Inhibition (mm)				
	F_1	**F_2**	**F_3**	**F_4**	**Chlorhexidine**
C. albicans	19.00*	21.00	24.67	26.33	25.66
S. aureus	12.34*	15.34	16.66	20.	20.66
Enterococcus	13.00*	14.67*	21.00	21.66	21.00

* The mean difference is significant at the 0.05 level as compared to the standard.

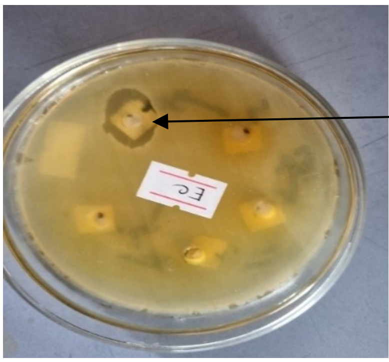

Figure 3: Zone of inhibition of *E. coli* (Sensitive)

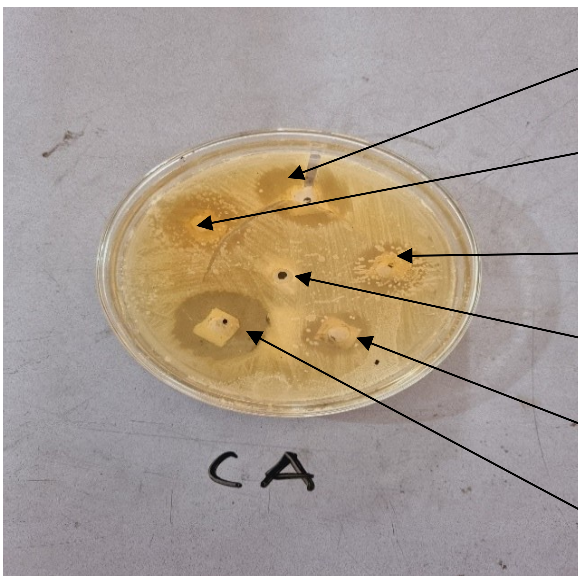

Figure 4: Zone of Inhibition of *C. albicans*

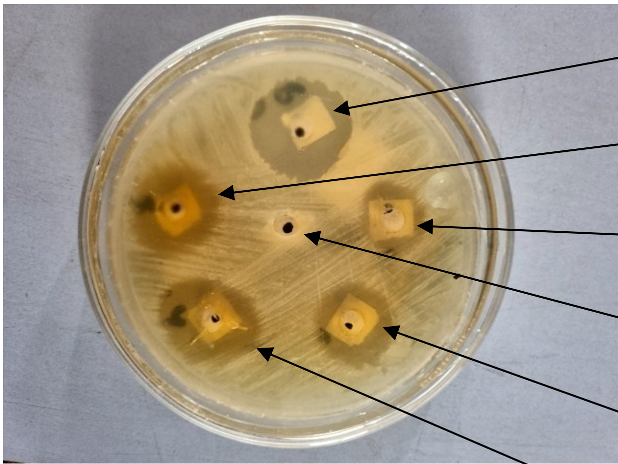

Figure 5: Zone of nhibition of *E. faecalis*

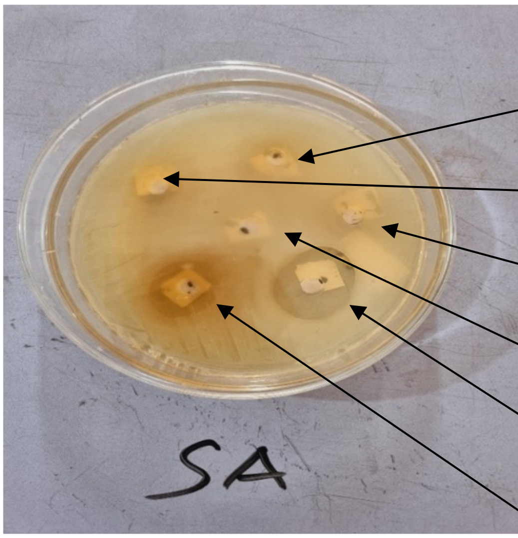

Figure 6: Zone of Inhibition of *S. aureus*

4. Discussion

Herbal mouthwash is prepared from the extract of leaves of neem, leaves of betel plant, rhizome of turmeric and pericarp of barro. The prepared herbal mouthwash is formulated in four different formulations F_1, F_2, F_3 and F_4 among them F_4 formulation is the best formulation as compared to the standard. The pH was found to be 5.7 which was found within the range of pH suitable for the mouthwash and the pH of the standard was 6.1 and the relative density & viscosity of the prepared herbal mouthwash were found to be 1.03 g/cm3 and 1.12 mPa. Sec respectively, which is easily pourable and completely poured into the container. Similarly, the relative density and viscosity of standard mouthwash are found to be 1.02 g/cm3 and 1.03 mPa.sec respectively.

The prepared herbal mouthwash is found to be highly effective in *C. albicans, S. aureus* and *E. faecalis.* Similarly, formulated herbal mouthwash is found resistant to *E. coli* (resistant), *Klebsiella pneumoniae* and *E. coli* (sensitive). The antimicrobial efficacy of the prepared herbal mouthwash is tested by using the agar well diffusion method and by measuring their zone of inhibition of the bacteria. The zone of inhibition of prepared mouthwash in *C. albicans (*26.33mm), S. aureus (20.66mm), *E. faecalis* (21.66mm) and zone of inhibition of standard in *C. albicans* (25.66mm), *S. aureus*(20.66mm), *E. faecalis* (21.00mm), [*E.coli*(resistant) (18.66mm)], *K. pneumoniae*(14.66mm), [E.coli(sensitive) (16.66mm)].

Prepared herbal mouthwash was found sensitive to *C. albicans, S. aureus* and *Enterococcus* and found resistant to *K. pneumoniae, E. coli*(resistant) and *E. coli* (sensitive). By observing the above zone of inhibition of the bacteria, we can say that our prepared herbal mouthwash is comparatively highly effective in *C. albicans*, *S. aureus* and *E. faecalis* as compared to the standard (chlorhexidine 0.2%). The F_4 formulation is the best alternative to chlorhexidine in candidiasis and Enterococcal infection. This formulation is found resistant in gram-negative bacteria and highly effective in gram-positive bacteria.

5. Conclusion

Results obtained in this study conclude that the extract of Neem leaves, leaves of Betel plant, rhizome of Turmeric and pericarp of Barro can be used to prepare polyherbal mouthwash as the mouth has antimicrobial activity against oral pathogens. The significant antimicrobial efficacy of the herbal mouthwash in this study is due to the presence of bioactive compounds in the plant extract. Therefore, the zone of inhibitory is shown by herbal mouthwash containing the above plant extract against *C. albicans, E. faecalis and S. aureus* proving that polyherbal mouthwash can be used to replace the use of chemical mouthwash in oral hygiene. As a result, formulated polyherbal mouthwash will help in the maintenance of oral hygiene.

Limitation and Recommendation

The study on the herbal mouthwash formulated from neem leaves, betel leaves, turmeric rhizome, and barro pericarp, while promising, has several limitations. It only examines a few formulations (F1 to F4), limiting the scope for finding potentially more effective alternatives. Additionally, a dose-dependent study was not performed, which is necessary to establish the optimal concentration of each extract. The study also lacks an evaluation of interactions between different plant extracts and excipients, which could affect the mouthwash's stability and efficacy.

To address these limitations, future research should include clinical trials to confirm safety and efficacy in a broader population. Dose-dependent studies are recommended to determine the ideal extract concentration. Exploring different extraction methods, such as aqueous or combined with ethanol, and assessing toxicity would further validate the herbal mouthwash's potential benefits.

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Drone and Electrical Resistivity Tomography (ERT) survey assisted slope instability risk assessment: A case study of Phyllitic landslide in Lesser Himalayas of Nepal

Buddhi Raj Joshi[1], Netra Prakash Bhandary[2*], Indra Prasad Acharya[3], Niraj K.C.[4]

[1] School of Engineering, Faculty of Science and Technology, Pokhara University, Kaski

[2] Faculty of Collaborative Regional Innovation, Ehime University, Matsuyama, Japan

[3] Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, TU, Nepal

[4] Institute of Engineering and Information Technology, Lumbini Technological University, Banke, Nepal

*Corresponding Email: netra@ehime-u.ac.jp

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Abstract

This study investigates the geological and geotechnical drivers of roadside slope failures along the Khanigaon Rural Municipality-2 (Likhu) road section in Nuwakot, Nepal, where excavation for road expansion has triggered landslides with significant socio-economic consequences. Geologically situated within the Seti Formation, the area consists of grey-greenish gritty phyllites and conglomerates, which were analyzed through a combination of Electrical Resistivity Tomography (ERT) and laboratory testing. The investigation identified a critical slip surface between 1 m and 6 m depth within Sandy Silt (ML) and Sandy Lean Clay (CL) soils characterized by low cohesion (1-11 kN/m^2*) and friction angles (*26.5-30°). *Stability modeling using the Limit Equilibrium Method (LEM) via Geo-studio and Slide2 software yielded an initial Factor of Safety (FoS)* (Geo-studio FoS=0.668, and Slide2 FoS=0.679) *as low as 0.668, confirming a high risk of soil slope failure despite rock stability. While the removal of loose materials was found insufficient to stabilize the site* (Geo-studio FoS=0.828, and Slide2 FoS=0.832*), a proposed integrated design comprising a reinforced concrete shear wall, concrete cribs, and 25 mm diameter anchor bolts successfully increased the FoS to 1.84. This research concludes that combining these structural reinforcements with bio-engineering vegetation offers a sustainable and technically sound solution for Himalayan infrastructure restoration.*

Keywords: *Geotechnical, Geophysical, Landslide, Roadside slope failure, Factor of safety.*

1. Introduction

Landslide is the downslope movement of soil, rock, and debris under the influence of gravity(Arisanty et al., 2022; Kolapo et al., 2022). Landslides can result in significant harm to social and economic infrastructure, and environmental elements. The occurrence of frequent catastrophic mass movements in the Himalaya that cause the loss of infrastructure and human lives, pose a threat to millions of people (Dubey et al., 2023; Sati & Kumar, 2022). Nepal Himalayas is a product of collision between Indian and Eurasian plates. The coupling effect of seismo-tectonic movement and Asian rainfall is generating numerous landslides in the Nepal Himalayas. The fragile geology, rugged topography and steep slope are favourable conditions for slope stability. Previous researchers (Dangi, et al., 2019; Sati & Kumar, 2022) entioned that the generation of landslide is mainly due to non-engineering road construction practices in Nepal. It is evident that the occurrences of landslide are widespread near the road. Tiwari and Hideaki (1998) have mentioned that Nepal should change its conventional landslide prevention practices to the appropriate one as landslides are increasing in recent years. The causes of landslides are interaction of intense rainfall, seismicity, change in water level, storm waves or rapid stream erosion, geology, land cover, slope geometry, groundwater saturation, slope cut, vegetation cover, and anthropogenic activities are the major factors for the landslide generation (Gariano & Guzzetti, 2016). The landslide occurs with the interactions of one or more triggering factors where one hazard triggers another or increases the probability of others occurring (Gill & Malamud, 2014). Rainfall and roadside slope cut-induced landslides are common and frequent triggering factors for landslides in the mountainous region. The previous study based on 55-years of landslides and rainfall record in the Himalaya suggested that many landslides in occurred under the influence of 5 hours to 90 days of rainfall durations (DAHAL, 2012).

The United Nations has emphasized disaster and climate risk reduction as a core component of sustainable development, integrating these priorities across all levels of planning through the Sustainable Development Goals (SDGs). Among natural hazards, landslides pose a serious threat to linear infrastructure, particularly road networks in mountainous and developing regions, where they frequently cause loss of life, disruption of mobility, and significant economic damage. The International Disaster Database (EM-DAT) reports that landslides account for approximately 4.9% of all natural disaster events and 1.3% of total fatalities between 1990 and 2015, with Asia experiencing nearly 54% of global landslide events (Guha-Sapir & Checchi, 2018). Roads are especially vulnerable due to slope cutting, inadequate drainage, and increasing exposure to intense rainfall and seismic activity. Globally, 55,997 fatalities were recorded from 4,862 landslide events between 2004 and 2016, many of which were associated with transportation corridors (Froude & Petley, 2018). In Nepal, the 25 April 2015 Gorkha earthquake triggered over 21,000 landslides, severely damaging strategic road links and isolating communities (Valagussa et al., 2021). Furthermore, regional landslide inventories developed using remote sensing techniques in Nepal's Far-Western Region identified 26,350 landslide events, highlighting the high susceptibility of road-adjacent slopes over extended periods (Muñoz-Torrero Manchado et al., 2021). These findings underline the critical need for systematic assessment, monitoring, and mitigation of landslide hazards along road sections to enhance infrastructure resilience and ensure sustainable transportation development.

Nepal is a predominantly mountainous country with high tourism potential and an increasing demand for rapid transportation infrastructure development. However, unplanned and accelerated road construction activities have significantly contributed to slope instability, posing serious challenges to the sustainability of road networks. In particular, irrational hillslope excavation during road construction has increased the susceptibility of slopes to shallow rainfall-induced landslides. Non-engineered road construction practices—characterized by informal excavation methods without proper planning, design, drainage, or slope protection—have substantially amplified landslide risks across Nepal (Pradhan et al., 2022).

Rainfall-induced landslides along road cut slopes are further influenced by continuous excavation and modification of natural slopes. The reactivation of ancient landslides often manifests as retrogressive movement caused by prolonged engineering excavation, which results in rock mass unloading and degradation of the mechanical properties of the soil–rock mixture (He et al., 2019). From a geotechnical perspective, rainfall infiltration reduces soil shear strength through increased hydrostatic pressure, dynamic loading, and the loss of matric suction (Kim et al., 2015). Previous studies have demonstrated that prolonged or intense rainfall increases the degree of saturation in near-surface soils, leading to a reduction in suction and shear strength and ultimately triggering slope failure (Islam et al., 2021).

In the present study area, the landslide was triggered by the combined effects of irrational road construction practices and intense rainfall. Although an immediate remedial measure in the form of a gabion wall was implemented, it failed to adequately support the backfill material, resulting in outward bulging and continued instability. This failure highlights a critical limitation in current slope management practices. Existing guidelines issued by the Government of Nepal for rural road slope excavation lack site-specific geological and geotechnical characterization, limiting their effectiveness in landslide risk mitigation (Paudyal et al., 2023). Accurate estimation of slip surface depth and overburden thickness is therefore essential for reliable slope stability assessment and effective design of stabilization measures.

Reliable subsurface characterization can be achieved through the integration of geophysical and geotechnical investigations, such as electrical resistivity tomography (ERT) combined with laboratory testing, which together provide comprehensive information on geological structures and material properties (Dezert et al., 2019). Similar integrated approaches have successfully enhanced the understanding of landslide mechanisms in complex terrains, such as in Chira town, Ethiopia (Pasierb et al., 2019). However, many studies have not sufficiently examined the relationship between soil types and landslide occurrence, nor have they adequately evaluated the effectiveness of various remediation measures.

For sustainable infrastructure development, it is essential to incorporate geological, geotechnical, and site-specific parameters into slope stabilization and ecological restoration design. Although geotechnical investigation–based preventive measures have been proposed for debris landslides along unstable road cut slopes in the Himalayan region of India (Prakasam et al., 2020), detailed evaluation of subsurface conditions and material properties is often lacking. Field-based evidence suggests that road cut slopes excavated during the dry season remain temporarily stable due to soil suction, but infiltration of monsoon rainfall leads to saturation at shallow depths, resulting in suction loss and reduced soil strength, ultimately causing slope failure (Meena & Piralilou, 2019).

In this study, slip surface identification using electrical resistivity tomography (ERT), laboratory-based evaluation of soil properties for bearing capacity assessment, detailed geological mapping, and high-resolution topographic surveying were carried out. Slope stability was analyzed by estimating the Factor of Safety (FoS) using the Limit Equilibrium Method (LEM) based on the Mohr–Coulomb failure criterion (Ismail et al., 2021). The analyses were performed using GeoStudio (SLOPE/W) and Slide2 software, incorporating geotechnical parameters obtained from laboratory tests and topographic data derived from a high-resolution Digital Terrain Model (~30 cm).

In addition to structural stability, ecological restoration of roadside slopes must be scientifically evaluated to ensure long-term sustainability. Although bioengineering techniques are widely recognized for erosion control, slope stabilization, and ecological restoration (Raut & Gudmestad, 2017), restoration effectiveness varies spatially and temporally (Wang et al., 2021). Incorporating indigenous knowledge and locally adapted vegetation can help preserve site originality and accelerate restoration outcomes. Despite their potential, integrated geophysical–geotechnical approaches combined with ecological restoration strategies remain underutilized in the Nepalese context.

Therefore, this study aims to investigate the complex interaction between rainfall and road cut slope instability in the Nepal Himalaya by analyzing a representative landslide case from central Nepal. The study integrates drone-based topographic surveying, electrical resistivity tomography, geotechnical investigation, numerical slope stability analysis, and bioengineering-based restoration measures to propose sustainable solutions for roadside slope stabilization

1.1 Study Area

The landslide is located along the road section of Likhu Rural Municipality Ward Number-2 of Nuwakot District of Nepal (Latitude: 27°56'03.61" N, and Longitude: 85°11'51.33" E , and elevation of 1027 m from a.s.l.) (Fig.1). In geological terms, the landslide has 160 - 180° (SE-S) failure orientation plane with failed slope angle of head to crown is ~ 34°. Before 2021 AD the slope remained relatively stable over time though the road section was constructed during 1995 AD. The problem was encountered due to rainfall and toe cutting during road extension, resulted in the roadside slope failure in the year of 2021 AD. Furthermore, the gabion structure was constructed in 2022 AD, further excavation during the trenching of the foundation lead to the failure of the soil mass in the form of landslide.The landslide is in irregular shape length of about 65 m and breadth is about 80 m which covers the area of about 5000 m^2.

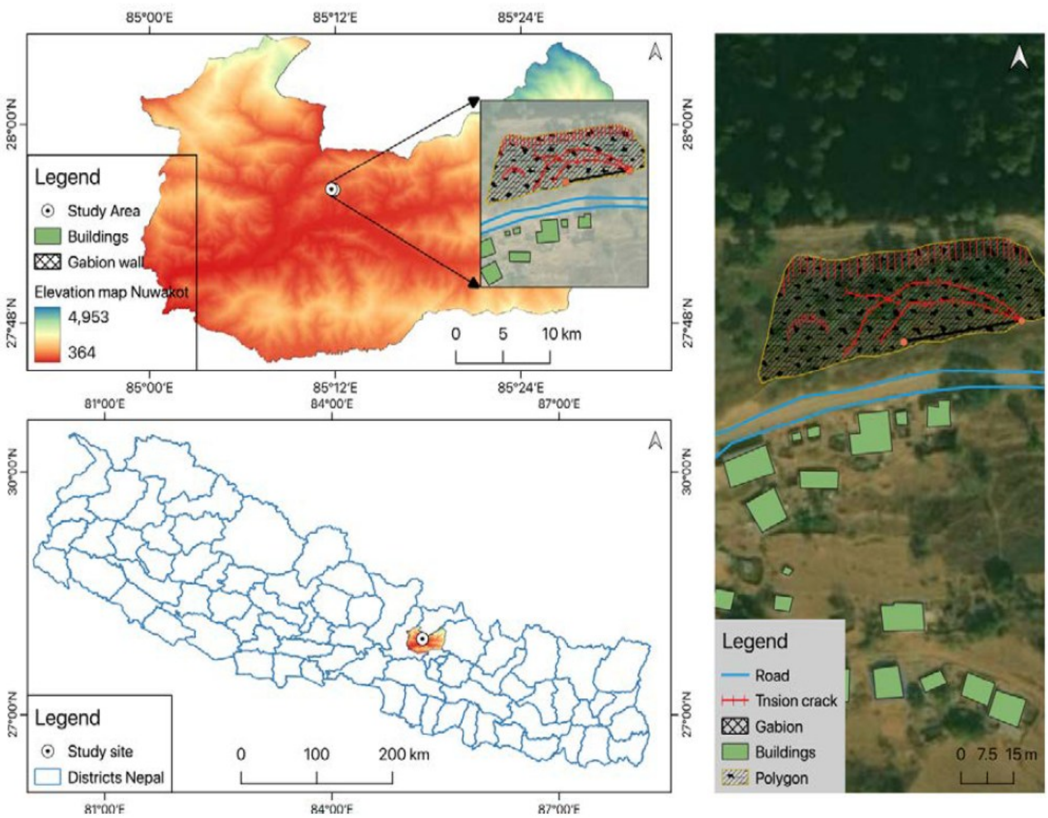


Figure 1: Locational Map of the study area.

1.2 History of the landslide:

Nuwakot district also suffered from the earthquake triggered landslide and earthquake-induced hazard map has been prepared though the proposed site was not vulnerable during that period (Dangi et al., 2019; Joshi et al., 2017). The aerial photographs of the area from 2021 AD suggest that the area is relatively stable and landslide events are recent. The image shown in Figure 1 indicates that there is an existing road section that was constructed around 1995 AD and had remained relatively stable over time. The problem was encountered during the road extension which involves the toe cutting of previously steadied slope, resulted in the roadside slope failure in the year of 2021 AD. Furthermore, the gabion structure was constructed in 2022 AD, further excavation during the trenching of the foundation lead to failure of the soil mass in the form of landslide.

Figure 1: Figure shows the aerial photograph of the study area

2. Methodology

2.1. Geology of the study area:

The study area lies within the Upper Pre-Carabean to late Paleozoic era, especially in the Seti formation (English et al., 2000). The lithology of the area consists of Grey greenish grey gritty phyllites gritstones with conglomerates with partly intruded massive white quartzite in upper part. The following figure highlights the regional geology of the area (Figure 3).

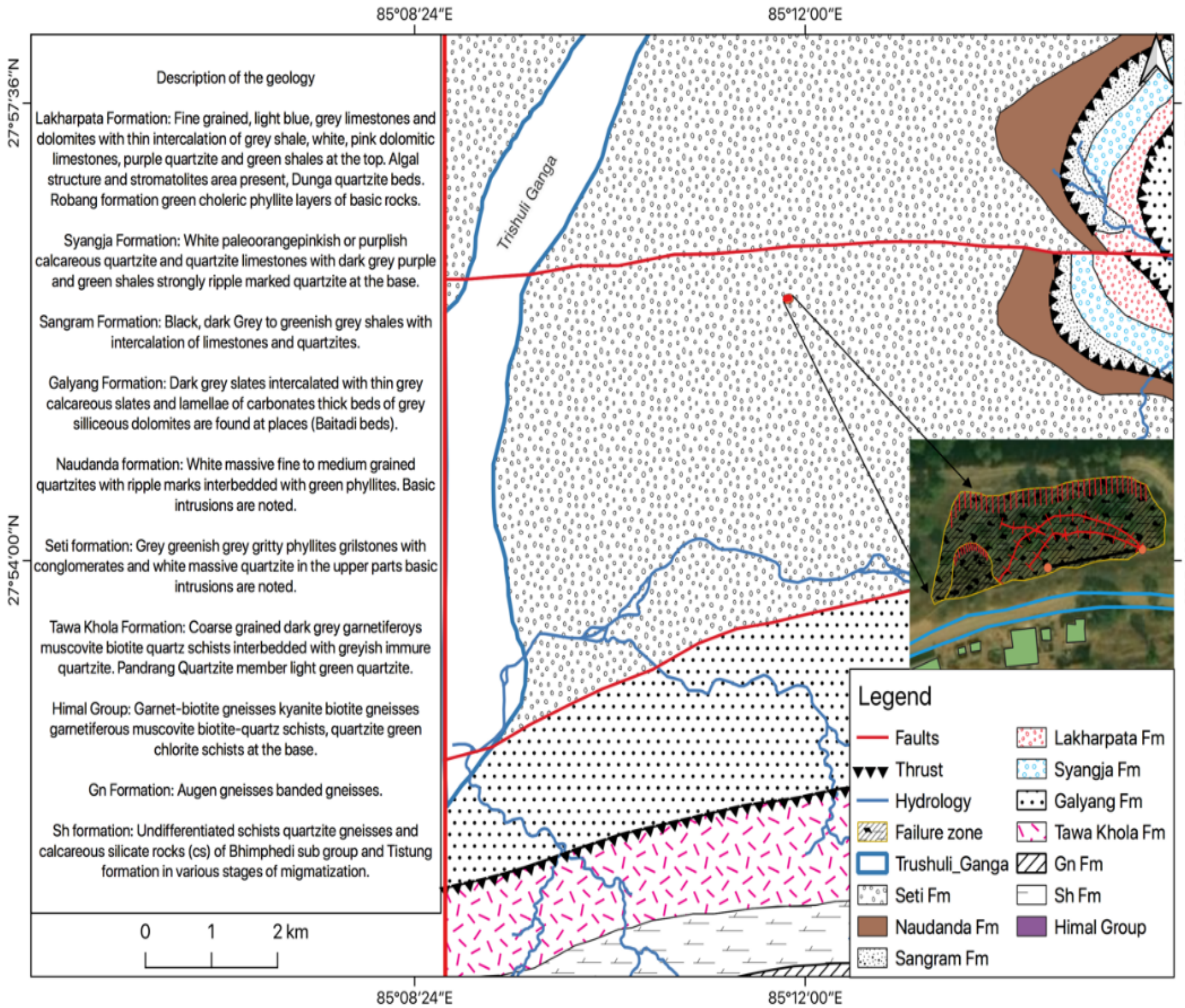


Figure 3: The geological map of the study area (inventory on the zoom)

2.2 Ortho-photo interpretation:

The unmanned aerial vehicle (UAV) is utilized for the monitoring of the landslide and produce high-resolution digital elevation models (DEM), orthophotos, and aerial photos based density point clouds obtained from structure-from-motion (Eker et al., 2018; Tian et al., 2020).The UAV captured images that were processed in Pix4Dmapper and obtained Ortho-photo and Digital Terrain Model (DTM) having a resolution of 0.3 meters (30 cm). The houses observed in the Ortho-photo were digitized and the linear features such as the drainage and debris flow channel were delineated. The contour of the terrain was prepared from the DTM accordingly the cross-sectional profile of the terrain was constructed, and road alignment was overlaid.

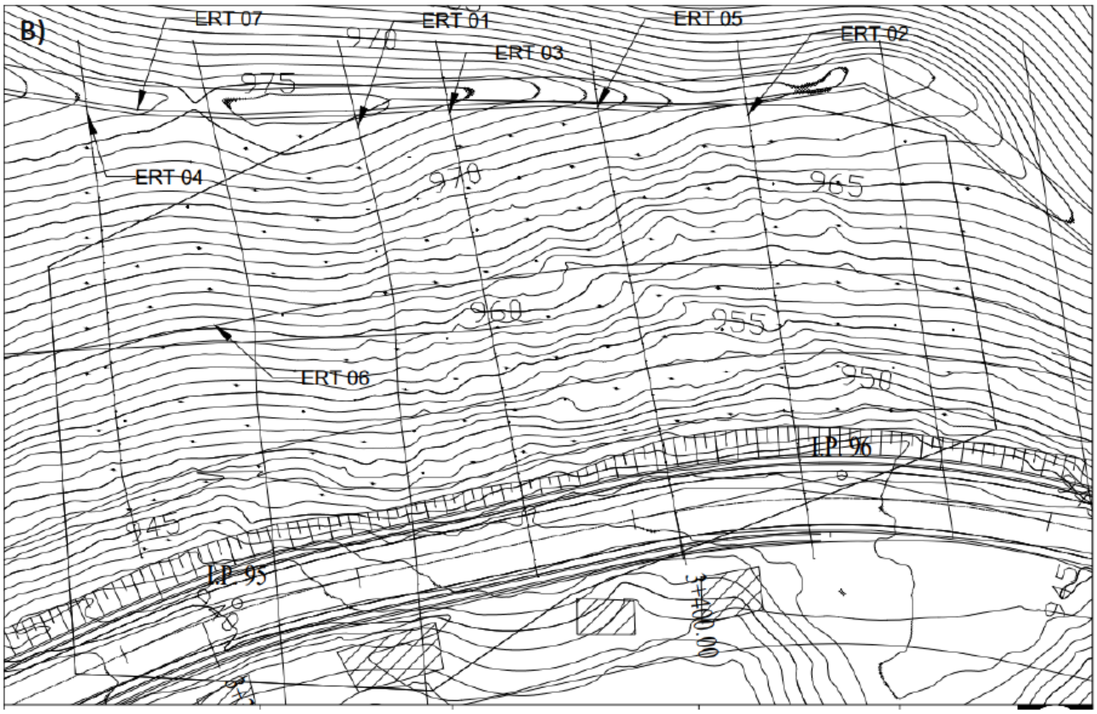


Figure 4: A) Orthophoto of landslide and B) contour map aligned with the designed road.

2.3 Electrical Resistivity Tomography (ERT):

The geophysical survey based on ERT is useful to identify the slip surface and groundwater table which can be utilized for the stability analysis (Haider et al., 2023;

Sigdel & Adhikari, 2020). The ERT survey was conducted with WDJD-4 Resistivity/IP equipment. The District Map, GPS, Drone, Photographic Camera, Brunton Compass, and Geological Hammer were used during the data collection. Due to the undulated site conditions, topographic correction has been adopted for the ERT profiling. Field data were gathered to obtain a continuous coverage of the sub-surface along the line of investigation which illustrates different resistivity zones due to presence of different lithological types (Figure 5).

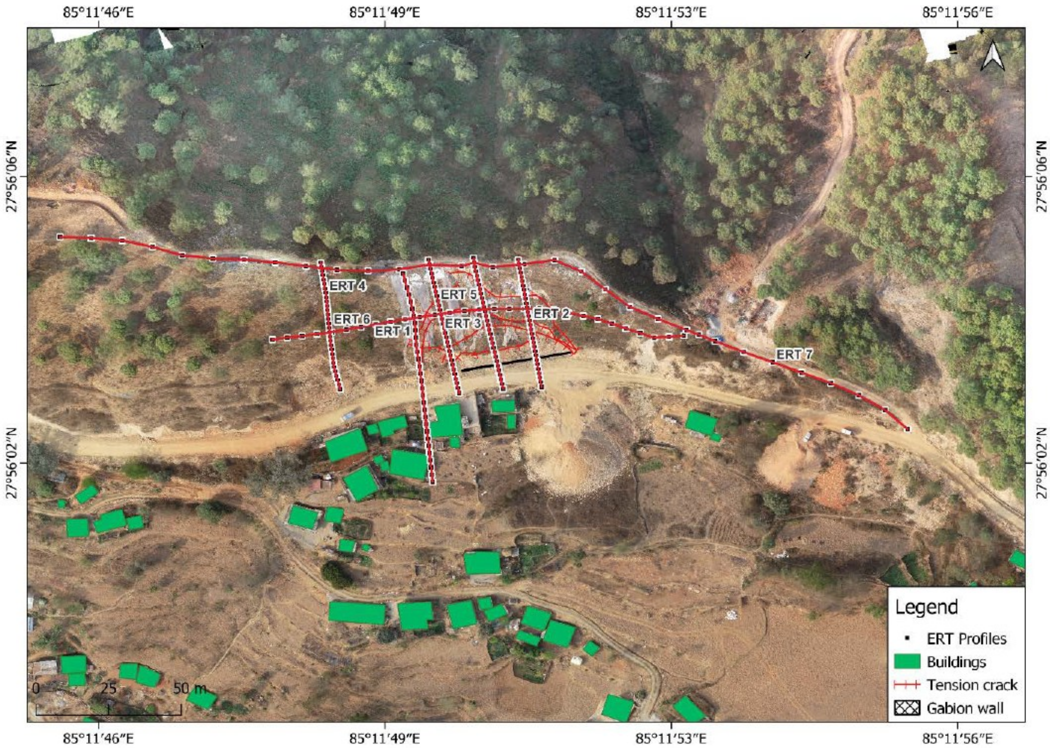


Figure 5: ERT profiles conducted in the study area.

The detail of the ERT profile that has been taken for the analysis has been presented which illustrates the general background of the ERT survey (Table 1)

Table 1: Table shows background of ERT Survey

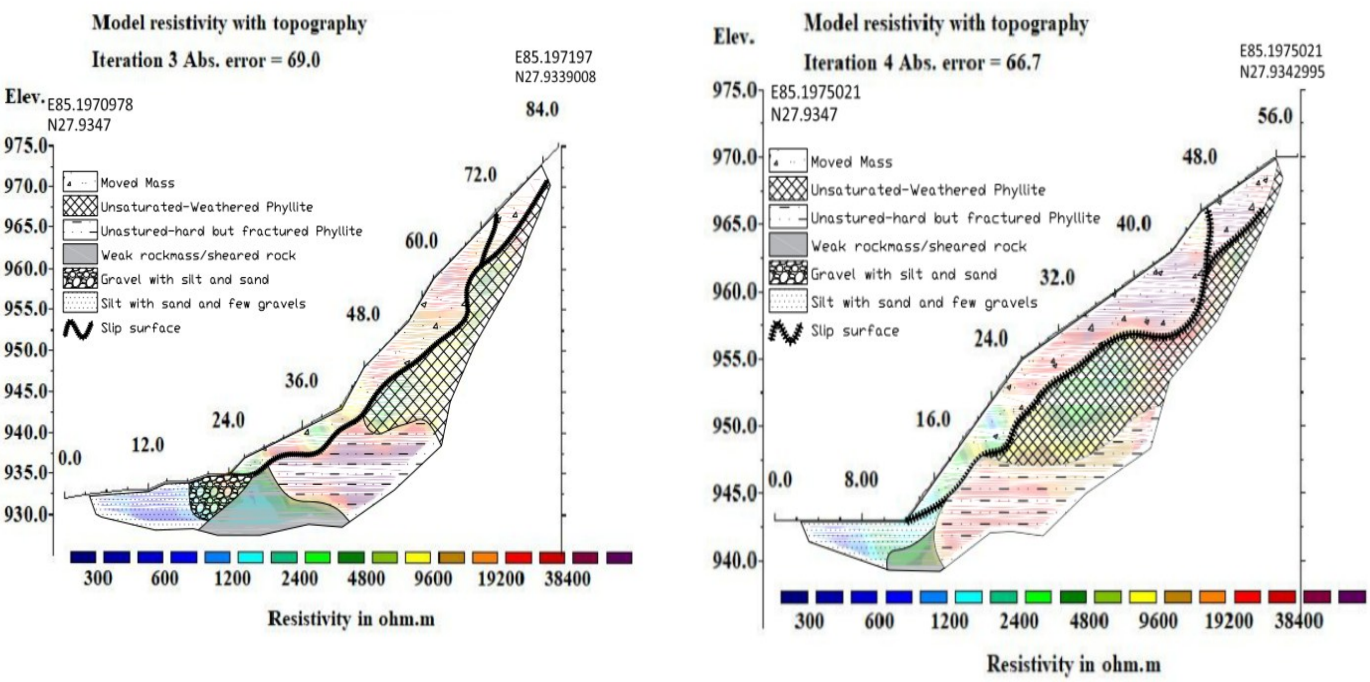
ERT profile	Length of ERT (m)	Thickness of Moved mass (m)
1	87	2-6
2	58	1-5
3	58	1.5-5
4	58	1.5-4
5	58	2.5-6

3. Result and Discussion

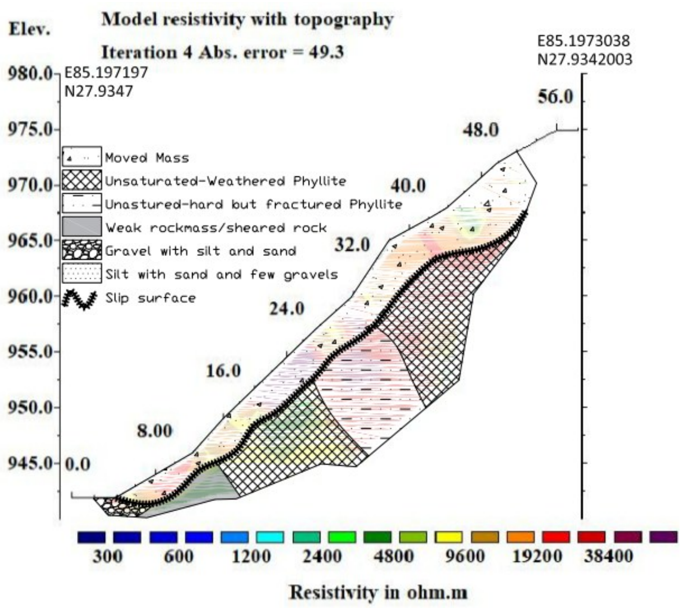
Field investigation and orthophoto interpretation revealed the presence of tension cracks and distinct lines of movement across the slope. The terrain slope varies between 32° and 42°, with a maximum elevation difference of approximately 37 m. The road is located on the south-facing ridge of the hill, where the slope has become unstable due to the absence of persistent groundwater conditions, whereas the north-facing slope remains relatively stable, as shown in Figure 4.

3.1 Interpretation of ERT profile

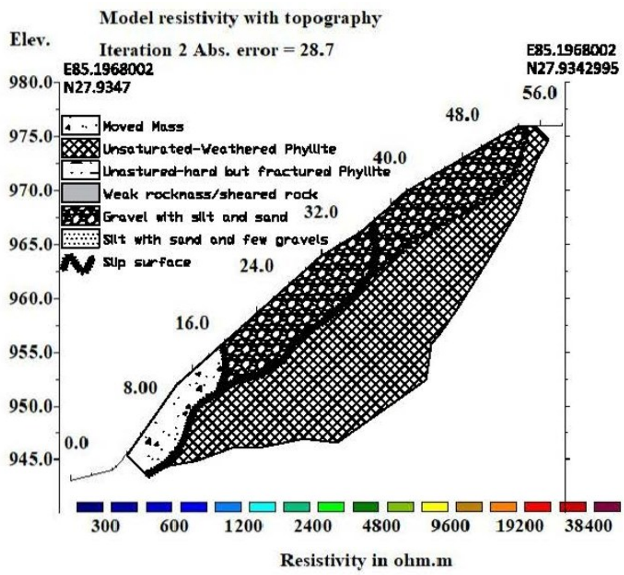
The very low resistivity zone <1200 Ohm-m which represents silt with sand and less gravel. The low resistivity zone 1200 to 2400 Ohm-m which represents weak rock mass or sheared rock. The moderate resistivity zone 2400 to 9600 Ohm-m represents unsaturated weathered rock. The high resistivity zone 2400 to 38400 Ohm-m denotes the moved mass (unsaturated silt-fine sand with gravels and gravels with silt-sand), and very high resistivity zone >38400 Ohm-m denotes unsaturated hard to fractured rock. The similar results were presented in the previous research conducted in Ngozumpa glacier of Nepal (Thompson et al., 2017). The detail sub-surface condition and slip surface estimation has been presented below (Figure 6).



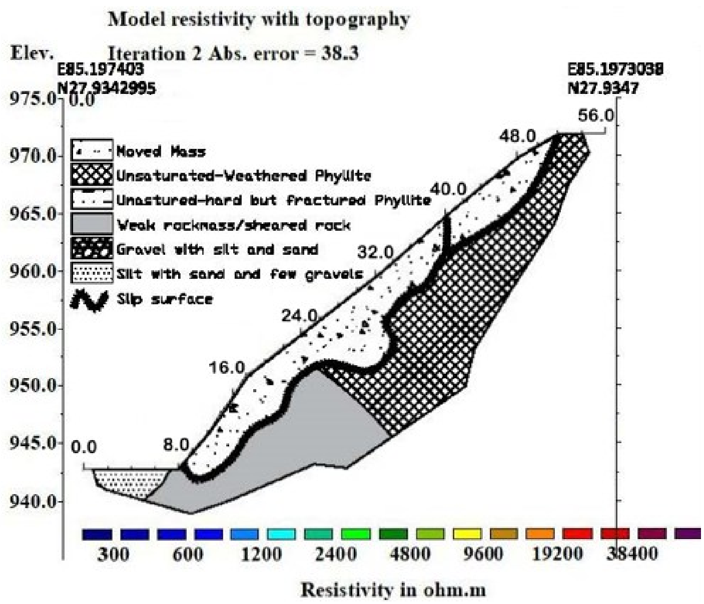
(a) (b)



(c)



(d)



(e)

Figure 6: a) ERT profile 1 b) ERT profile 2 c) ERT profile 3 d) ERT profile 4, and e) ERT profile 5 of the study area with slip depth interpretation.

3.2 Geotechnical Investigation:

The soil lithology of the area is dominated by fine grained silty and clay minerals and rock lithology is dominated by the metamorphic rock Phyllites. Slope stability analysis was performed to determine the failure mechanism of soil and create a stable slope at the proposed site. The existing slope characterization and strength properties of the soil were determined from fieldwork and laboratory analysis. Geotechnical properties of the soil samples collected from the following locations have been derived from the laboratory testing (Figure 7).

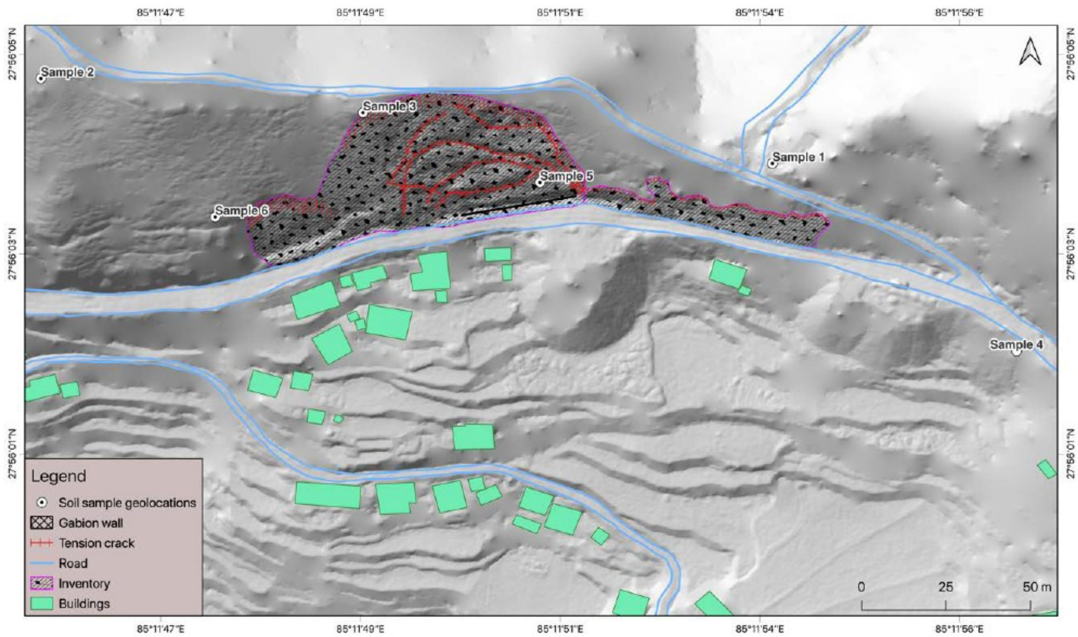


Figure 7: Inventory map (with hill-shade overlay) shows the location of soil samples collected.

The following laboratory tests have been carried out to assess the physical properties of the soil which are critically analysed for the stability analysis and design.

Table 2: Type and number of laboratory tests performed in this study.

Test	Test frequency	Standard	Significance of the study
Sieve analysis	6	IS: 2386 (Part 1)-1963	Particle size distribution of coarse-grained soil having particle size of<4.75->0.075mm
Hydrometer	6	IS: 2720 (Part 4)	Particle size distribution of fine-grained soil having particle size of<0.075mm
Natural Moisture Content	6	IS: 2720 (Part 2)	Moisture content in the soil at natural condition

Atterberg Limits	6	IS: 2720 (Part 5)	Evaluate the critical water contents of fine-grained soils before changing its state.
Specific gravity	6	IS: 2720 (Part 3)	Evaluation of porous behavior of soil for the estimation of phase relationship and FoS
Direct Shear	6	IS: 2720 (Part 15)-1986	To find Cohesion (c), Angle of Internal Friction (Ø) and Density of soil (γ) that are used for FoS calculation
Hydraulic Conductivity	1		

3.2.1 Index properties of soil:

According to the Unified Soil Classification System (USCS), the soil is Sandy silt with and without gravel of ML and Sandy Lean Clay with Gravel or sand of CL group that contains 5-26% clay (Table 3 and Table 4). The liquid limit of soil samples resembles value ranges from 38-47% which indicates soil sample 2, and 5 losses its shear strength and becomes liquid-like at a lower water content than soil samples S1, S3, S4 and S6 (Table 3). The plastic limit of the soil ranges from 20-27% except soil sample 5 which indicates that there is no clay content (Table 3).

Table 3: Index properties of soil samples.

Soil Sample	% passing 0.075mm	% passing 0.005mm	D_{60}	D_{30}	D_{10}	C_u	Atterberg Limit (%)			USCS* Soil Classification	
							LL	PL	PI	Group	Description
1	62.14	32.000	0.052	-	-		43	27	16	ML	Gravelly Silt
2	78.59	34.38	0.022	-	-		40	26	14	ML	Silt with Sand
3	50.15	21.50	0.080	-	-		45	26	19	ML	Sandy Silt with Gravel
4	44.78	17.00	1.25	0.0015	0.077		42	20	22	CL	Sandy Lean Clay with Gravel

5	30.52	7.00	2.00	0.006	0.025	38	NP	NP	ML	Sandy Silt with Gravel
6	53.11	15.00	0.60	0.005	3.33	47	27	20	CL	Gravelly Lean Clay with Sand

Notations: LL=Liquid Limit, PL=Plastic Limit, and PI=Plasticity Index

Table 4: Index properties of soil samples.

Soil Sample	**Sieve Analysis (%)**			
	Gravel	**Sand**	**Silt**	**Clay**
1	23.31	14.55	40.14	22.00
2	4.61	16.80	52.59	26.00
3	19.71	30.15	32.15	18.00
4	25.38	29.84	32.78	12.00
5	31.93	37.55	25.52	5.00
6	25.29	21.60	38.11	15.00

Grain size and their nomenclature: 50mm - 4.75mm is considered as Gravel, 4.75mm - 0.075mm is considered as Sand, 0.075mm - 0.002mm is considered as Silt, and < 0.002mm is considered as Clay.

3.2.2 Specific gravity:

The specific gravity of the soil ranges from 2.592 to 2.827 which indicates that the Sandy Clay has minimum value and Sandy Silt with Gravel has maximum value (Table 5).

Table 5: Specific gravity of soil

Soil Sample	Specific gravity of Soil Sample
1	2.719

2	2.712
3	2.690
4	2.708
5	2.827
6	2.592

3.2.3 Strength parameters:

Direct Shear test was carried out on 6 umber of soil sample samples retrieved from different locations. The graph between normal and shear stress has been plotted (Figure 8). The friction angle value indicates that the friction angle of sandy soil decreases with increase in confining pressure, thus implying a circular soil failure envelope. The typical sandy soil has negligible shear strength at zero confining stress which can generally be modelled with a cohesion value of zero (Sigdel & Adhikari, 2020).

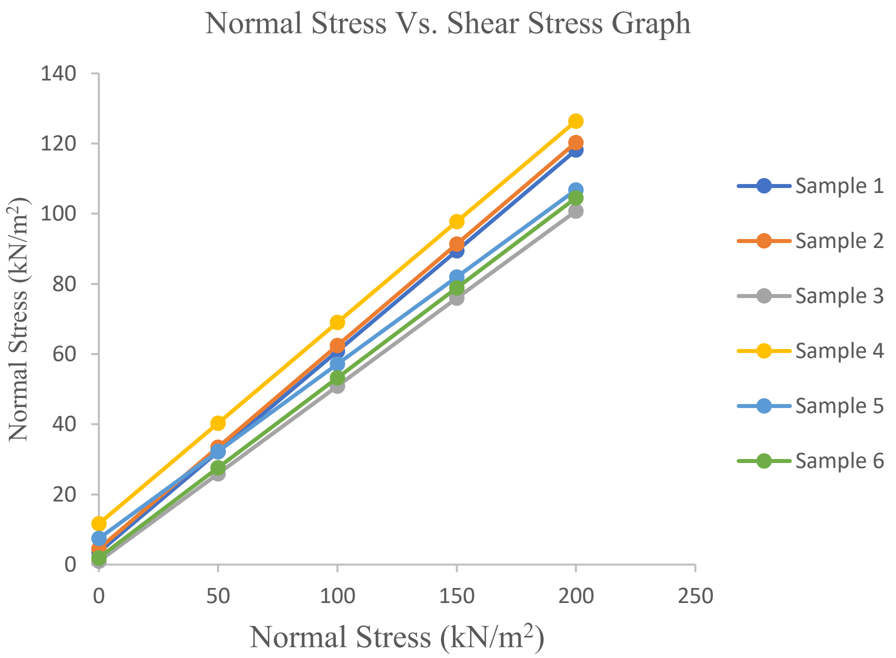


Figure 8: Normal stress vs. Shear stress curve for 6 different locations.

The cohesion (c) and angle of internal friction (ϕ^{o}) of the soil was found in the range of 1.0 to 11.60 kN/m^2 and 26.5^{o} to 30^{o} respectively which can be tabulated in the following table 6.

Table 6: Geotechnical parameters of soil samples.

Soil Sample	Natural Moisture Content (NMC %)	γ_{dry} (kN/m^3)	γ_{bulk} (kN/m^3)	Direct Shear	
				c (kN/m^2)	ϕ°
1	27.32	12.28	15.635	3.6	30.0
2	24.13	12.13	15.057	4.5	30.0
3	29.97	14.25	18.521	1.0	26.5
4	24.21	15.23	18.917	11.6	30.0
5	17.78	15.49	18.244	7.4	26.5
6	24.01	13.02	16.146	2.0	27.0

Natural moisture content of the soil varies from a minimum value of 17.78% to a maximum value of 29.97%. Bulk unit weight determination on selected samples of soil shows the values in the range of 15.057kN/m3 to 18.917kN/m3 and that of dry density value ranges from 12.12kN/m3 to 15.49 kN/m3. Unit weight, cohesion, and friction angle parameters are considered for the factor of safety analysis.

3.3 Slope Stability analysis:

Slope stability analysis is the core aspect of the research so that slope failure can be handled to ensure the safety of the infrastructure as well as the people living in the vicinity. The stability analysis has been done by adopting two approaches which includes a) rock slope stability analysis, and b) soil slope stability analysis.

3.3.1 Rock slope stability analysis:

The DIPs software has been adopted to estimate the rock slope stability which employs the graphical approach for the analysis. It analyses the stability of the slopes with complex geometries that include multiple dip direction and variable dip angles. The software also incorporates different methods, including limit equilibrium and kinematic analysis, to determine the factors influencing slope stability (Rahman et al., 2023). Limit equilibrium analysis assumes the equilibrium between the driving and resisting forces acting on a slope. On the other hand, kinematic analysis is useful for identifying potential failure modes and their associated geometries. The analysis of 30 vectors for the Phyllite rock in the area shows that the area has low possibility of plane failures. The hill slope is placed concordant to the bedrock dip. However, the steeper terrain is not in the daylight for the failure, indicated that the slope failure is mainly due to the toe excavation and the failure material is overlaying soil and detached rock blocks (Figure 9).

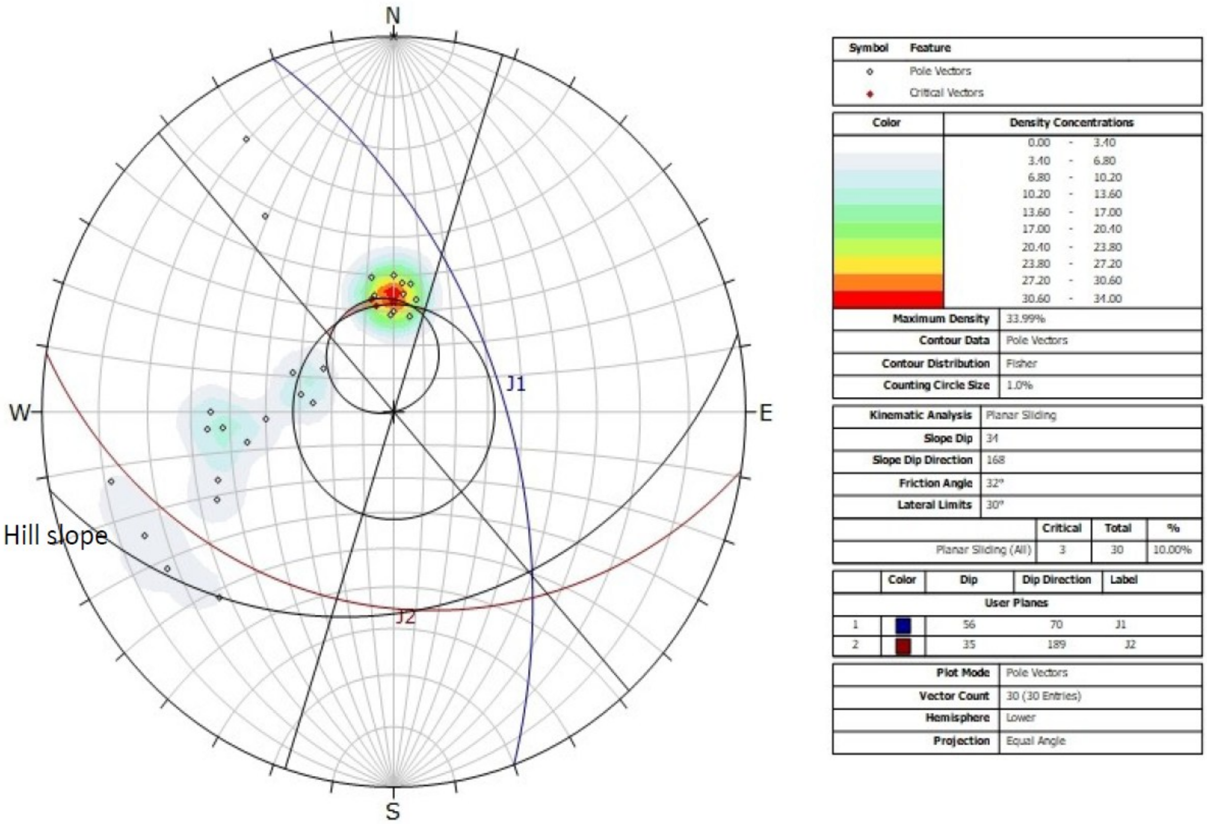


Figure 9: Rock slope stability analysis

3.3.2 Soil Slope stability:

The slope stability was assessed using the Geo-Studio Software (Package SLOPE/W) and Slice2 software that works on limit equilibrium model (LEM) for which laboratory analyzed geotechnical parameters obtained from the laboratory testing and topographical parameters obtained from high resolution Digital Terrain Model (~30 cm) were used. The Geo-studio and Slope2 software packages have been widely accepted software for the slope stability analysis using Bishops' method for the estimation of factor of safety (Geo-Studio, 2012; Salmasi et al., 2019; Su et al., 2022). The stability model was implemented for the soil profile (Figure 10, and Figure 11) depicted that the slope is unstable which has FoS less than 1 (Geo-studio FoS=0.668, and Slice FoS=0.679).

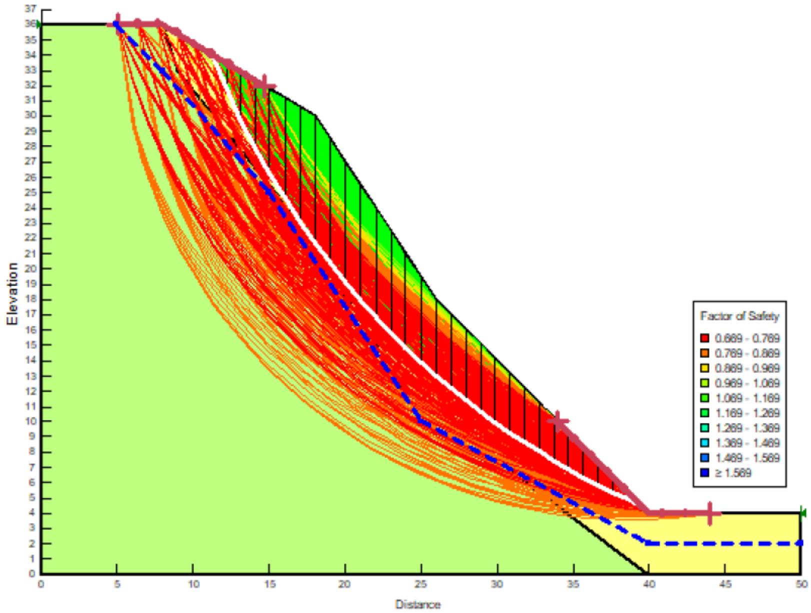


Figure 10: Limit Equilibrium Analysis (FoS) of the slope profile based on Geo-studio.

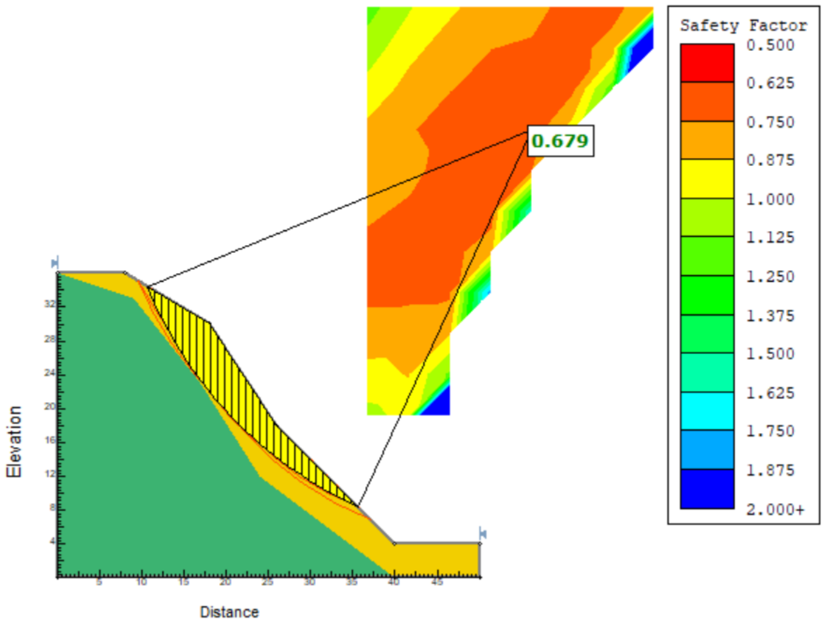


Figure 11: Limit Equilibrium Analysis (FoS) of the slope profile based on Slice2.

To achieve the roadside slope stable, firstly a model was constructed by removing the loose materials on the slope (i. e. removing the surcharge load) and checked the FoS with a 2-meters bench in the middle of the slope without anchor bolt. The model depicted FoS which is still lower than 1 indicates that the slope is still unstable (Geo-studio FoS=0.828, and Slide2 FoS=0.832).

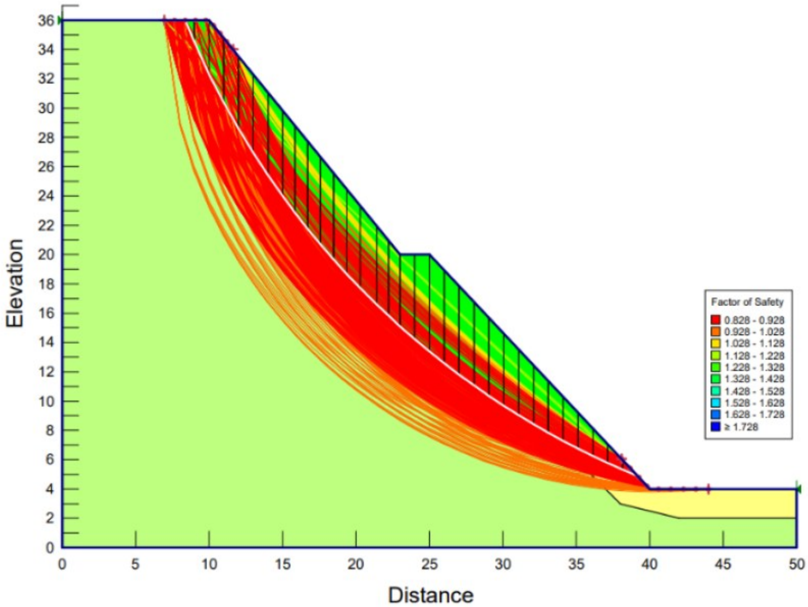


Figure 12: Limit Equilibrium Analysis (FoS) of the slope profile based on Geo-studio.

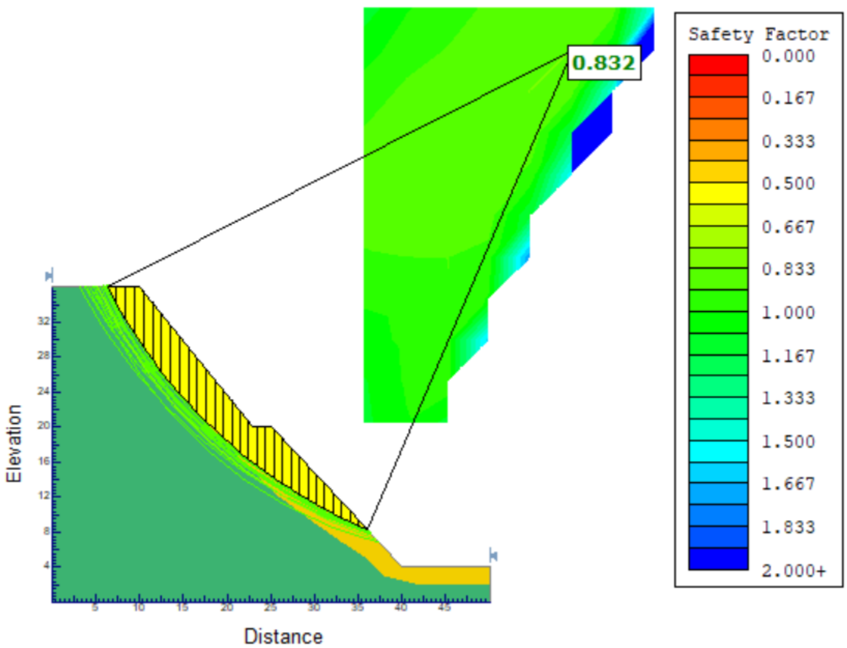


Figure 13: Limit Equilibrium Analysis (FoS) of the slope profile based on Slice2.

The above models clearly indicated the requirement of the Anchorage. Finally, a Geo-studio-based model was set for the reinforced concrete shear wall (Height=1.8 m, and Length=81 m), concrete crib (Size= 0.3m×0.3 m, and total length=1843m), and anchor bolts (Size= 25 mm diameter, bond length=3 m, and numbers=182) for 150kN/m^2 point load. The appropriate design-based stability analysis indicates that the slope became stable (FoS=1.84) (Figure 14).

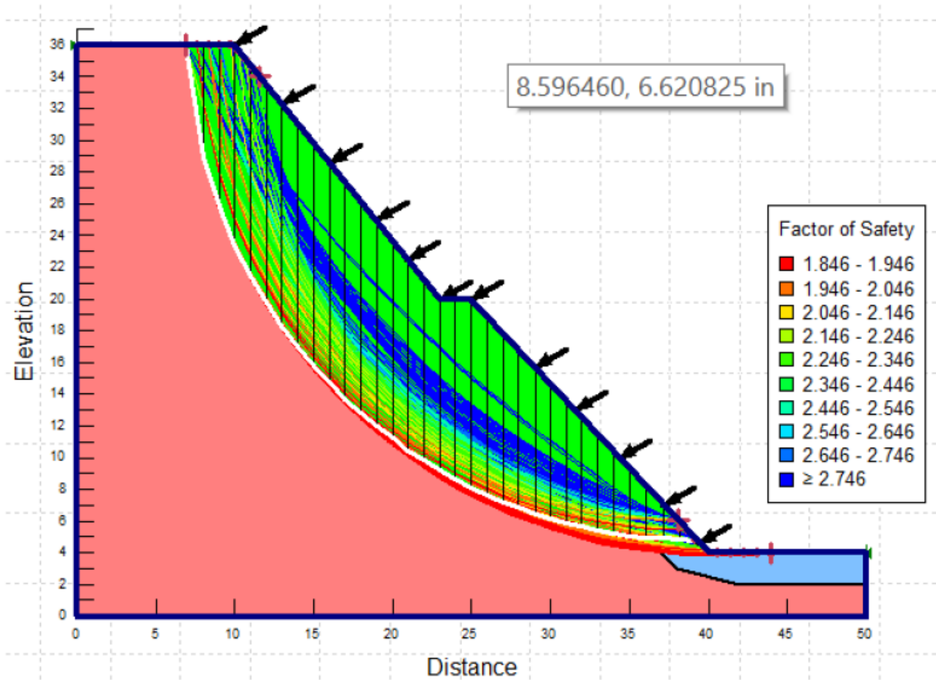


Figure 14: FoS Model with the point load of 150 kN/m^2.

4. Conclusions

The landslide induced by roadside slope cut along the road section of Khanigaon Rural Municipality-2, Likhu of Nuwakot district of Nepal is shallow and a non-uniform circular slip surface in nature. The field and laboratory investigations have been carried out to analyse the geological and geotechnical aspects of the landslides. Filed investigation reveals that there are no chances of rock slope failure, but the slope is unstable due to soil slope failure. The slope stability analysis of the existing condition reveals that the slope is not stable having the factor of safety (Geo-studio FoS=0.669, and Slide2 FoS=0.679). A model was constructed by removing the loose materials on the slope (i. e. removing the surcharge load) and checked the FoS with a 1.5-meters bench in the middle of the slope without anchor bolt depicted (Geo-studio FoS of 0.828, and Slide2 FoS=0.832), which is lower than 1 indicates that the slope is still unstable. The proposed Geo-studio-based model clearly indicates that there is the requirement of the anchorage system and construction of shear wall, concrete crib, and rock nail system has been proposed to make the slope stable. To withstand 150kN/m^2 point load 10-12 number of anchor bolts having length of 3m are required which suggest that the improved slope stability with FoS of 1.84. Based on the result analysis and the comprehensive design the following preventive measures are recommended for the slope stability.

a. Removal of loose earth material: It is suggested to remove the loose earth material from slope which results in the reduction of the surcharge load thereby increasing the FoS. The modelling also indicated that the removing of the loose earth material increases the FoS from 0.68 to 0.82.

b. Construction of RCC shear wall: Steel Reinforced Cement Concrete (RCC) shear wall is proposed along the hillside or the toe of the slope parallel to the roadside drainage. The share wall is 81-meter in length and 1.8-meter high along with the height of the foundation. A shallow shear wall has been proposed to reduce the cost and to support the concrete crib to be built on the hill slope.

c. Construction of concrete crib and anchors: The slope to be protected is long and the slope varies from 33-40 degrees below which settlement is located. Field Observation, modelling and design work depicted that the concrete crib along with the rock bolt is the best option in terms of cost, stability, and sustainability.

d. Vegetation: The restoration of the natural environment and ecology can be achieved by applying vegetation in the free space available between the cribs of the slope protection system.

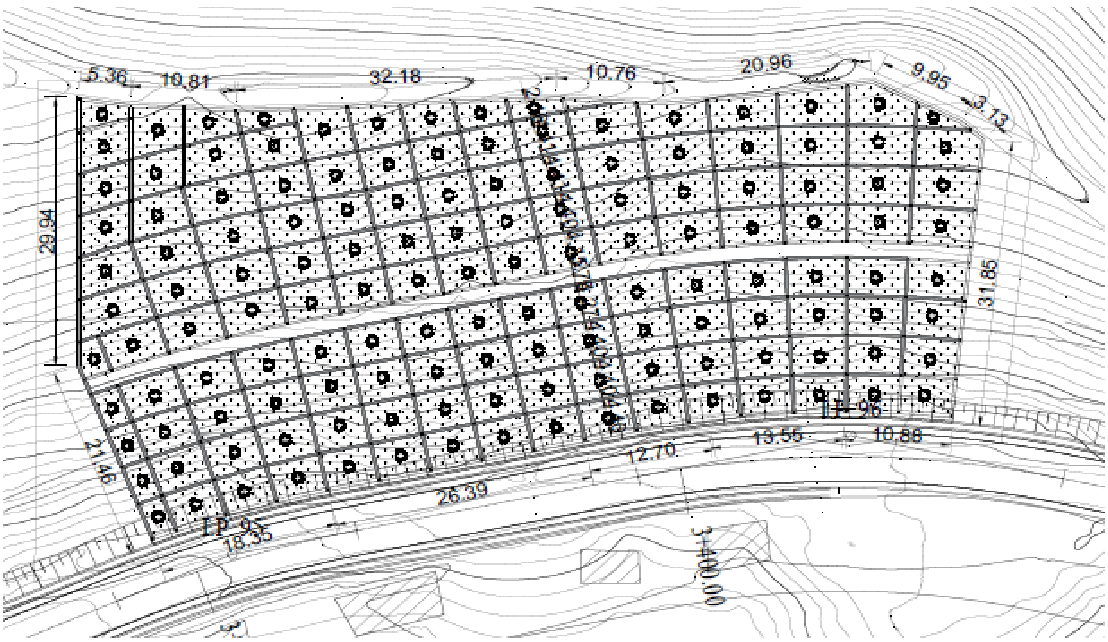


Figure 15: Plan for landslide structure

Data Availability Statement:

The data that support the findings of this study are available to the main author, upon reasonable request.

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Competing Interests Disclaimer

Authors have declared that no competing interests exist. The data used for this research are commonly and predominantly used data in our area of research and country. There is absolutely no conflict of interest between the authors and other stakeholders because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by any authorities rather it was funded by the personal efforts of the authors.

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PLAXIS 3D Simulation and Field Validation of Static Load Behaviour for Bored Pile Foundations: A Comparative Study on Technical Accuracy and Efficiency

Aashish Deo[1], Manish Ayer[2], Niraj K.C.[3]*, Narayan Ghimire[2]

[1] Mandan Bhandari College of Engineering, Pokhara University, Urlabari, Nepal

[2] Institute of Engineering and Information Technology, Lumbini Technological University, Banke, Nepal

[3] Institute of Engineering and Information Technology, Lumbini Technological University, Banke, Nepal

*Corresponding Email: dean.niraj@ltu.edu.np

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Abstract

This study investigates the static axial load behaviour of bored cast-in-situ pile foundations through three-dimensional numerical simulation using site-specific geotechnical data obtained from the Kamal Khola Bridge under the SASEC Highway Enhancement Project, Nepal. Although static load testing (SLT) provides reliable pile performance assessment, it is often time-consuming and costly; therefore, this research evaluates the applicability of finite element modelling using PLAXIS 3D as an efficient and economical alternative. Detailed subsurface characterization, including borehole logs, standard penetration test (SPT) data, and engineering soil parameters at the pier location, was incorporated into the numerical model. The soil was simulated using the Mohr–Coulomb constitutive model, while the pile was modelled as a linear elastic material. A mesh sensitivity analysis was conducted using very fine, fine, medium, coarse, and very coarse mesh configurations to examine their influence on prediction accuracy. The numerical results were validated against field SLT data comprising load–settlement responses, initial and final settlements, and elastic rebound measurements. The comparison demonstrated strong agreement between simulated and measured responses, with percentage differences in allowable load ranging from 9.7% to 11.8% and settlement variations between 2.2% and 13% across different mesh refinements. Additionally, a comparative assessment of testing time and cost revealed that numerical simulation reduced overall duration and expenditure by approximately 58.33% and 66.67%, respectively, compared to field

SLT. The findings confirm that PLAXIS 3D can reliably replicate field pile load behaviour and serve as a practical verification tool, enabling economical, time-efficient, and safe foundation design practices under Nepalese soil conditions.

Keywords: *Static Load Test, Numerical Simulation, PLAXIS 3D, Pile Foundation, Kamal Khola Bridge, Mesh Refinement, Load-Settlement Behaviour, Allowable Load.*

1. Introduction

Pile foundations are essential in bridge engineering for safely transferring large axial loads to deeper, competent soil or rock strata, particularly in compressible or geotechnically complex ground conditions. The static load test (SLT) is widely recognized as the most reliable method for determining pile load-bearing capacity and load–settlement behavior; however, its application is often limited by high cost, long testing duration, and logistical complexity, especially in developing countries such as Nepal (Siemaszko, 2024). Consequently, pile design frequently relies on empirical methods that may result in unsafe under design or uneconomical overdesign.

Recent advances in Finite Element Method (FEM)–based numerical modeling provide a practical alternative by enabling realistic simulation of soil–pile interaction under static loading conditions. When calibrated with site-specific geotechnical data, numerical simulations can accurately predict load–settlement response and allowable load, offering a cost- and time-efficient substitute for extensive field testing (Teshager, 2019). In this study, PLAXIS 3D was used to simulate the static load behavior of a bored cast-in-situ pile at the Kamal Khola Bridge, Nepal, and the results were validated against field static load test data to assess the reliability and practical applicability of numerical simulation for pile foundation verification.

Static Load Tests (SLTs) remain the benchmark method for evaluating pile load-bearing capacity and load–settlement behaviour, as they directly capture soil–pile interaction under in-service loading conditions (Siemaszko, 2024). Field-based studies continue to confirm the reliability of SLTs for capacity estimation in various soil conditions. For instance, (Verumandy et al., 2024) demonstrated that SLTs provide dependable estimates of ultimate bearing capacity for screw piles in soft soils, although uncertainties related to groundwater fluctuations were identified, highlighting the need for complementary analytical or numerical approaches.

Due to the high cost, long testing duration, and logistical challenges associated with SLTs, Finite Element Method (FEM)–based numerical modelling has gained widespread acceptance as an effective alternative or supplementary tool. FEM allows realistic simulation of soil stratigraphy, constitutive behaviour, and soil–pile interaction beyond the simplifying assumptions of traditional analytical methods

(Teshager, 2019). Among FEM-based software, PLAXIS 3D has been extensively used for simulating pile load tests and predicting settlement and load transfer behaviour.

Several studies have validated the capability of PLAXIS-based simulations through comparison with field test data. (Krasiński and Wiszniewski, 2017) investigated large-diameter bored piles and reported close agreement between numerical predictions and static load test results, although discrepancies were attributed to simplified soil parameters and uncertainties in material stiffness. (Gong et al., 2018) demonstrated that finite element simulations accurately predicted ultimate bearing capacity and consolidation settlement of PHC pile foundations, particularly when advanced soil models were employed.

Research has also emphasized the importance of soil constitutive modelling and interface representation. (Gowthaman and Nasvi, 2018) showed that combined nonlinear–linear modelling approaches, incorporating nonlinear soil behaviour near the pile shaft, significantly improve settlement predictions compared to fully linear or fully nonlinear analyses. Similarly, (Teshager, 2019) highlighted that mesh refinement and proper soil–pile interface calibration are critical factors governing numerical accuracy.

Studies focusing on Nepalese conditions remain limited. (Gupta and Dahal, 2023) applied PLAXIS 3D to model axially loaded piles in sandy soils in Nepal and reported that simulation accuracy strongly depends on appropriate soil modulus correlations derived from local SPT data. Their findings underline the need for site-specific calibration and further validation of FEM approaches under Nepalese geotechnical conditions.

Overall, the literature confirms that PLAXIS-based FEM simulations can reliably replicate pile load–settlement behaviour when calibrated with accurate geotechnical data. However, careful selection of soil models, mesh density, and interface parameters is essential. These findings support the use of numerical simulation as a credible and efficient alternative to full-scale static load testing, particularly in resource-constrained and geotechnically complex environments.

2. Methodology

The approach comprised site investigation, data acquisition, material characterization, numerical modeling, specification of boundary and meshing conditions, load application, and model validation. Field and laboratory investigation data were integrated with three-dimensional finite element simulations performed using PLAXIS 3D to enable a comparative evaluation of simulated pile behavior and field static load test (SLT) results for a bored cast-in-situ pile foundation.

2.1 Study Area

The study was conducted at the Kamal Khola Bridge along the Kakarbhitta–Laukahi section of the East–West Highway (NH-01), constructed under the SASEC Highway Enhancement Project. The bridge site lies within the Terai plains, an alluvial depositional environment characterized by fine- to coarse-grained sands interbedded with gravel and silt layers. The groundwater table was observed at approximately 0.3 m below ground level. The bridge substructure employs bored cast-in-situ piles, selected for their load-carrying efficiency and suitability for granular soils.

2.2 Soil Investigation Summary

Confirmatory drilling was conducted at the pier location up to 27 m deep. Field tests included Standard Penetration Test (SPT) and Dynamic Cone Penetration Test (DCPT) at 1.5 m intervals. Laboratory tests included grain size analysis, specific gravity, moisture content, and shear strength parameters through direct shear tests.

2.3 Model Geometry and Boundary Conditions

A 3D soil domain of $40m * 40m * 30m$ was developed using PLAXIS 3D to minimize boundary effects. The pile was centrally positioned within the model.

Boundary conditions were defined as follows:

a. Bottom boundary: Fully fixed in all directions
b. Lateral boundaries: Fixed horizontally but allowed vertical movement to simulate realistic ground conditions

2.4 Soil Profile Summary

a. Top layers: loose to medium dense sand with gravel
b. Deeper layers: medium dense to dense sandy gravel and silty sand
c. Groundwater table: 0.3 m below surface for pier

The results revealed a layered soil profile comprising loose to medium-dense sand near the surface and dense sandy gravel and silty sand at depth. These findings informed the selection of soil parameters for numerical modeling.

Table 1: Stratigraphy and Soil Layers

	Geotechnical		Pile Depth											
Layer No.	**Top Depth (m)**	**Bottom Depth (m)**	**Top Depth(m)**	**Bottom Depth (m)**	**Soil Type**	**N**	**γ (kN/m³)**	**γ_sat (kN/m³)**	**E50 (kPa)**	**ν**	**φ' (deg)**	**psi**	**c' (kPa)**	**R_{inter}**
1	0	1.5	Effective length of pile starts from 3.26 m below drilling level		Sand	13	17.1	19.1	13172	0.3	29	-	0	0.98
2	1.5	3			Sand```	14	17.1	19.1	14186	0.3	29	-	0	0.98
3	3.2	3.26			Sand	17	17.1	19.1	17225	0.3	30	0	0	0.98
4	3.26	4.5	0	1.24	Sand	17	17.1	19.1	17225	0.3	30	0	0	0.98
5	4.5	6	1.24	2.74	Sand	18	19.5	21.5	18239	0.3	31	1	0	0.98
6	6	7.5	2.74	4.24	Sand	17	19.5	21.5	17225	0.3	31	1	0	0.98
7	7.5	9	4.24	5.74	Sand	32	19.5	21.5	32424	0.3	33	3	0	0.98
8	9	10.5	5.74	7.24	sand	32	18.5	20.5	32424	0.3	33	3	0	0.98
9	10.5	12	7.24	8.74	Silty Sand	22	17.4	19.4	11146	0.32	32	2	0	0.98
10	12	13.5	8.74	10.24	Silty Sand	19	17.4	19.4	9626	0.32	31	1	0	0.98
11	13.5	15	10.24	11.74	Silty Sand	21	17.4	19.4	10639	0.32	31	1	0	0.98
12	15	16.5	11.74	13.24	Sand	29	19.2	21.2	29384	0.3	33	3	0	0.98
13	16.5	18	13.24	14.74	Sand	50	18.3	20.3	50663	0.3	36	6	0	0.98
14	18	19.5	14.74	16.24	Sand	35	18.3	20.3	35464	0.3	34	4	0	0.98
15	19.5	21	16.24	17.74	Sand	30	18.3	20.3	30398	0.3	33	3	0	0.98
16	21	22.5	17.74	19.24	Sand	32	19.3	21.3	32424	0.3	34	4	0	0.98
17	22.5	24	19.24	20.74	Sand	29	19.3	21.3	29384	0.3	33	3	0	0.98
18	24	25.5	20.74	22.24	Sand	30	19.3	21.3	30398	0.3	34	4	0	0.98
19	25.5	27	22.24	23.74	Sand	50	20.1	22.1	50663	0.3	37	7	0	0.98
20	27	28.56	23.74	25.24	Sand	27	20.1	22.1	27358	0.3	34	4	0	0.98
21	28.56	33.26	25.2	30	Sand	27	20.1	22.1	27358	0.3	34	4	0	0.98

2.5 Data Used in Simulation

The different layers of pile parameter and soil parameter are listed in Table 2 and Table 3.

Table 2 Pile parameter

S. N	Property	Pier Pile
1	Pile Type	Bored Cast-in-Situ
2	Diameter (m)	1
3	Length (m)	25
4	Material	Concrete (M35)
5	Ep (kPa)	30000000
6	ν_p	0.2
7	Rinter	0.98
8	Material Modeled	Linear Elastic
9	Drainage type	Non-porous
10	Unit Weight (KN/m^3)	24

Table 1 : Key parameters adopted for numerical modelling

SN	Parameters	Symbol	Range Used	Sources/Basis	Importance
1	Friction Angle	ϕ	30°–38°	From corrected SPT-N and lab shear tests	Controls shear resistance in granular soil
2	Dilation Angle	ψ	0°–8°	Eq. (1)	soil tends to expand (dilate) or contract
3	Cohesion	c	0–5	Lab data and assumptions for fine content	Used in Mohr-Coulomb strength model
4	Unit Weight	γ	17–21 kN/m^3	Lab tests	Used to calculate self-weight of soil mass

5	Elastic Modulus	E	10–45 MPa	Empirical correlation with N-value (Eq. (2))	Defines stiffness and deformation behavior
6	Poisson's Ratio	ν	0.3 for sandy soil, 0.32 for silty sand, and 0.2 for concrete	Literature	Describes volumetric strain response
7	Pile Diameter	D	1.0 m	Design specification	Width of bored cast-in-situ pile
8	Pile Length	L	25 m for pier	Design specification	Depth based on bearing strata
9	Concrete Modulus	Ep	30 GPa	Concrete standard	Defines the pile's elastic stiffness
10	Interface Reduction	R_{inter}	0.98	Typical value for concrete-soil	Reduces strength at soil-structure interface

2.6 Material Modeling

2.6.1 Soil Model

The Mohr–Coulomb elastic–perfectly plastic model was adopted due to its suitability for granular soils and widespread use in geotechnical analysis. The model parameters included: elastic modulus (E), Poisson's ratio (ν), cohesion (c), friction angle (φ) & dilatancy angle (ψ).

2.6.2 Pile Model

The pile was modeled as a linear elastic material with diameter= 1.0 m, length= 25 m, Elastic modulus= 30 GPa, Poisson's ratio = 0.2 and unit weight = 24 kN/m^3

2.6.3 Soil–Pile Interface

An interface reduction factor (Rinter = 0.98) was used to represent realistic soil–pile interaction behavior.

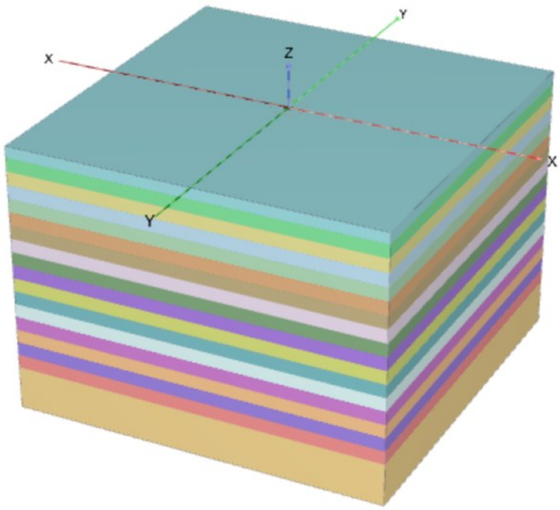


Figure 1: Soil Stratigraphy

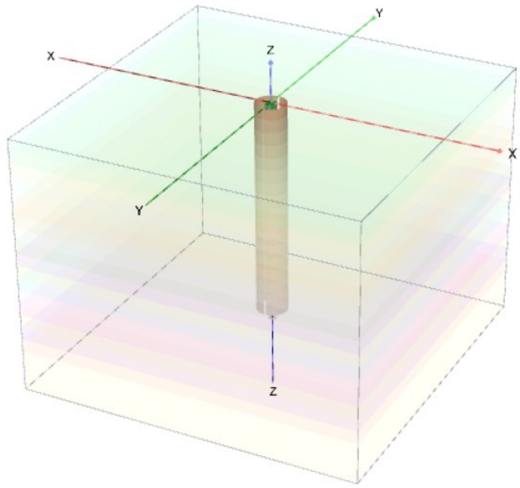


Figure 2: Soil-Pile Configuration

2.7 Simulation of Static Load Test and allowable load

2.7.1 Simulation of Static Load Test

2.7.1.1 Loading Procedure

The static load was applied incrementally following IRC 78:2014 and ASTM D1143 standards.

a. Initial load: 25% of design load

b. Subsequent increments: 25% of design load per stage

c. Maximum applied load: 2937 kN

d. Loading stages: 0 KN, 391.6 KN,783 KN, 1174KN, 1566KN,1958 KN, 2349 KN, 2741 KN, 2937 KN

e. Holding period: Each load stage was held constant until the simulated settlement reached equilibrium

2.7.1.2 Unloading Procedure

Load was released in similar decrements from 2937KN to 2741 KN, 2349 KN, 1958KN, 1566KN, 1174KN, 783KN, 392KN, and 0 KN until zero, to capture elastic rebound behavior.

2.7.1.3 Conversion of Point load to Surface load

Since PLAXIS uses surface loading, the point loads were converted to equivalent pressure values (kN/m²) based on pile head area as follows:

Table 4: Applied load stages and equivalent surface loading

Stage	Diameter (m)	Area (m^2)	Load(P) (KN)	Surface Loading (KN/m^2)
Loading Stage	1	0.785	0	0.00
	1	0.785	391.6	498.85
	1	0.785	783.2	997.71
	1	0.785	1174.8	1496.56
	1	0.785	1566.4	1995.41
	1	0.785	1958	2494.27
	1	0.785	2349.6	2993.12
	1	0.785	2741.2	3491.97
	1	0.785	2937	3741.40
Unloading Stage	1	0.785	2741.2	3491.97
	1	0.785	2349.6	2993.12
	1	0.785	1958	2494.27
	1	0.785	1566.4	1995.41
	1	0.785	1174.8	1496.56
	1	0.785	783.2	997.71
	1	0.785	391.6	498.85
	1	0.785	0	0.00

2.7.1.4 Model type 1

Load-displacement curves were generated from PLAXIS results. Deformation values(u_z) for each equivalent loading and unloading case.

2.7.2 Simulation for Allowable load

A secondary model configuration (Model type 2) was developed to estimate the allowable load using prescribed displacement method. Displacement increments of 0 mm, 6 mm, 12 mm, 25 mm, 50 mm, 75 mm, 100 mm, 125 mm were applied at the pile head. The corresponding load response was analyzed to determine the load corresponding to allowable settlement limits as per IS2911 (Part 1,2010) using the following criteria:

a. Total settlement =12 mm

b. Total Settlement = 10% of pile diameter

c. Net settlement criterion was not applicable as net settlement was < 6 mm

2.8 Mesh Refinement Study

Finite element meshing was performed using five density levels: very fine, fine, medium, coarse, and very coarse.

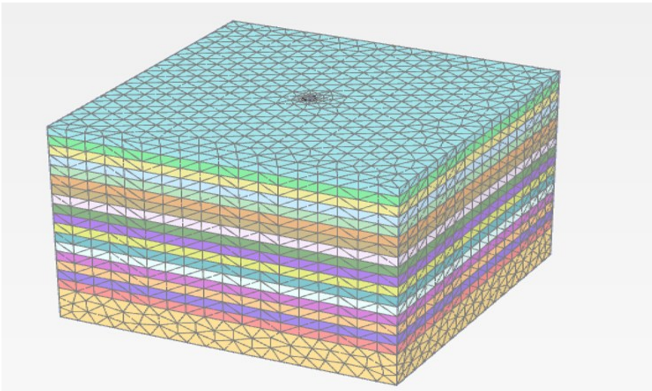


Figure 3: Mesh Statistics of Finite Element Model in PLAXIS 3D.

Table 5: Mesh Statistics of finite element model in PLAXIS 3D

S. N	Statistics	Very Fine	Fine	Medium	Coarse	Very Coarse
1	Number of soil elements	92756	49677	28742	24722	24546
2	Number of nodes	132753	72696	43209	37446	37089
3	Average element size(m)	1.736	2.092	2.468	2.554	2.549
4	Maximum element Size(m)	3.468	4.947	6.330	7.288	7.452
5	Minimum element size(m)	0.2697	0.1625	0.2703	0.2487	0.2487

2.9 Time and Cost Comparison Framework

Practical implementation in engineering projects also requires consideration of economic and temporal efficiency. Therefore, to extend the scope of evaluation beyond technical parameters, the present study introduces a Time and Cost Comparison Framework, which systematically assesses the differences in testing duration and total expenditure between the field SLT and the PLAXIS 3D simulation. This framework enables a holistic comparison by integrating both performance and practicality, thereby providing a realistic basis for recommending simulation-based verification in geotechnical design. The comparative assessment utilizes actual project records and simulation logs as summarized in Table 6

Table 6: Data sources for economic and time comparison

S. N	Parameter	Field SLT Data Source	Simulation Data Source
1	Duration	Field test log	PLAXIS 3D analysis log and computational record
2	Cost	Site testing expenditure, labor and equipment records	Software license cost and engineer time estimate
3	Manpower	On-site technical and mechanical team	One design engineer
4	Equipment	Reaction frame, Kentledge, hydraulic jack, dial gauges	Licensed PLAXIS 3D software, standard workstation

The quantitative comparison is based on two governing relations

a. Time Saving Percentage

$$\text{Time Saving}(\%) = \frac{T_{field} - T_{simulation}}{T_{field}} \quad \text{Eq. 1}$$

b. Cost Saving Percentage

$$\text{Cost Saving}(\%) = \frac{C_{field} - C_{simulation}}{C_{field}} \quad \text{Eq. 2}$$

Where:

T_{field} = Total duration of field static load test (days)

$T_{simulation}$ = Duration of PLAXIS 3D analysis (days)

C_{field} = Total cost of field static load test (NPR)

$C_{simulation}$ = Total cost of simulation (NPR)

These relations express the proportional reduction in testing time and cost that can be achieved through simulation compared to the traditional field test

3. Results and Discussion

3.1 Load–Settlement Behavior

The numerical load–settlement response closely matched the field static load test results. Settlement increased gradually with applied load, indicating elastic behavior within working load limits.

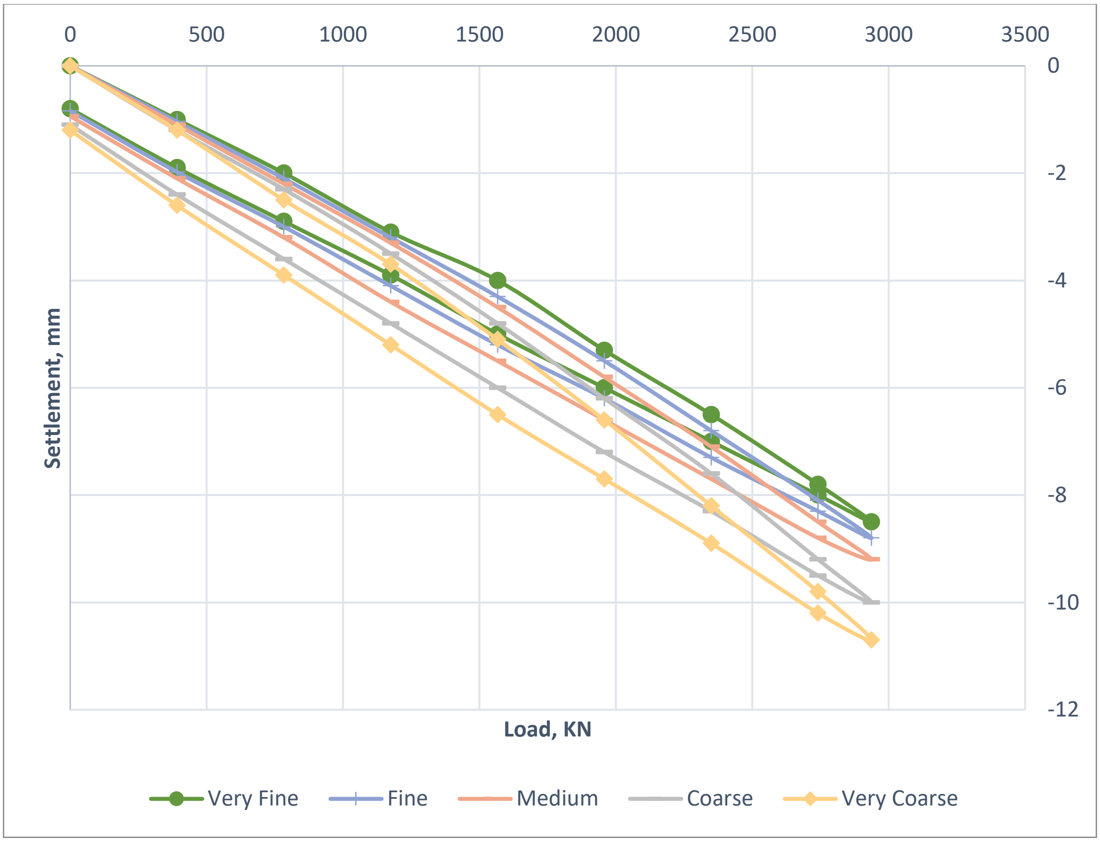


Figure 4: Load vs Settlement Curve for primary model(Loading and Unloading cases)

The simulated load-settlement curves (Figure 4) generated from the PLAXIS simulations exhibit a characteristic non-linear trend, which is characteristic of pile foundations under axial loading. The response can be divided into three phases:

a. Initial Elastic Phase:

At lower load levels (up to ~30% of design load), the settlement increased linearly with applied load. This stage represents the elastic deformation of the soil-pile system.

b. Transition Phase:

Beyond 30–70% of the design load, a deviation from linearity was observed. The slope of the curve gradually decreased, indicating the onset of plastic deformation within the soil mass and partial mobilization of shaft resistance.

c. Plastic Phase:

Beyond 70 % of the ultimate load, the settlement increased disproportionately relatively to load increments. This nonlinear behavior corresponds to the mobilization of the ultimate bearing capacity and the formation of plastic zones around the pile shaft and base.

The overall shape and trend of the simulated load–settlement curve closely resemble those observed in the field static load test, thereby confirming that the finite element model successfully captured the progressive mobilization of pile resistance under static axial loading. The model realistically represented both the elastic and plastic response of the pile–soil interaction system, validating the suitability of the Mohr–Coulomb soil model for drained conditions prevalent at the Kamal Khola Bridge site.

The clear distinction between the elastic, transition, and plastic phases further demonstrates the capability of the numerical model to replicate the actual behaviour of pile foundations under incremental loading.

3.2 Comparison of Simulated and Field Load-Settlement Curves

A graphical comparison between simulated and field load-settlement curves indicates:

a. The average simulated net settlement is 0.97mm, which was 5.74% difference from the field net settlement(0.92mm).

b. Up to the design load, the simulated and field curves exhibited almost identical trends, demonstrating that the PLAXIS model accurately represented elastic soil–pile behaviour.

c. At higher loads, simulation predicted slightly higher settlements than observed in the field. This discrepancy is attributed to:

   Simplification of soil constitutive behavior using the Mohr-Coulomb model, which does not fully capture strain-dependent stiffness degradation (stiffness reduction at small strains).

   Idealized pile-soil interface (Rinter=0.98) assumptions in the numerical model that neglects minor slippage and shear transfer variations observed in real conditions.

Despite these simplifications, deviations remained within acceptable geotechnical tolerance limits (<10%), validating the reliability of the FEM approach in simulating pile performance under Nepalese soil conditions.

3.3 Allowable Load Determination

The allowable load capacity of the pile was determined from the simulated load–displacement responses using the prescribed displacement method in accordance with IS 2911 (Part 1, Section 1, 2010). This approach defines the allowable load as the load corresponding to the smaller of two criteria: (i) a total settlement of 12 mm, or (ii) a total settlement equal to 10% of the pile diameter (100 mm in this study). The simulated load–settlement curves for various mesh densities were analysed to evaluate the influence of mesh refinement on the computed allowable load.

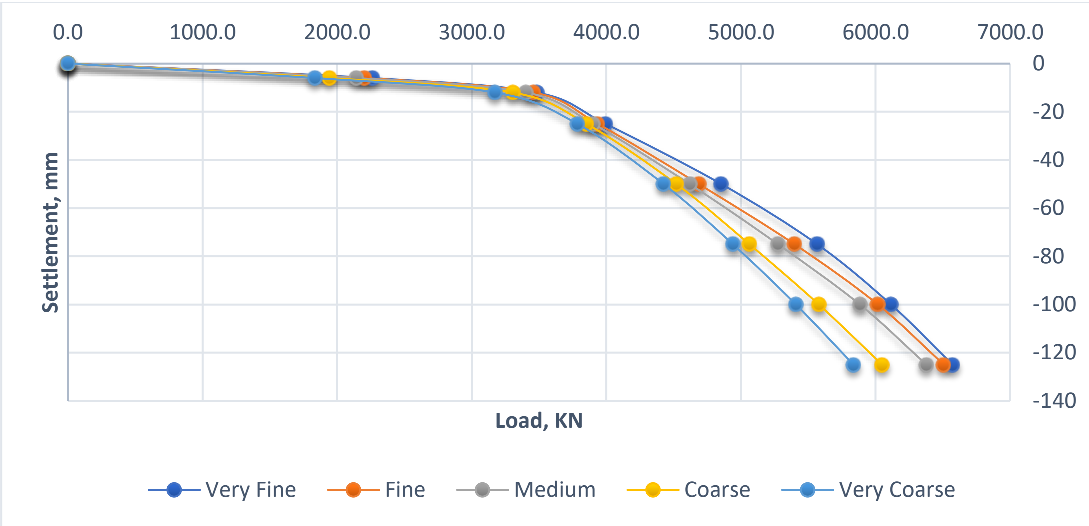


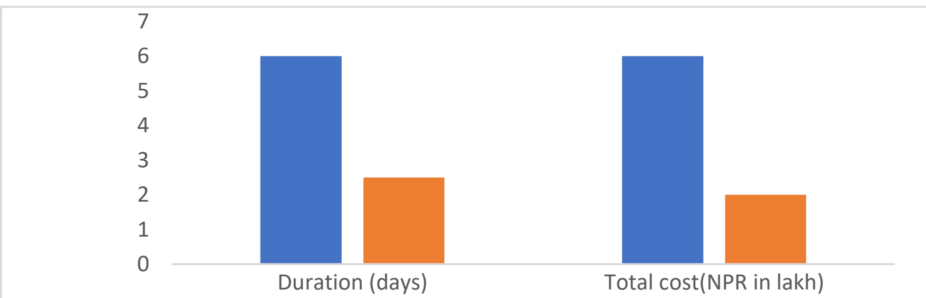
Figure 5: Load vs Settlement Curve for determining allowable load

3.4 Validation with Field Data

The net settlement in field was 0.92mm where as we obtained 0.8mm, 0.84mm, 0.94mm, 1.1mmand 1.2mm for different mesh from very fine to very coarse. The allowable load in field was 2572KN whereas we obtained 2322KN, 2305.3KN, 2268KN, 2202.7KN and 2114.7KN for different meshes from very fine to very coarse. The comparison between simulated and field results revealed: Settlement deviation: 2.2%–13%. and allowable load deviation: 9.7%–11.8%. These results confirm the reliability of PLAXIS 3D for predicting pile performance.

3.5 Time and Cost Comparison

A comparative assessment of time and cost was carried out between the conventional static load test and numerical analysis. The results indicate that numerical modeling significantly reduces both testing duration and overall cost. Overall, numerical simulation resulted in approximately 58.33% reduction in time and 66.67% reduction in cost, highlighting its practical advantage for design-stage evaluation.



	Duration (days)	Total cost(NPR in lakh)
Field SLT	6	6
Simulation	2.5	2

Figure 6: Comparison of time and cost between field and simulated SLT

The numerical analysis demonstrated that the simulated pile behavior closely matched field performance, confirming the validity of the finite element approach for static load prediction. Mesh refinement significantly influenced both accuracy and computational demand, with the medium mesh proving optimal. Deviations between simulated and field data were within the range of 2.2–13% for settlement and 9.7–11.8% for allowable load — well within acceptable geotechnical tolerances. Meanwhile, the economic and temporal analysis established that simulation consumes only 66.67% of the total cost and 58.33% of total time with much less manpower compared to field testing.

4. Conclusion

This study evaluated the static axial load behaviour of a bored cast-in-situ pile foundation using three-dimensional finite element modelling in PLAXIS 3D and validated the numerical results against field static load test data from the Kamal Khola Bridge project in Nepal. Site-specific geotechnical parameters obtained from detailed field and laboratory investigations were incorporated into the numerical model to realistically simulate pile–soil interaction under axial loading conditions.

The numerical simulations demonstrated good agreement with field static load test results in terms of load–settlement response, pile head displacement, and elastic rebound behaviour. The percentage difference between numerically predicted and measured allowable load capacities ranged from approximately 9.7% to 11.8%, while settlement variations were observed within a range of 2.2% to 13% depending on mesh refinement. These results confirmed that PLAXIS 3D can reliably replicate field pile behaviour when appropriate soil parameters, constitutive models, and boundary conditions are adopted.

In addition to technical validation, a comparative assessment of testing duration and cost revealed that numerical simulation reduced overall time and cost by approximately 58.33% and 66.67%, respectively, compared to conventional field static load testing.

Overall, the findings demonstrated that three-dimensional numerical simulation using PLAXIS 3D provides a reliable, economical, and time-efficient alternative for evaluating pile foundation performance. The study supports the integration of FEM-based numerical modelling as a practical verification tool in bridge foundation design under Nepalese geotechnical conditions and similar alluvial environments, while reducing dependence on extensive full-scale field testing.

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Construction and Demolition Waste (C&DW) Management

Priyeshchandra Neupane[1], Rajib Pokhrel[2]*

[1] School of Engineering, Pokhara University, Pokhara, Nepal

[2] School of Engineering, Pokhara University, Pokhara, Nepal

*Corresponding Email: rajibp@pu.edu.np

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Abstract

Construction and Demolition Waste (C&DW) constitutes a substantial fraction of the global solid waste stream and presents a critical impediment to sustainable development. This paper critically examines prevailing practices, emerging trends, and pressing concerns in C&DW management worldwide, with particular emphasis on Asia and Nepal. Established practices such as recycling, reuse, material recovery, selective demolition, and the integration of digital technologies including Building Information Modeling (BIM) and artificial intelligence for waste sorting are reviewed in relation to their efficacy and scalability. While developed economies have advanced integrated systems underpinned by stringent regulatory frameworks and market-based instruments, most developing regions remain constrained by fragile policy environments, financial limitations, technical deficits, and a reliance on informal waste economies.

The circular economy (CE) paradigm offers a transformative framework to reconceptualize C&DW as a secondary resource, reduce dependence on virgin materials, and diminish the sector's carbon footprint. By reinforcing lifecycle awareness, material efficiency, and innovative business models, CE strategies align directly with broader global sustainability agendas. However, implementation remains highly uneven, largely due to entrenched systemic, economic, and institutional barriers. Overcoming these challenges necessitates targeted investment, adaptive policy reform, inclusive stakeholder engagement, and accelerated technological innovation. Collectively, these measures are essential for advancing C&DW management toward a circular trajectory and unlocking its potential as a catalyst for sustainable growth within the construction sector.

Keywords: *Construction and Demolition Waste (C&DW), Recycling, Circular Economy, Building Information Modeling (BIM), Sustainable Construction, Waste Management Policy, Material Recovery, Informal Sector*

1. Introduction

The rapid rate of urbanization and population growth has therefore greatly increased the demand for housing, urban development, and infrastructure globally (Lee et al., 2024). Building, rebuilding, and reconstruction of bridges, roads, and buildings have therefore become increasingly prevalent, leading to an increase in the generation of construction and demolition waste (C&DW) (Dodampegama et al., 2024). C&DW is a variety of materials that are manufactured in the construction, renovation, or demolition of built structures (Wang et al., 2019), and also results from natural occurrences such as earthquakes, hurricanes, and floods (Radica et al., 2024).

Globally, C&DW constitutes a considerable fraction of municipal solid waste and varies between 20% to 50% of municipal waste in the majority of developed nations (Menegaki & Damigos, 2018). For example, in 2020, construction activities generated approximately 38.4 million tons of waste in the European Union, 600 million tons in the United States, 66.2 million tons in the United Kingdom, and 2,360 million tons in China (Yuan et al., 2023; Gao et al., 2024). Despite this, even large quantities of C&DW are landfilled or even dumped in open piles, causing serious environmental problems such as air and water contamination, noise pollution, and landfill capacity depletion at a very rapid rate (Jahan et al., 2022; Nawaz et al., 2023).

Recycling has emerged as one of the significant solutions for reducing C&DW environmental loads. Recycling decreases landfill demands, conserves natural resources, and enhances sustainability (Patil et al., 2024; Caferra et al., 2023). Recycling supports the principles of the circular economy (CE), which assures waste minimization generation, reuse, and recycling of materials through their lifespan (Maliha et al., 2023; Balletto et al., 2021; Camana et al., 2021). CE principles also emphasize the following actions as Refuse, Rethink, Repair, Refurbish, Remanufacture, Repurpose, and Recover to reduce environmental impacts while increasing resource efficiency (Yang et al., 2022).

These efforts must be grounded in the three pillars of sustainable development-environmental conservation, economic growth, and social justice-to construct more resilient and equitable systems (Yilan et al., 2022). On a policy level, the European Union's Waste Framework Directive (2008/98/EC) has served as the gold standard of advanced waste management. It promotes the waste hierarchy, with the objective of reaching 70% recovery from non-hazardous C&DW and promoting selective demolition and safe handling of materials to facilitate high-quality recycling (European Parliament & Council, 2008).

This review is looking to examine the composition and impact of C&DW, assess the effectiveness of current recycling operations, discuss significant management issues, and provide insight into the way forward, notably within circular economy transformations.

2. Methodology

This review paper adopts a qualitative and narrative method to synthesize and critically examine recent progress, practices, and innovations in the management of construction and demolition waste (C&DW), circular economy principles, and region-specific challenges, including in Nepal. The existing scholarly literature, policy reports, and technical reports between the years 2012 and 2024 were systematically retrieved from databases such as ScienceDirect, ResearchGate, MDPI, SpringerLink, and Google Scholar. A list of keywords was used to attain a broad spectrum of materials, including terms such as "construction and demolition waste," "C&DW recycling," "circular economy in construction," "building information modeling (BIM) and waste," "sustainable construction," and "C&D waste management." The inclusion criteria were peer-reviewed journal papers, case studies, meta-analyses, government reports, and international directives that spoke about some facet of C&DW, such as waste generation, material recovery, reuse strategies, policy implications, and technological interventions. Exclusion criteria removed sources that lacked sufficient relevance, methodological clarity, or peer-review confirmation. A number of sources were selected and reviewed, and information was thematically collated into key topics covering C&DW composition, current management practice, institutional and economic barriers, best practice of developed and developing nations, and emerging innovations such as BIM integration and AI-optimized recycling facilities (Dodampegama et al., 2024; Gao et al., 2024). Specific focus was given to developing country-specific research, particularly Nepal, to strengthen the applicability of global models to local waste problems. This allowed for the identification of evolving trends, important policy and technological gaps, and practical steps for steering towards sustainable and circular construction waste management.

3. Composition of Construction and Demolition Waste

Construction and demolition waste (C&DW) typically comprises waste generated during demolition (90 percent of C&DW), and waste from construction (10 percent of C&DW) (Rodriguez-Morales et al., 2024). Demolition and construction waste streams have very different physical and material characteristics where construction waste is generally cleaner and uniform in quality, making it simpler for recycling, whereas demolition waste is often very heterogeneous, especially in post-disaster scenarios like earthquakes (Wang et al., 2024). Traditional C&DW may involve multiple materials including concrete, brick, tile, wood, plastics, ceramics, metals, glass, cardboard, gypsum, bituminous mixtures, and the excavation of soils (Wang et al., 2024).

Demolition waste can be classified into three main categories of material, based on the potential for reuse and risk; (1) reuse value, related to the total percentage of waste that consists of the hard materials potential for reuse. These hard materials generally consist of 40-85% hardened concrete, 10-25% ceramics, and 20-25% bricks and tiles, are frequently reused or recycled into cementitious precursors; (2) recyclable value through easy recycling like glass and metals which represent less than 10% of the waste stream; and (3) hazardous components (i.e., lighting systems, paints and coatings, and materials containing asbestos) (Osmani, 2011; Radica et al., 2024).

The composition of C&DW can differ widely depending on the type of project and location. For example, concrete waste can represent between 40 and 85% of the total waste on site, depending on the construction activities (Yuan et al., 2024). In many EU countries EoL (End-of-Life) concrete is greater than 40% of the total C&DW, and in someareascould be 60 to 70% for the region. This leads to feasible strategies such as urban mining, as recycling this material effectively and efficiently reduces reliance on virgin materials, reduces reliance on landfills, and aims to reduce carbon emissions which acts toward sustainability and resource efficiency goals (Yuan et al., 2024).

Construction material in most Asian regions, including India and Thailand, contains a higher proportion of organic and mixed material such as wood, bamboo, and packaging due to traditional construction and the involvement of the informal sector (Chandrappa & Das, 2012; Luangcharoenrat et al., 2019).

In Nepal's Kathmandu Valley, the dominant compositions of C&DW are mortar waste, concrete, and bricks. Increases in volumes of post-2015 Gorkha earthquake waste indicated the system's vulnerability and the need for better segregation and material recovery policy. Most of the waste is sorted manually by undocumented workers, and recycling quality is thus variable, with inefficient application of the materials (Tuladhar et al., 2016).

C&DW classification practices differ region-wise and influence the companion waste management strategies. Materials are sorted as inert-like earth, soil, rocks, slurry, and crushed concrete-or non-inert-like wood, vegetation, packaging, and other organic wastes-based on their chemical and biological stability (Villoria Sáez & Osmani, 2019). Physical heterogeneity of these materials creates significant recycling challenges, particularly in producing nearly homogeneous mono-material streams with minimal contamination levels. Impurities such as organic matter, imbedded metal, and harmful substances like asbestos can negatively impact the quality of the reclaimed products and limit their application for building construction. Therefore, comprehensive information regarding C&DW composition becomes unavoidable to increase recycling levels, enable more effective sorting measures, and overall quality of reclaimed material.

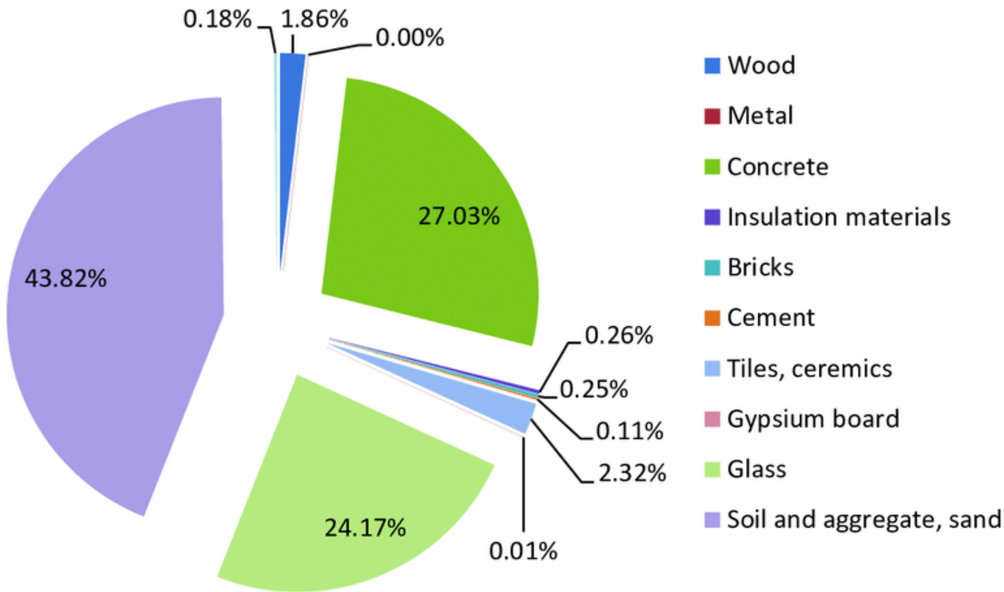

Figure 1: Composition of construction waste materials disposed of at illegal dumpsites (Source: Mahayuddin et al., 2008)

4. Sources of Construction and Demolition Waste

Construction and demolition waste (C&DW) originates from a variety of sources across the building lifecycle. The primary sources can be categorized into construction, renovation, and demolition activities, natural disasters with each contributing differently in terms of waste quantity and material type (Osmani, 2011; Yuan et al., 2024).

4.1 Construction Activities

Waste generated during the construction phase often results from over-ordering of materials, improper storage, design changes, human errors, and off-cuts from cutting materials like wood, concrete, or tiles (Luangcharoenrat et al., 2019). These wastes are usually cleaner, less contaminated, and easier to recycle compared to demolition waste.

4.2 Demolition Activities

Demolition is the largest contributor to total C&DW, accounting for up to 90% of the volume in some contexts (Rodriguez-Morales et al., 2024). The process of dismantling buildings results in mixed materials such as concrete, bricks, metals, wood, and hazardous substances like asbestos-containing materials. In disaster-prone regions, large volumes of heterogeneous waste are generated due to earthquake or flood damage, which complicates recycling efforts (Radica et al., 2024).

4.3 Renovation and Remodeling

Renovation and repair work also generate substantial waste, especially from interior refurbishments where tiles, fittings, plaster, and insulation materials are discarded. These works often involve partial demolition, producing both recyclable and non-recyclable fractions (Wang et al., 2024).

4.4 Infrastructure Development

Road construction, bridge building, and infrastructure upgrades generate large quantities of asphalt, concrete, and excavation waste (Villoria Sáez & Osmani, 2019). Unlike building C&DW, infrastructure waste is typically more inert and bulkier.

4.5 Excavation and Land Clearing

Excavated materials such as soil, rocks, and sand from site preparation are another major source of C&DW. Though inert, they can burden landfills if not reused in landscaping or backfilling (Chandrappa & Das, 2012).

4.6 Natural Disasters

Earthquakes, floods, hurricanes, and tsunamis generate massive quantities of debris, often in an unplanned and urgent context. These materials can include collapsed concrete, timber, roof tiles, furnishings, and hazardous materials such as oil containers and asbestos (Radica et al., 2024). Post-disaster C&DW is usually highly mixed, contaminated, and logistically difficult to manage due to the urgency of relief efforts and the absence of formal segregation processes.

5. Current Practices in C&DW Management

5.1 Recycling, Reuse & Recovery

C&DW management typically includes the collection, sorting, transport, reuse, recycling, landfilling, and resource recovery of materials-supported by comprehensive planning and monitoring frameworks (Yuan et al., 2024). Recycling broken concrete into recycled aggregates (RA) conserves natural resources and reduces CO_2 emissions (Yuan et al., 2024). In the European Union, recovery rates vary between 10% and 95%, averaging 89% in the EU-28, thanks to established waste separation systems and life-cycle thinking (Villoria Sáez & Osmani, 2019; Banias et al., 2022). Recycling methods typically involve two-stage crushing, washing, and contaminant screening. Advanced techniques such as vertical shaft impactors and autogenous cleaning improves aggregate quality by removing adhered mortar (Sivamani et al., 2021; Trivedi et al., 2023). Nonetheless, ensuring material purity remains critical, as contamination (e.g., fine particles, organics, heavy metals) can limit market acceptance and usability (Serranti & Bonifazi, 2020).

5.2 Selective Demolition

Selective demolition sorting valuable materials on-site before full demolition boosts recovery rates and reduces contamination. Although often more labour-intensive and costly, the approach is recommended through EU circular economy policies and shows increasing uptake in some pilot projects (Villoria Sáez & Osmani, 2019; Al-Raqeb et al., 2023).

5.3 Informal vs. Formal Sector Roles

In developing nations, informal workers frequently perform manual sorting of C&DW under precarious and unsafe conditions; while this supports livelihoods, it results in inconsistent recovery quality (Tuladhar et al., 2016). In contrast, formal collection and processing systems,common in Europe-offer better-standardized outputs but require higher investment and regulatory oversight (Villoria Sáez & Osmani, 2019).

5.4 Digital Tools: BIM, AI & Automated Sorting

Digital tools are emerging as game-changers in C&DW. Building Information Modeling (BIM) supports material quantification, design-for-deconstruction, and waste reduction during planning (Chandrappa & Das, 2012). Artificial Intelligence (AI) and machine vision are being piloted for automated sorting such as the CODD image dataset that demonstrates improved object recognition for recycling (Demetriou et al., 2024). Despite this, adoption in regions like Hong Kong is slow due to cost and technical training barriers (Bao et al., 2020). Stakeholder engagement and capacity-building are essential to integrate these systems more widely.

6. Challenges in Construction and Demolition (C&D) Waste Management

An effective C&D waste management (C&DWM) approach must strike a balance between economic feasibility, policy and regulatory consistency, market readiness, sustainability, and appropriate business models (van den Berg et al., 2023). Each of these dimensions presents distinct challenges that hinder the successful implementation of circular economy (CE) principles in the construction sector.

6.1. Economic Feasibility

In many cases, the cost of recycling C&D waste (including transportation, labor, and sorting) exceeds the cost of landfilling, especially in developing countries with resource constraints (van den Berg et al., 2023). Although reuse-oriented demolition can yield environmental benefits and long-term savings, it typically involves higher initial labor costs (Roussat et al., 2009; Bentaha et al., 2020).

In Asia, particularly in Nepal, the lack of large-scale recycling infrastructure and investment further inflates recycling costs, making informal dumping more common. Construction waste is often mixed with municipal waste due to poor segregation practices and limited financial incentives for recycling (ADB, 2020; Sapkota, 2023).

6.2. Policy and Regulatory Inconsistencies

Despite the EU's push for CE integration, a lack of harmonized definitions and procedures among member states has led to fragmented waste management systems (Colmenero Fonseca et al., 2023; D'Adamo et al., 2024). Ghisellini et al. (2018) emphasize that such gaps reduce recycling incentives and perpetuate backfilling as a disposal method. The regulatory variance creates barriers to cross-border knowledge sharing and standardization (Ghaffar et al., 2020; Alhawamdeh et al., 2024).

In Nepal and other South Asian nations, national-level regulations on C&D waste are either weak or nonexistent. Most municipal plans do not distinguish between household and construction waste, resulting in regulatory blind spots and enforcement challenges (UN-Habitat, 2018; Sapkota, 2023).

6.3. Market Readiness and Acceptance

Recycled materials often suffer from lower quality (downcycling), leading to skepticism among construction professionals and clients (Allwood et al., 2011; Otasowie et al., 2024). Resistance is compounded by restrictive standards such as those limiting recycled aggregates in structural concrete (de Andrade Salgado & de Andrade Silva, 2022; Plaza et al., 2021) and the limited availability of commercial-grade recycled products (Papamichael et al., 2023).

In many Asian contexts, including Nepal, there is minimal awareness or confidence in recycled materials due to the absence of product standards and labeling systems, further deterring their adoption in mainstream construction projects (ADB, 2020; Victar & Waidyasekara, 2024).

6.4. Sustainability Assessment Limitations

While Life Cycle Assessment (LCA) is increasingly employed, its application remains inconsistent across project phases (Stylianou et al., 2023; H & S, 2022). Studies recommend shifting focus toward early-stage interventions during design to fully realize CE benefits (Islam et al., 2024; Li et al., 2023). Integrating sustainability into early planning is also essential to support SDG 12 (responsible consumption and production) (D'Adamo et al., 2025).

6.5. Inadequate Circular Business Models

Circular business models are key to CE success but are underdeveloped globally (Ingrao et al., 2025). Many demolition contractors lack decision-support tools for planning sustainable waste strategies (van den Berg et al., 2023; Bentaha et al., 2020). Moreover, certifications such as environmental labels and consumer-driven recognition (Colasante et al., 2024) are not widely adopted, despite their ability to enhance market trust and transparency (Chioatto et al., 2024).

Across Asia, including Nepal, business models for CE are rarely implemented due to low private sector participation, weak incentives, and a lack of scalable partnerships between public institutions and private waste processors (Sapkota, 2023; ADB, 2020).

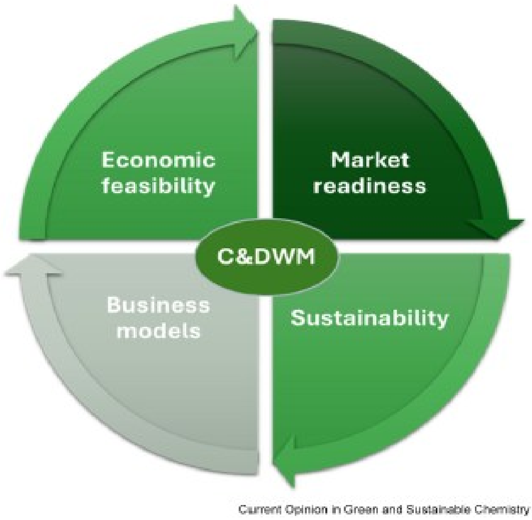

Figure 2: Elements of an Effective Construction and Demolition Waste Management (C&DWM) Approach (Source: Papamichael et al. (2024))

7. Future Directions

7.1 Merging Circularity in Policy & Design

Circular design techniques-such as design-for-deconstruction, modularity in construction, and material passports-must be incorporated into initial building cycles and supported by policy. The European Environment Agency (2020) explains that the incorporation of proper regulatory systems and clearly established recycling criteria would facilitate a shift from low-grade backfilling to high-grade reuse of C&D waste.

7.2 Upscaling Digital and Smart Technologies

Interoperability of Building Information Modeling (BIM) and Geographic Information Systems (GIS) improves precision in waste forecasting, resource planning, and overall project management (Oti et al., 2020). IoT-based sensors and AI-based sorting systems also further enhance real-time waste monitoring and sorting, as pioneered by Zolfagharian et al. (2018), but large-scale deployment waits on cost reduction and providing technical training.

7.3 Emerging Circular Business Models

To recycle economically, new business models such as materials leasing, reverse logistics, and product-as-a-service need to emerge. These, along with monetary incentives such as green bonds or purchasing requirements, can significantly drive investment in recycling plants and service-based construction activities.

7.4 Formalising the Informal Sector

In most developing nations, informal operators perform the majority of material recovery in C&D activities. Dias et al. (2018) present compelling evidence of formal integration of informal laborers-through training, certification, and protection-to improve recovery performance along with ensuring social inclusion.

7.5 Data Transparency, Education & Research

Openness to construction material flow data and circular performance indicators facilitates enhanced policy planning and innovation. Training higher education curricula on circular design principles will shape future experts. Xue et al. (2021) promote expanded academic and industrial R&D in synergies of BIM-LCA recommend upscaled research on waste tracking to piloted and large-scale application.

Table 1: Summary Table of C&D Waste Types and Management Techniques

C&DW Type	Management Technique
Concrete and Masonry (Bricks, Tiles)	Crushed to recycled aggregates; used in road sub-base, pavement, or as cement replacement. (Yuan et al., 2024; Rodriguez-Morales et al., 2024)
Wood and Timber	Recycled in construction or furniture; bioenergy generation from waste wood. (Chandrappa & Das, 2012; Villoria Sáez & Osmani, 2019)
Metals (Steel, Iron, Aluminum)	Sorted and sent for melting and reuse in metal industries. (Osmani, 2011; Patil et al., 2024)
Glass and Ceramics	Crushed for aggregate or insulating material; used in tile and asphalt. (Gao et al., 2024; Serranti & Bonifazi, 2020)
Plastics and Packaging Waste	Recycled into plastic pellets, reused, or used in energy recovery. (Camana et al., 2021; Jahan et al., 2022)
Gypsum and Drywall	Processed to be recycled into new plasterboards or soil conditioners. (Ghisellini et al., 2018)

Soil and Excavation Waste	Reused in land reclamation, backfilling, or landscaping. (Luangcharoenrat et al., 2019; Papamichael et al., 2023)
Hazardous Waste (Asbestos, Paints)	Requires special treatment and disposal in controlled facilities. (Serranti & Bonifazi, 2020; Radica et al., 2024)

8. Implications for Nepal

Referring to the table and global best practices, Nepal can significantly increase C&DW management through initiating segregation at the source, especially in cities like Kathmandu where most of the waste is mixed and sorted manually (Tuladhar et al., 2016). Promoting crushing plants for bricks and concrete, establishing metal and wood collection centers, and coordinating with industries for timber reuse and plastic recycling would all improve circular flows. Further, formalizing the informal sector's contribution, backed by training and protection, can upgrade recycling quality and livelihood. For dealing with hazardous waste like asbestos, Nepal must strengthen regulations and adopt specialized disposal facilities. Municipalities must also adopt digital tools like BIM for better planning, promote selective demolition, and invest in pilot-scale recycling plants that can later be scaled up. These actions, as tailored to the Nepalese socio-economic context, will convert C&DW from an environmental hazard to a sustainable development resource.

9. Conclusion

Rapid urbanization has sharply increased construction and demolition waste (C&DW) worldwide. Although circular economy (CE) principles offer sustainable solutions, adoption remains constrained by economic, technical, and regulatory barriers. Landfilling dominates due to its lower short-term costs, despite resource depletion and environmental harm. Advances in recycling technologies, market incentives, and EU policy reforms show potential, yet global progress requires stronger policy alignment and industry collaboration. Emerging tools such as AI-driven sorting, hyperspectral imaging, BIM, and LCA-based decision systems—enhance recovery efficiency, reuse design, and material traceability. However, operationalizing CE demands institutional frameworks, robust data systems, and incentives that offset the cost disadvantage of recycling. Improving sorting precision and material quality is crucial to build market confidence in secondary construction materials.

In Asia, particularly Nepal, C&DW management remains nascent. Kathmandu illustrates common issues: weak regulation, poor segregation, and insufficient infrastructure. Recycling initiatives are limited, highlighting the need for locally adaptive approaches such as integrating informal operators, piloting recycling plants, and incentivizing source segregation. Partnerships among municipalities, contractors, NGOs, and academia could scale context-specific models. Achieving a circular C&DW system requires blending technological innovation with inclusive governance and sustainable business models. For South Asia, balancing global CE frameworks with grassroots engagement is essential. With targeted investments, policy reform, and community participation, C&DW can evolve from a burden into a catalyst for sustainable development and green employment.

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https://www.ltu.edu.np
info@ltu.edu.np
journalioeit@ltu.edu.np
+977-081-539601
Nepalgunj, Banke, Lumbini Province, Nepal