Turkish Journal of Food and Agriculture Sciences

T U R J F A S

7(1): 66-79 (2025)

Research Article

DOI: https://doi.org/10.53663/turjfas.1628699

Digital soil mapping for soil fertility analysis: A case study of Rong Rural Municipality, Ilam, Nepal

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ARTICLE INFO

HISTORY

Received: 28 January 2025
Revised: 4 March 2025
Accepted: 10 March 2025
Online Published: 30 June 2025

KEYWORDS

GIS mapping
Nutrient management
Precision agriculture
Soil fertility
Spatial variability

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A B S T R A C T

Soil fertility is the important factor for the sustainability and productive ability of soil. Soil fertility is an ability to provide plant with necessary nutrients in adequate amounts, suitable forms, and appropriate proportions enabling optimal plant growth. This study was carried out to determine the soil fertility status of Rong Rural Municipality, Illam, Nepal. Altogether, 100 samples were collected randomly from the depth of (0-30 cm). The exact location of the soil samples was recorded using a GPS toolbox Application. All the samples were tested, analyzed at a soil and manure testing Laboratory, Surunga, Illam, Nepal to find out the 6 parameters of soil i.e. soil pH, soil organic matter, soil texture, available nitrogen, phosphorus, potassium status. The soil pH was tested by using Digital pH meter, soil texture by hydrometer, soil organic matter by Walkey and Black method, nitrogen by Kjeldahl Distillation unit, phosphorus by Modified Olsen's Bicarbonate method and potassium by Flame photometer method. Moreover, soil fertility maps were made by using Arc GIS 10.5 software. Primarily the study area consists of 70.83% of sandy loam and 29.16% of loam-textured soil. The soil pH was slightly acidic ranging from 5.49 to 6.07. Soil organic matter (1.08-2.53%), nitrogen (0.032-0.24%), phosphorus (18.16-69.22 kg ha^{-1}) was in the range. Potassium (50.39- 463.05 kg ha^{-1}) are available in the soil with the status of low to high in the study area. To achieve sustainable crop production, it is essential to have a thorough understanding of the soil's fertility status and implement suitable nutrient management approaches.

Citation: Poudel, R., Yadav, P.K., Baniya, A., Bharati, R., Pyakurel, Y., Gautam, T., Khadka, A. & Acharya, R. (2025). Digital soil mapping for soil fertility analysis: A case study of Rong Rural Municipality, Ilam, Nepal. *Turkish Journal of Food and Agriculture Sciences*, 7(1), 66-79.

ORCİD> 0009-0000-8881-2131 (RP), ORCİD> 0009-0007-2710-6058 (PKY), ORCİD> 0009-0003-8148-5129 (AB), ORCİD> 0009-0001-2830-8379 (RB), ORCİD> 0009-0009-6468-8661 (YP), ORCİD> 0009-0003-0405-9384 (TG), ORCİD> 0000-0002-1773-1366 (AK), ORCİD> 0009-0003-4122-289X (RA)

1. Introduction

Soil is considered the foundation of life and a vital natural resource, though its slow renewal makes its conservation essential for sustainability (Khaki et al., 2017). As a key component of ecological systems, it provides crucial services such as carbon storage, water regulation, soil fertility, and food production, all of which impact human well-being (Panday et al., 2019). Its complexity stems from its composition of mineral nutrients, organic matter, water, air, and living organisms, influenced by various environmental factors (Ghimire et al., 2019). Soil fertility, defined as its capacity to supply adequate nutrients for plant growth, is influenced by intrinsic factors like parent material, climate, and soil age, along with human activities such as fertilizer and pesticide use. It is a fundamental yet concealed attribute of soil productivity, particularly significant in Nepal's hilly regions, where population pressure affects land resources (Shrestha et al., 2018). Agriculture supports 65.6% of Nepal's active population and contributes 29.23% to the GDP, making healthy soils essential for sustainable crop production and food security (Kharal et al., 2018). Soil properties vary spatially due to both natural and anthropogenic factors, including soil-forming processes, fertilizer application, liming, crop rotation, and pesticide use (Ghimire et al., 2019). Physical attributes like texture, structure, and color, along with chemical properties such as pH, organic matter, and nutrient content, are key determinants of soil quality. Assessing these characteristics through physical and chemical soil testing provides critical insights into soil nutrient availability and overall fertility (Panday et al., 2019).

Sustainable land-use and effective soil management strategies are crucial for restoring and maintaining soil quality to ensure long-term agricultural productivity (Panday et al., 2019). Variations in soil properties due to land-use practices must be understood to address nutrient-related production constraints. Continuous fertilizer use, agrochemical applications, and tillage practices alter soil microbial communities and impact key physical properties like bulk density and texture (Rawal et al., 2018). These changes can disrupt vital functions such as water infiltration, leading to potential soil degradation if not managed properly. Soil fertility is a dynamic attribute influenced by both natural and human factors (Desbiez et al., 2004). To tackle soil fertility challenges, Nepal's Department of Agriculture has implemented various programs promoting organic manure, composting, green manuring, balanced fertilizer use, and soil testing as part of an integrated plant nutrient management system. Among these, soil testing is a priority, serving as a crucial tool for assessing nutrient availability and guiding sustainable fertility management (Khadka et al., 2016). It helps determine the soil's nutrient supply capacity, forming the basis for effective soil management and crop cultivation strategies (Pandey et al., 2018). The three primary macronutrients essential for plant growth; nitrogen (N), phosphorus (P), and potassium (K) play distinct roles. Nitrogen supports vegetative growth, phosphorus aids root development and energy transfer, and potassium regulates water and nutrient transport, contributing to flowering and fruiting (Masrie et al., 2018). Predicting soil productivity based on N, P, and K content is essential for optimizing crop yields. Additionally, soil pH significantly influences biogeochemical processes, microbial activity, and nutrient availability. Rather than merely indicating acidity or alkalinity, pH provides valuable insights into critical soil functions that impact overall agricultural productivity (Khadka et al., 2018). In Nepal, soil pH generally ranges between 4.5 and 6.5, making it moderately acidic, which is suitable for crops like tea, cardamom, maize, and millet (Ghimire et al., 2020). Nitrogen levels in agricultural soils vary between 0.12% and 0.26%, with higher concentrations promoting leafy vegetable growth such as spinach and cabbage (Shrestha et al., 2021). Phosphorus content, ranging from 9 to 30 mg/kg, is crucial for leguminous crops like soybeans and lentils, ensuring proper root formation and seed production (Khadka et al., 2018). Potassium levels, found between 110 and 290 mg kg^{-1}, support tuber crops like potatoes and yams, as well as fruit-bearing plants such as citrus and bananas (Jena et al., 2024). Soil pH influences nutrient availability, and proper liming practices can help maintain optimal conditions for crop productivity while minimizing soil acidity issues (Poudel et al., 2023).

Soil fertility mapping is an essential approach for assessing nutrient levels based on soil test results and developing thematic maps for land use, land cover, and soil fertility. The integration of geographic information systems (GIS) and global positioning systems (GPS) has revolutionized soil fertility assessment (Jena et al., 2024). GPS technology enables precise spatial data collection, which facilitates site-specific nutrient management planning.

GIS-based soil fertility mapping provides valuable insights into soil nutrient status and supports informed decision-making for land-use planning, soil conservation, and agricultural productivity enhancement (Lanki and Onwu, 2024). These technologies help address key challenges related to soil erosion, degradation, and nutrient deficiencies (Havlin and Heiniger, 2020). In the context of Nepal, GIS and GPS-based soil fertility mapping can be instrumental in diagnosing soil conditions and providing targeted nutrient recommendations for specific crops (Panday et al., 2019). By offering spatially explicit soil fertility assessments, these technologies empower decision-makers and farmers to implement effective strategies for managing soil acidity, optimizing fertilizer application, and maintaining soil organic matter. Given the direct influence of soil quality on agricultural output, understanding the interactions between biological, chemical, and physical soil properties is crucial for optimizing nutrient availability while minimizing environmental degradation (Rawal et al., 2018). Despite extensive research efforts on soil fertility improvement through organic and inorganic amendments and soil and water conservation techniques, Nepalese farmers continue to face significant soil fertility challenges. Adoption rates for improved soil management practices remain low, highlighting the need for increased awareness and capacity-building initiatives to promote sustainable soil fertility management (Desbiez et al., 2004). Digital soil mapping, through the integration of GIS and GPS technologies, offers a promising approach to addressing these challenges by providing comprehensive insights into soil variability and supporting precision agriculture. Therefore, this study focuses on digital soil mapping for soil fertility analysis in Rong Rural Municipality, Ilam, Nepal, with the goal of assessing soil nutrient distribution and facilitating sustainable agricultural practices.

2. Materials and methods

2.1. Study area

The research was conducted in Rong Rural Municipality, located in the Ilam district of Koshi Pradesh in southeastern Nepal. This area spans an elevation range from 300 meters to 2,250 meters above sea level, contributing to its diverse climatic and ecological conditions. Geographically, it is positioned at approximately 27.052° N latitude and 87.8057° E longitude. Rainfall in Rong Rural Municipality varies depending on the specific location and season, with annual precipitation typically ranging between 2,000 mm and 3,000 mm. The climate is generally mild to moderate throughout the year, with daytime temperatures ranging from 15°C to 25°C. In winter, nighttime temperatures can drop significantly, often reaching between 5°C and 15°C. Agriculture plays a vital role in the region's economy and community life, with approximately 71% of the land dedicated to farming. The soil composition varies due to the mountainous terrain and climatic influences, ranging from fertile alluvial soils in valley areas to less fertile, rocky soils on steep slopes. Farmers primarily practice subsistence agriculture, cultivating crops such as maize, millet, rice, and various vegetables. Given the rugged landscape, terraced farming is a common technique used to facilitate cultivation on sloped land. While traditional farming methods are prevalent, there are ongoing efforts to enhance productivity through modern techniques and crop diversification. Additionally, the rural municipality is engaged in various development initiatives, particularly in improving infrastructure and agricultural practices.

2.2. Soil sample and sampling techniques

Soil samples were collected from seven wards (1, 2, 3, 4, 5, 6, and 7) of Rong Rural Municipality, Ilam, using a simple random sampling technique. Each soil sample was taken from a depth of 20 cm below the land surface by making a V-shaped cut. The zigzag method was employed to collect samples from each land type, ensuring equal representation. A total of 100 soil samples were gathered from Rong Rural Municipality for the analysis of various soil parameters, including soil pH, organic matter, nitrogen (N), phosphorus (P), potassium (K), and soil texture. Sampling locations were determined based on morphology, geology, and land use conditions. The precise coordinates (latitude and longitude) of each sample site were recorded using the GPS Toolbox application and later imported into ArcGIS 10.5 software to generate thematic soil fertility maps.

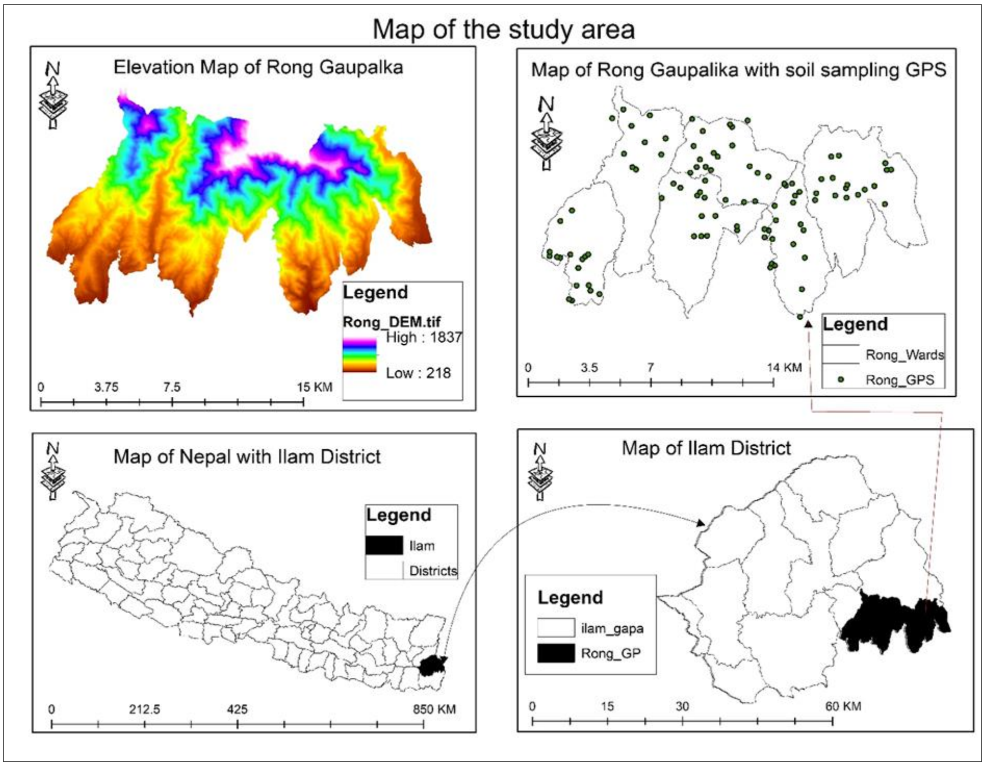
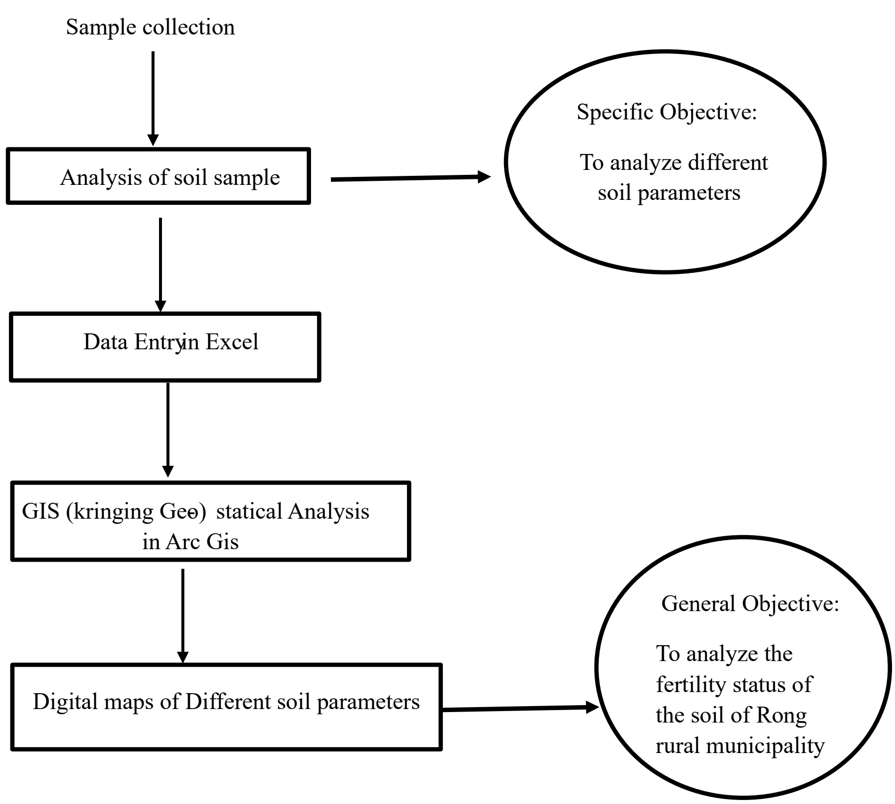


Figure 1. Location map of the study area

2.3. Research design



2.4. Research instruments

Various instruments and devices were used for soil sample collection in the field and for measuring the physico-chemical properties of the soil in the laboratory. Different types of augers and spades were utilized based on the land type to ensure efficient sample collection. Additionally, various chemical reagents and laboratory equipment were employed for both qualitative and quantitative analysis of the soil samples. The laboratory analysis of soil parameters in this study employed a range of established methods to ensure accurate assessment of soil health and fertility. Soil organic matter was determined using the Walkley and Black Method, a widely used wet oxidation technique that involves the oxidation of organic carbon with potassium dichromate in acidic conditions, followed by titration to measure the organic content. Soil texture was analyzed using the Hydrometer Method, which determines the relative proportions of sand, silt, and clay by measuring particle settling rates in a suspension, providing critical information on soil structure and water-holding capacity. The soil pH was measured using a digital pH meter, an electronic device that precisely determines the hydrogen ion concentration in soil-water suspension, indicating soil acidity or alkalinity, which directly affects nutrient availability. Available nitrogen was quantified using the Kjeldahl distillation unit, a technique that involves digestion with concentrated sulfuric acid followed by distillation and titration to estimate total nitrogen content, crucial for plant growth. Available phosphorus was assessed using the Modified Olsen's Bicarbonate Method, which extracts phosphorus using a sodium bicarbonate solution at a controlled pH, ensuring reliable measurement in both neutral and calcareous soils. Finally, available potassium was analyzed using a Flame Photometer, an instrument that detects potassium ions based on the emission of characteristic wavelengths when introduced into a flame, providing precise quantification of potassium levels essential for plant metabolism.

2.5. Digital elevation model

A Digital Elevation Model (DEM) is a digital representation of the Earth's surface that provides elevation data for various locations (Guth et al., 2021). It is widely used in fields such as geography, cartography, hydrology, environmental modelling, and urban planning. DEMs play a crucial role in generating topographic maps, calculating slopes, identifying landforms, and assessing land susceptibility. Additionally, they can be used to derive various maps, including slope maps, aspect maps, hillside maps, and contour lines. The elevation in the study area ranges from 67 meters to 122 meters.

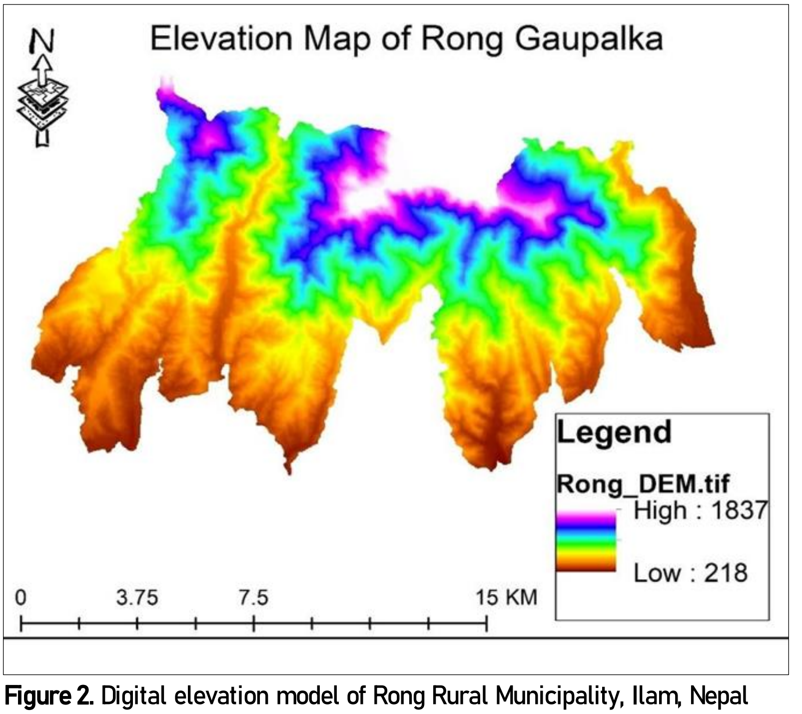


Figure 2. Digital elevation model of Rong Rural Municipality, Ilam, Nepal

2.6. Soil pH and nutrient-based soil fertility ratings

The Soil and Manure Testing Laboratory, Ilam, Nepal, classifies soil pH into four categories based on Table 1: Acidic (4.5–5.5), Slightly Acidic (5.5–6.5), Nearly Neutral (6.5–7.5), and Alkaline (>7.5). Table 2 categorizes soil fertility into Low, Medium, High, and Very High classes based on organic matter, total nitrogen, available phosphorus (P_2O_5), and potassium (K_2O). For instance, Low fertility includes organic matter (1.25–2.25%), total nitrogen (0.05–0.1%), P_2O_5 (10–31 mg kg^{-1}), and K_2O (55–110 mg kg^{-1}), whereas very high fertility exceeds 10% organic matter, 0.4% nitrogen, 110 mg kg^{-1} P_2O_5, and 500 mg kg^{-1} K_2O. These classifications help guide soil amendments and nutrient management for sustainable agricultural productivity.

Table 1. Rating of soil pH adapted by soil and Manure Testing Laboratory, Ilam, Nepal

S.N.	pH Range	Soil reaction (pH)
1	4.5-5.5	Acidic (A)
2	5.5-6.5	Slightly Acidic (SA)
3	6.5-7.5	Nearly Neutral (NN)
4	More than 7.5	Alkaline (ALK)

Table 2. Different rating classes of soil test data adapted by Soil and Manure Testing Laboratory, Ilam, Nepal

S.N.	Classes	Organic matter (%)	Total Nitrogen (%)	Available P_2O_5	Available K_2O
1	Low (L)	1.25-2.25	0.05-0.1	10-31	55-110
2	Medium (M)	2.5-5.0	0.1-0.2	31-55	110-280
3	High (H)	5 to 10	0.2-0.4	55-110	280-500
4	Very High	>10	> 0.4	> 110	> 500

2.7. Laboratory analysis

The collected soil samples were analyzed at the Soil and Manure Testing Laboratory in Surunga, Ilam. The physico-chemical data, including pH, organic matter (OM), nitrogen (N), phosphorus (P), and potassium (K), were measured quantitatively, while soil texture was assessed qualitatively. Before analysis, the soil samples were air-dried in the shade, crushed, and sieved. The various parameters that were tested, along with the methods used for analysis, were presented in Table 3.

Table 3. Parameters and methods adopted for laboratory analysis

Parameters	Analysis methods
Soil organic matter	Walkey and Black Method
Soil texture	Hydrometer Method
Soil pH	Digital pH meter
Available nitrogen	Kjeldahl Distillation unit
Available phosphorus	Modified olsen's Bicarbonate method
Available potassium	Flame photometer method
Available phosphorus	Modified olsen's Bicarbonate method
Available potassium	Flame photometer method

Some glimpses of Research Activities

2.8. Data analysis

The collected sample was analyzed at the Soil and Manure Testing Laboratory in, Ilam, Nepal. All the observed data and findings were compiled and tabulated using Microsoft Excel. The mean and standard deviation were calculated through Excel, and spatial analysis was conducted using ArcGIS 10.5.

3. Results

The statistical summary of soil parameters in the study area (Table 4) provides insights into soil fertility and variability. Organic matter (OM%) ranges from 2.005% to 4.298%, with a mean of 3.230% and a low standard deviation (SD = 0.436), indicating moderate to high fertility and uniform distribution. Soil pH varies between 5.895 and 6.762, with a mean of 6.331 and minimal variation (SD = 0.191), suggesting a slightly acidic to near-neutral soil condition suitable for most crops. Total nitrogen (N%) appears to have inconsistencies in data representation, but it shows moderate levels with high variability (SD = 5.306), suggesting uneven nitrogen distribution requiring site-specific fertilization. Available phosphorus (P_2O_5) ranges widely from 43.641 to 273.06 kg ha^{-1}, with a mean of 138.817 kg ha^{-1} and a high SD (51.649), indicating significant spatial variation, where some areas may need phosphorus supplementation. Potassium (K_2O) levels range from 340.202 to 762.23 kg ha^{-1}, with a mean of 547.144 kg ha^{-1} and SD of 80.812, showing moderate to high availability but varying across the region. Overall, the soil exhibits moderate fertility with some nutrient imbalances, requiring site-specific soil management strategies to optimize agricultural productivity.

Table 4. Summary of statistical overview of the study area

Parameters	Min	max	Mean	S.D.
OM (%)	2.005	4.298	3.230	0.436
PH	5.895	6.762	6.331	0.191
N (%)	2.001	1.536	0.164	5.306
P_2O_5 (kg ha^{-1})	43.641	273.06	138.817	51.649
K_2O (kg ha^{-1})	340.202	762.23	547.144	80.812

3.1. Soil texture

The textural map presented in figure 3, provides a detailed spatial distribution of soil textures across the survey area, represented using distinct symbols and colors. The legend categorizes soil textures into clay loam, loam, clay, sandy clay, sandy clay loam, sandy loam, silty clay loam, and silty clay. The sampling locations are marked with blue circles, indicating the precise points where soil data was collected. From the map analysis, the clay loam texture, represented by red triangles, is predominantly found in the central and eastern sections of the region. These areas are likely to have moderate drainage properties and good nutrient-holding capacity. The loam soil, depicted by dark purple circles, is scattered throughout the region, particularly in the western and southeastern parts. Loamy soils are well-balanced in terms of sand, silt, and clay, making them highly suitable for agriculture. The sandy clay loam, represented by green squares, appears widely across the map, especially in the northern and central zones. This texture has a moderate level of sand and clay, affecting its permeability and water retention properties. The sandy loam, marked with green plus signs, is distributed across different parts of the study area, particularly in the northern and western regions, indicating higher sand content and lower water retention capacity. The silty clay loam, identified by hollow squares, appears less frequently, concentrated in limited sections, and exhibits a fine texture with moderate drainage. The silty clay, marked by green-circled dots, is sparsely distributed, suggesting minimal presence in the surveyed region. Clay soils, represented by black triangles, are found in certain pockets, indicating regions with high water retention but poor drainage. The scale of 1:120,000 suggests that each centimeter on the map corresponds to 1.2 kilometers on the ground. The distance bar at the bottom indicates that the surveyed area spans approximately 22 km in width, allowing for a broad analysis of soil texture distribution. This information is critical for precision agriculture, land-use planning, and soil fertility management.

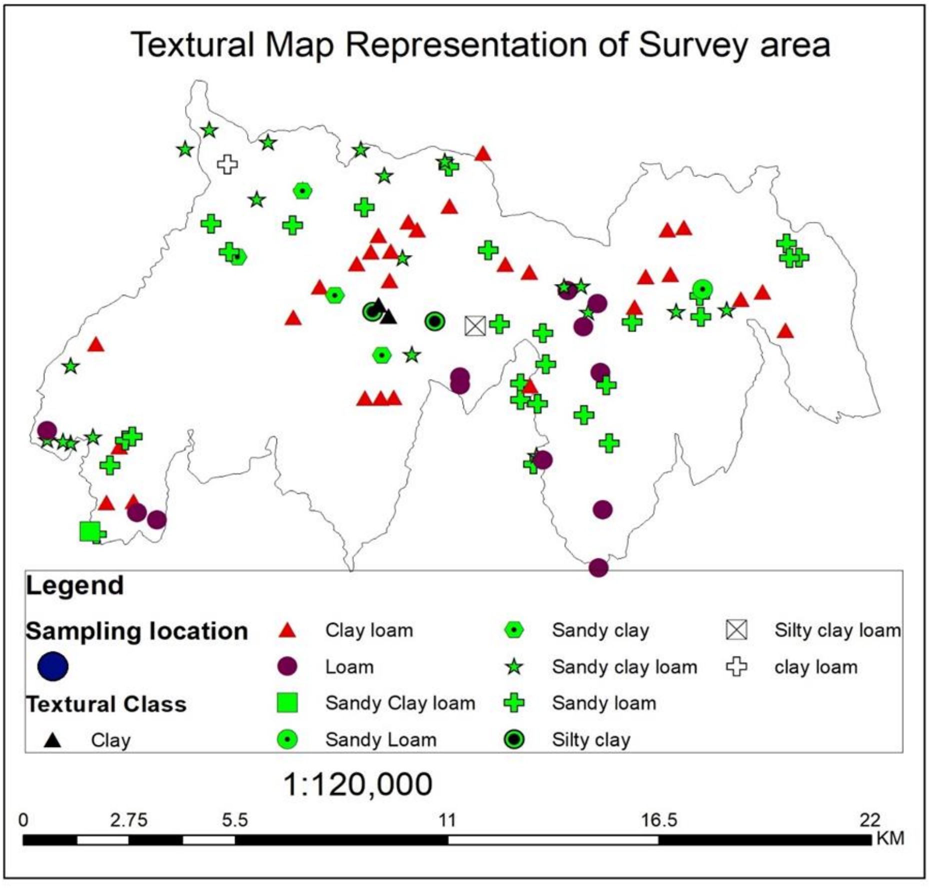


Figure 3. Soil texture map of survey area

3.2. Spatial distribution of soil pH

The pH map of Rong Rural Municipality, Ilam, Nepal (Figure 4) illustrates the spatial distribution of soil pH across the region. The color gradient in the map represents variations in soil acidity, with green shades indicating higher pH values (less acidic soils) and red to orange shades representing lower pH values (more acidic soils). The pH values in the study area range from 5.89585 (most acidic) to 6.76272 (least acidic), as shown in the legend. The northwestern and central regions exhibit higher pH levels, suggesting moderately acidic to neutral soil conditions, whereas the eastern and southeastern parts display lower pH levels, indicating higher soil acidity. A distinct highly acidic zone is observed in the northeastern region, where the pH values drop significantly. These variations in soil pH have important implications for agriculture and land management in the region. Lower pH levels in the eastern and southeastern areas suggest higher soil acidity, which can negatively impact nutrient availability and crop productivity. This indicates the need for proper soil amendments, such as liming, to neutralize soil acidity and enhance fertility. The spatial distribution of pH also highlights the importance of site-specific soil management for optimal crop selection and fertilization strategies. Farmers and agricultural planners can use this data to implement precision farming techniques and sustainable land-use planning to improve crop yield and soil health.

3.3. Spatial distribution of organic matter (OM)

Figure 4 illustrates the spatial distribution of soil organic matter (OM) content across Rong Rural Municipality, Ilam, Nepal. The organic matter values range from a minimum of 2.00592% to a maximum of 4.29894%, as indicated in the legend. The color gradient on the map represents variations in OM content, with green shades indicating higher organic matter levels and red to orange shades representing lower organic matter content.

The eastern and southeastern regions exhibit lower organic matter percentages, suggesting depleted soil fertility, while northwestern and some central parts show relatively higher OM levels, indicating better soil health and nutrient retention. The distribution pattern suggests that organic matter is not uniformly distributed, with certain areas having significantly lower levels, potentially affecting soil structure, moisture retention, and microbial activity. Areas with lower OM levels may require organic amendments such as compost or manure to enhance fertility. On the other hand, regions with higher OM content indicate good soil fertility, which can support better crop growth. Understanding this spatial variation is essential for implementing precision soil management practices, ensuring sustainable agriculture and optimal land-use planning in the study area. Spatial distribution of nitrogen (N):

Figure 4 presents the spatial distribution of available nitrogen (N) content across Rong Rural Municipality, Ilam, Nepal. The nitrogen concentration varies significantly, ranging from a minimum of 0.0200131% to a maximum of 1.53661%, as depicted in the legend. The color gradient illustrates these variations, where green areas indicate higher nitrogen availability, while red and orange shades represent lower nitrogen levels. The majority of the study area exhibits low nitrogen content, with only small, scattered patches showing higher concentrations, particularly in central, southeastern, and northwestern regions. The uneven distribution of nitrogen suggests spatial variability in soil fertility, possibly influenced by land-use patterns, crop rotation, organic matter content, and fertilization practices. The low nitrogen levels in most regions indicate potential nitrogen deficiency, which may limit crop productivity and necessitate supplementary nitrogen fertilization to maintain soil fertility. Conversely, areas with higher nitrogen concentrations may have received more organic inputs or fertilizers, enhancing soil nutrient availability. Therefore, targeted nutrient management strategies are essential to balance nitrogen levels across the municipality, ensuring sustainable agricultural productivity and efficient fertilizer application.

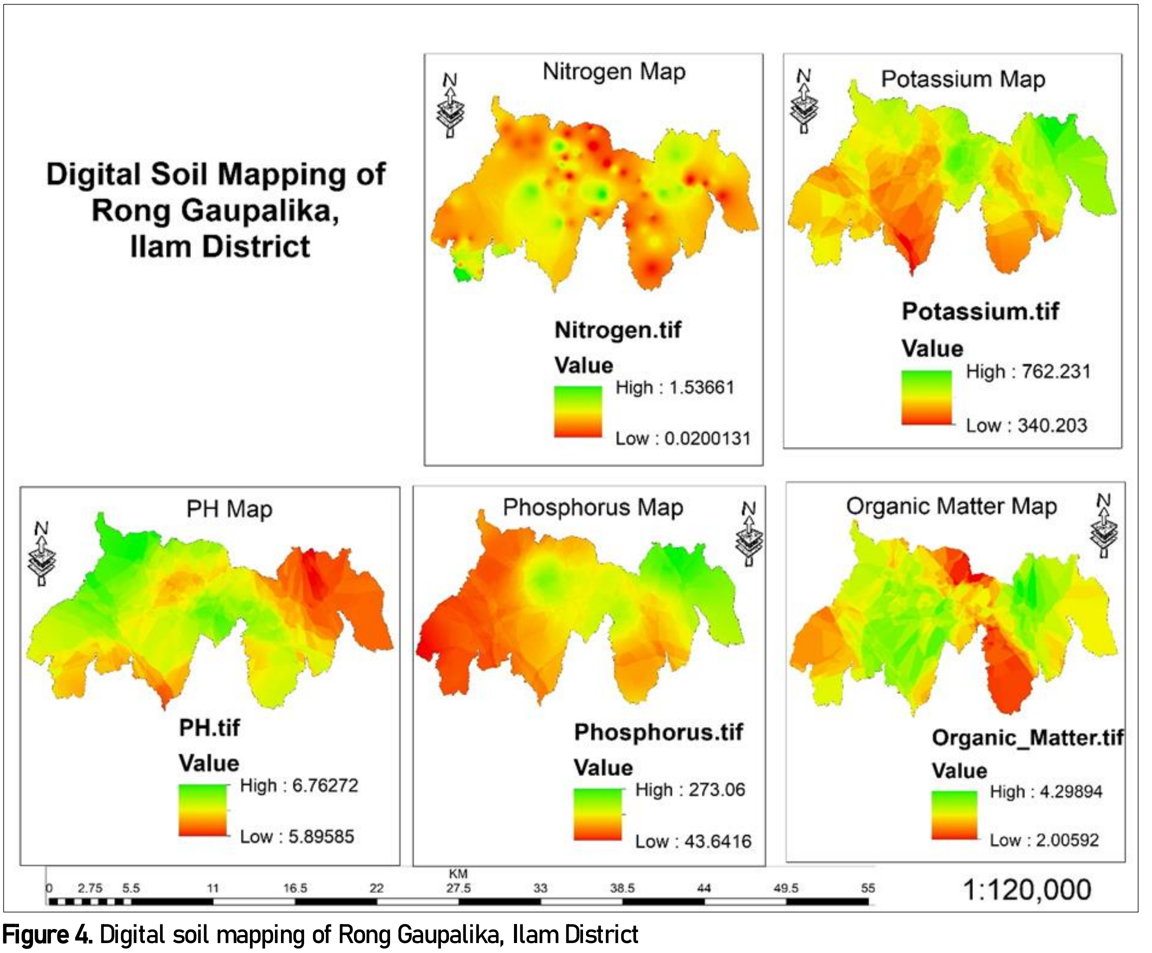


Figure 4. Digital soil mapping of Rong Gaupalika, Ilam District

3.4. Spatial distribution of available phosphorus

The map presented figure 4 illustrates the spatial distribution of available phosphorus in Rong Rural Municipality, Ilam, Nepal, with values ranging from 43.64 to 273.06. The color gradient, from red (low phosphorus) to green (high phosphorus), highlights significant variability in soil fertility across the region. Areas with higher phosphorus availability, shown in green, are likely to support better crop growth, whereas red zones with lower phosphorus levels may require nutrient supplementation. This variation is influenced by factors such as land use, soil type, topography, and farming practices. The map provides valuable insights for targeted soil management and sustainable agricultural planning.

3.5. Spatial distribution of available potassium

Figure 4 depicts the spatial distribution of available potassium in Rong Rural Municipality, Ilam, Nepal, with values ranging from 340.20 to 762.23. The map uses a color gradient where green represents areas with higher potassium availability, indicative of more fertile soils, while red indicates regions with lower potassium levels, suggesting potential nutrient deficiencies. This variation in potassium distribution could result from differences in soil characteristics, agricultural practices, and topographical features. The map serves as an essential tool for identifying nutrient-deficient areas and implementing targeted soil fertility management strategies to enhance agricultural productivity.

3.6. Rating map of different soil properties

The rating map of different soil properties of Rong Rural Municipality, Ilam provides a comprehensive evaluation of key soil parameters, including nitrogen, potassium, phosphorus, pH, and organic matter, across the surveyed region. The nitrogen map reveals that approximately 70% of the area falls under the low nitrogen category, primarily in central and western zones, while 20% of the land exhibits medium nitrogen levels, and only around 10% has a high nitrogen content, mostly concentrated in the northern region.

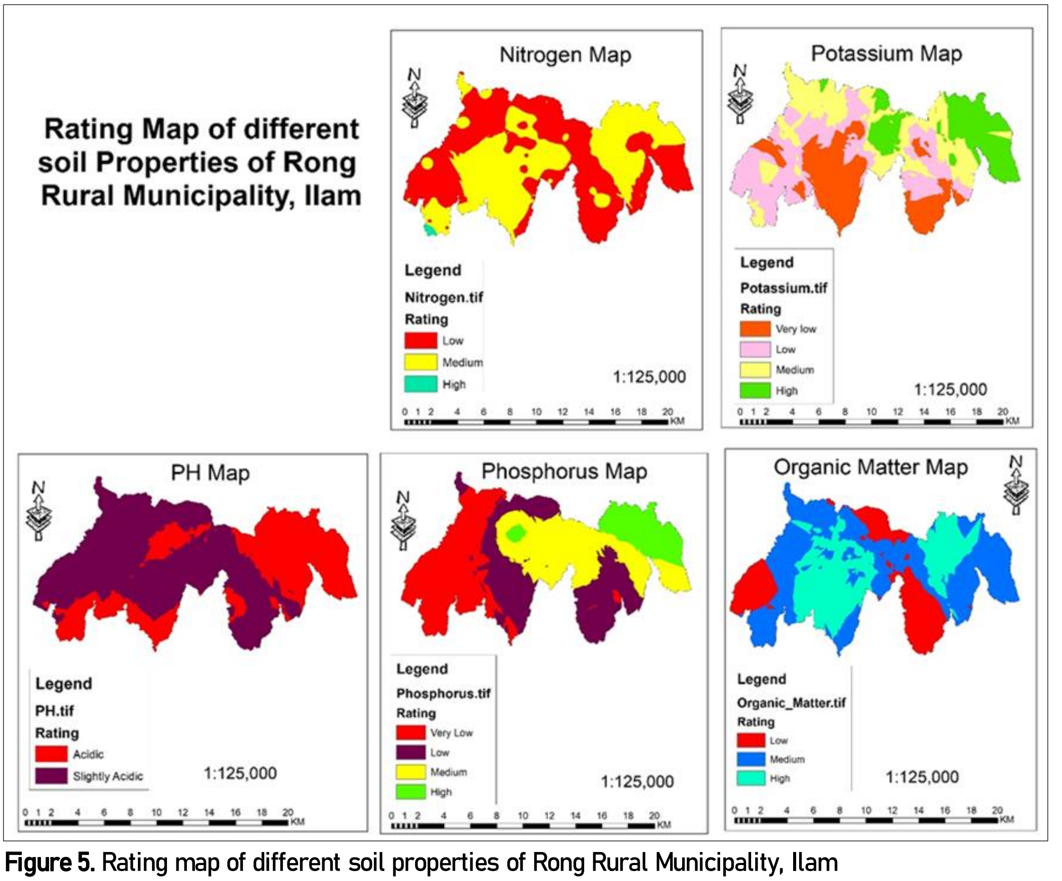


Figure 5. Rating map of different soil properties of Rong Rural Municipality, Ilam

The potassium map indicates a significant deficiency, with nearly 40% of the surveyed area showing very low potassium levels, mainly in the southern and western parts, while about 35% falls under the low category. The medium potassium zone covers roughly 20%, and only about 5% of the land has high potassium content, mostly in scattered patches across the central and northern regions. The pH map shows that around 65% of the land is acidic, predominantly in the central and southern areas, while 35% is slightly acidic, found mostly in the northeastern parts. Acidic soil conditions may limit nutrient availability and require liming to enhance productivity. The phosphorus map reveals that approximately 50% of the area has very low phosphorus content, particularly in the eastern and central sections, while 30% falls under the low category, 15% in medium, and only 5% of the land exhibits high phosphorus levels, mainly in the northernmost regions. The organic matter map indicates that about 50% of the land has low organic matter content, concentrated in the southern and central areas, while 30% of the region has medium levels, and 20% exhibits high organic matter content, primarily in the northern and northeastern zones. These findings emphasize the need for targeted nutrient management strategies, including fertilizer application, organic matter incorporation, and pH correction, to optimize soil health and enhance agricultural productivity in Rong Rural Municipality, Ilam.

4. Discussions

The study of soil parameters in Rong Rural Municipality, Ilam, Nepal, reveals significant spatial variability in organic matter, soil pH, nitrogen, phosphorus, and potassium. These findings are crucial for understanding soil fertility and implementing targeted soil management strategies to enhance agricultural productivity (Pokharel et al., 2023; Jena et al., 2024). The comparison of our results with previous studies highlights both consistencies and discrepancies, emphasizing the need for localized soil fertility management (Bajracharya et al., 2009). Our study found that soil organic matter (OM) ranged from 2.005% to 4.298%, with a mean of 3.230% and a low standard deviation (SD = 0.436), indicating moderate to high fertility with relatively uniform distribution. This is consistent with the findings of Pokharel et al. (2023) and Bhandari et al. (2020), who reported OM levels between 2.1% and 4.5% in eastern Nepal, indicating moderate fertility suitable for crop production. Similarly, Khadka et al. (2019) found that OM in mid-hill soils of Nepal ranged between 1.8% and 4.6%, supporting our results. However, compared to the study conducted by Shrestha et al. (2019) in the Terai region, which reported significantly lower OM levels (1.2%–3.0%), our findings suggest that the organic matter content in the hilly terrain of Ilam is relatively higher, likely due to organic farming practices and high biomass decomposition rates. The spatial distribution of OM in our study shows higher levels in the northwestern and central regions, aligning with findings by Bhandari et al. (2020), who observed that OM is generally higher in less-disturbed forested and upland areas due to greater leaf litter accumulation and slower decomposition rates. The pH of the study area ranged from 5.895 to 6.762, with a mean of 6.331 and minimal variation (SD = 0.191). This suggests a slightly acidic to near-neutral soil condition, which is suitable for most crops. Our findings are comparable to those of Ghimire et al. (2017) and Pokharel et al. (2023), who reported that soils in mid-hill regions of Nepal typically exhibit pH values between 5.5 and 6.8, supporting the slightly acidic nature observed in our study. A study by Bajracharya, et al. (2009) on Nepalese soils indicated that higher elevation areas generally have more acidic soils due to high rainfall, which leaches basic cations such as calcium and magnesium. The lower pH values in the eastern and southeastern parts of Rong Rural Municipality are consistent with this trend, highlighting potential soil acidity problems that may require liming to improve soil fertility. In contrast, the northwestern and central regions, which exhibit higher pH, are likely influenced by reduced leaching and higher base saturation, like the findings of Pokharel et al. (2023) in the mid-hill regions. Total nitrogen (N%) in the study area showed a wide range (0.020% to 1.536%) with a mean of 0.164% and a very high standard deviation (SD = 5.306), indicating significant spatial variation. The uneven nitrogen distribution suggests variable fertilizer application rates, land-use patterns, and organic matter decomposition rates. Shrestha et al. (2018) and Vista et al. (2018) reported similar nitrogen variability in eastern Nepal, emphasizing that the uneven application of nitrogen fertilizers and organic matter inputs can create large discrepancies in soil nitrogen levels. Compared to our study, Baral et al. (2021) found nitrogen levels in Nepalese agricultural soils to range between 0.12% and 1.65%, which closely matches our findings. However, our results indicate a greater variation, possibly due to differences in land use, erosion rates, and fertilizer application patterns.

Vista et al. (2019) and Shrestha et al. (2019) reported that nitrogen levels are generally higher in areas with higher organic matter content, which is consistent with our spatial distribution showing that central, northwestern, and southeastern parts have higher nitrogen levels. Phosphorus levels varied from 43.641 to 273.06 kg ha^{-1}, with a mean of 138.817 kg ha^{-1} and a high SD (51.649), indicating significant spatial variation. These results are in agreement with those of Cambardella and Karlen (1999) and Chang et al. (2024), who found phosphorus levels in Nepalese soils ranging from 50 to 250 kg ha^{-1}, with higher variability in hilly regions due to soil erosion and leaching. Our findings align with the results of Khadka et al. (2019), who suggested that phosphorus deficiency is common in acidic soils of Nepal, particularly in regions with high rainfall, as phosphorus is easily leached. The eastern and southeastern parts of our study area showed lower phosphorus availability, supporting this claim. In contrast, areas with higher phosphorus levels could be due to localized fertilizer applications or slow mineralization of organic phosphorus compounds. Potassium (K_2O) levels ranged from 340.202 to 762.23 kg ha^{-1}, with a mean of 547.144 kg ha^{-1} and SD of 80.812, indicating moderate to high availability but varying across the region. These values are comparable to those reported by Khadka et al. (2019), who found that potassium availability in Nepalese mid-hill soils typically ranges from 300 to 800 kg ha^{-1}. A study by Tiwari et al. (2018) suggested that high potassium levels in Nepalese soils are often associated with mineral-rich parent material. Our findings support this observation, as higher potassium availability was found in the northwestern and central regions, which are less affected by leaching and have higher clay content, leading to better potassium retention. Conversely, the low potassium levels in the southeastern parts may be due to intensive farming practices and soil erosion, consistent with the findings Venishetty et al. (2024).

5. Conclusion

This study highlights the significant spatial variability of key soil fertility parameters—organic matter, pH, nitrogen, phosphorus, and potassium—in Rong Rural Municipality, Ilam, Nepal, underscoring the critical importance of localized assessments for effective soil management. By utilizing GIS-based soil fertility mapping, this research demonstrates the effectiveness of spatial analysis in identifying nutrient distribution patterns and addressing region-specific challenges such as soil acidity, nutrient imbalances, and inconsistent fertilizer practices. These insights provide a foundation for implementing precise, targeted soil management strategies, enabling optimized crop productivity while minimizing input inefficiencies. The findings further emphasize the need for sustainable agricultural practices to enhance soil health and resilience. Future research should focus on long-term soil fertility monitoring and the development of adaptive, region-specific nutrient management frameworks to address evolving agricultural and environmental challenges effectively.

Compliance with Ethical Standards

Conflict of Interest

The authors declare that they have no conflict of interest.

Authors' Contributions

Riya POUDEL: Conceptualization, data curation, investigation, methodology, visualization, original draft writing, review and editing of writing, and validation. **Pawan Kumar YADAV**, **Tulasha GAUTAM**, **Radhika BHARATI**, **Yatiraj PYAKUREL** and **Abhishek BANIYA**: Data curation, investigation, methodology, visualization, original draft writing, review and editing of writing. **Ravi ACHARYA** and **Animesh KHADKA**: Supervision and validation.

Ethical approval

This study did not require ethical approval because it did not involve any experiments or human or animal subjects.

Funding

This study was conducted without any financial support or external funding.

Data availability

No data is available for this study.

Consent for publication

All authors have given their consent for the publication of this manuscript.

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