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Research Article

GIS-Based Analysis of Macronutrient Distribution in Agricultural Soils of Upparapalli Village, Andhra Pradesh

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Abstract

Declining soil fertility and pronounced spatial variability of nutrients remain major constraints to sustainable agricultural productivity, particularly under intensive and resource-limited farming systems in semi-arid regions. The study aimed to assess and map the spatial distribution of available macronutrients (N, P, K, Ca, Mg and S) in the surface soils of Upparapalli village to support site-specific nutrient management. A GPS-based grid soil sampling approach (170 × 170 m) was adopted, resulting in 200 surface soil samples (0-15 cm). Standard laboratory procedures were used to estimate available nitrogen, phosphorus, potassium, sulphur, exchangeable calcium, and magnesium. Spatial interpolation and thematic nutrient maps were generated using GIS with the inverse distance weighting (IDW) technique. Soils exhibited low to medium available nitrogen, with more than 96% of the area classified as nitrogen-deficient. Available phosphorus and potassium were predominantly in the medium category, with localized high concentrations linked to fertilizer use and soil mineralogy. Secondary nutrients sulphur, calcium, and magnesium were largely sufficient across the study area, though sulphur showed high spatial variability. The study revealed substantial spatial heterogeneity in soil macronutrient distribution, underscoring the inadequacy of uniform fertilizer recommendations for the region. GIS-based soil fertility mapping provides a robust decision-support tool for developing site-specific nutrient management strategies, enabling efficient fertilizer use, improved soil health, and enhanced sustainability of agricultural production systems.

Keywords: GIS; Macronutrients; Soil Fertility; Site Specific Nutrient Management; Spatial Variability

Abbreviation

IDW: Inverse Distance Weighting; GIS: Geographic Information System; GPS: Global Positioning System

Introduction

Soil quality is influenced by factors like fertility, compaction potential, and susceptibility to erosion. Of these, declining soil fertility is the most critical issue, as it significantly hampers the potential for increased agricultural productivity [1]. [2] highlighted that among the various challenges to sustainability, soil fertility depletion is the most severe. Factors such as cropping patterns, leaching, and erosion cause significant nutrient loss from the soil annually. When crops are grown continuously without replenishing these lost nutrients, soil fertility gradually diminishes, leading to a decline in crop productivity over time. Applying fertilizers without prior knowledge of the soil's fertility status can have negative impacts on both soil health and crop performance. This practice may lead to nutrient deficiencies or toxicities due to either insufficient or excessive fertilizer use [3].

The four South Asian nations that make up the majority of the world's population roughly 40% are in utter poverty. In these regions, farmers face significant challenges in improving their livelihoods, primarily due to small landholdings, intensive cropping patterns, and diverse field management practices applied to different crops [4]. These challenges are further compounded by the use of generalized nutrient recommendations and limited access to technological support. As a result, plant nutrients are often applied in an unbalanced and insufficient manner, leading to reduced crop productivity. Additionally, nutrient variability in the soil is considerable under such farming conditions, driven by differences in farmers' knowledge, fertilizer usage, cropping patterns, farm management practices, and the availability of resources.

Soil testing offers valuable insights into the nutrient content of soils, serving as a foundation for making effective fertilizer recommendations aimed to maximizing crop yields. Fertility maps are developed to illustrate the nutrient requirements of different areas at site-specific, based on the soil's fertility levels and any unfavourable conditions that need to be addressed for achieving optimal crop production [5]. In this context, soil fertility mapping using a Geographical Information System (GIS) has emerged as a valuable and effective approach.

With the advent of modern technologies such as remote sensing, GIS, and GPS, monitoring soil fertility and crop health has become more efficient and systematic. These tools enable detailed surveys that can track changes in soil fertility over time and support the development of site-specific nutrient management strategies tailored to crop needs [6]. This approach also enables the monitoring of nutrient status changes over time, as geo-referenced sampling locations can be accurately revisited using GPS technology—an advantage not easily achievable with traditional random sampling methods. Interpolation is a technique of estimating a variable at an unsampled location from observed values at the neighbourhood. Among the various methods of interpolation, IDW (Inverse Weighted Distance) is the faster technique than other methods.

Despite the increasing recognition of soil fertility mapping as a tool for sustainable nutrient management, significant research gaps persist at the village and community scales, particularly in semi-arid regions of southern India. Most existing soil fertility assessments rely on generalized or administrative-scale datasets, which fail to capture fine-scale spatial variability arising from heterogeneous land use, smallholder-driven management practices, and localized fertilizer application patterns. Moreover, conventional soil testing approaches are often disconnected from precise spatial referencing, limiting their practical utility for site-specific nutrient recommendations at the farm level. In many farming communities, including Upparapalli village, nutrient management decisions continue to be based on blanket fertilizer recommendations, with little consideration of within-village variability in soil nutrient status, leading to nutrient imbalances, declining nitrogen use efficiency, and unnecessary input costs.

Furthermore, while several studies have applied GIS techniques for soil nutrient mapping, comprehensive evaluations integrating primary macronutrients (N, P, K) with secondary nutrients (S, Ca, and Mg) at a high sampling density remain limited for the Tirupati region. There is also a lack of systematically generated, GPS-referenced fertility maps that farmers and extension agencies can readily use for targeted nutrient management. In addition, comparative evaluation of spatial variability using robust interpolation techniques such as inverse distance weighting (IDW) at the micro-watershed or village scale remains underexplored.

In this context, the present study addresses these gaps by employing a GPS-based grid soil sampling framework coupled with GIS-based spatial analysis to generate high-resolution fertility maps for all major and secondary macronutrients in Upparapalli village. By integrating laboratory-derived soil fertility data with geospatial interpolation techniques, this research provides new, location-specific insights into nutrient distribution patterns and establishes a methodological framework that supports precision nutrient management, improved fertilizer-use efficiency, and sustainable soil health management at the community level.

Considering the context outlined above, the current study was conducted with the objective of evaluating the spatial distribution of available macronutrients (N, P, K, Ca, Mg and S) in the surface soil. During this study, GPS-based soil testing was carried out to examine the macronutrient levels in the soils of Upparapalli village in Tirupati district, Andhra Pradesh, India.

Materials and Methods

Site description

Upparapalli village is situated in Pakala mandal of Tirupati district, Andhra Pradesh, covering a total geographical area of 922.8 hectares, of which 621.44 hectares are under agricultural use and the remaining 301.36 hectares are classified as non-agricultural land. The village lies between 13°28′25″ to 13°26′25″ North latitude and 79°07′11″ to 79°04′16″ East longitude, with an average elevation of 361 meters (1184 feet) above sea level.

A reconnaissance survey was undertaken across Upparapalli, which comprises three hamlet villages—Mallelacheruvupalli, Gollapalle, and Ramireddugaripalle. Representative soil sampling sites were identified based on field survey numbers and farmer holdings to ensure spatial and typological representation of the area's soils. The predominant crops cultivated in the region include groundnut, paddy, and sugarcane, reflecting the agronomic practices and land use patterns typical of the area. The location map of study area was shown Figure 1.

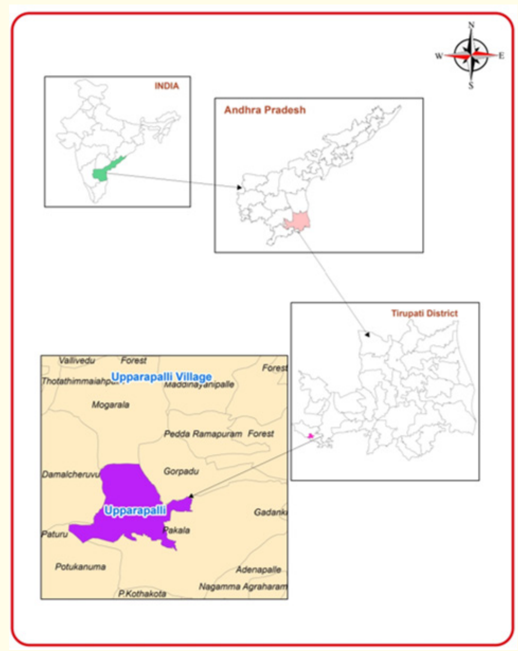

Figure 1: Location map of Upparapalli village.

Soil sampling and analysis

Surface soil samples (0-15 cm depth) were collected following the harvest of winter crops across Upparapalli village using a systematic grid-based sampling approach. The total geographical area of the village is 922.8 hectares, comprising 621.44 hectares of agricultural land and 301.36 hectares of non-agricultural land. Sampling was conducted across surveyed field numbers using a 170 × 170 m grid interval at a scale of 1:50,000, resulting in the collection of 200 composite surface soil samples. The geographic coordinates of each sampling location were recorded using a handheld GPS device (GARMIN 72H). At each sampling point, disturbed composite soil samples were collected in polythene bags and transported to the laboratory. Samples were air-dried, thoroughly homogenized, gently ground using a wooden mortar, and sieved through a 2-mm mesh for further analysis.

Available nitrogen (N) was estimated using the alkaline permanganate method as described by [7]. Available phosphorus (P) was determined following the Olsen method [8], where 2.5 g of soil was extracted with 50 ml of 0.5 M $NaHCO_3$ (pH 8.5) for 30 minutes, and phosphorus in the extract was measured using the L-ascorbic acid colorimetric method [9]. Available potassium (K) was extracted using 1N ammonium acetate (NH_4OAc) at pH 7.0 and quantified with a flame photometer [10]. Available sulphur (S) was extracted using 0.15% calcium chloride ($CaCl_2$), and sulphur content in the extract was measured turbidimetrically using barium chloride ($BaCl_2$) crystals, following the procedure of [11]. Exchangeable calcium (Ca) and magnesium (Mg) were determined by the Versenate titration method described by [12]. All nutrient concentrations and their limits were interpreted in Table 1.

Table 1: Ratings for available macronutrients.

Parameters	Ratings
Available macronutrients	
Nitrogen (kg ha^{-1})	
Low	< 280
Medium	280-560
High	>560
Phosphorus (P_2O_5) kg ha^{-1}	
Low	< 25
Medium	25 - 59
High	> 59
Potassium (K_2O) kg ha^{-1}	
Low	< 145
Medium	145 - 340
High	> 340
Calcium (cmol (p^+) kg^{-1})	
Sufficient	> 1.5
Deficient	< 1.5
Magnesium (cmol (p^+) kg^{-1})	
Sufficient	> 1.0
Deficient	< 1.0
Sulphur (mg kg^{-1})	
Sufficient	> 10
Deficient	< 10

Generation of maps

The agricultural land of Upparapalli village was delineated using mandal boundaries and a geo-referenced Survey of India toposheet (57O03). Geo-referencing of the toposheet was carried out using ERDAS IMAGINE software. The relevant spatial extent of the study area was extracted as a subset for further geospatial analysis. The toposheet provided a comprehensive overview of the village, capturing key features such as the village boundary, railway line, district roads, streams, and water bodies, which were used to generate a detailed base map.

*Arc*GIS version 10.3 was employed for spatial data processing. Sample location data were organized in Microsoft Excel and imported as point features into the GIS environment, where they were spatially linked to corresponding attributes using the 'Join' function. The integration of spatial and non-spatial data facilitated the development of thematic maps illustrating the spatial distribution of soil nutrients across the village landscape.

Results and Discussion

Available nitrogen

The available nitrogen content in soils of Upparapalli village falls under low to medium. The available nitrogen content of the soils varied from 25 to 439 kg ha^{-1} with a mean and standard deviation of 158 kg ha^{-1} and 92.04, respectively, the coefficient of variation of 58.16 per cent indicating that soils for available nitrogen were spatially varied (Table 2). Mapping of soil available nitrogen revealed that 96.39 per cent (599.03 ha) of the study area was low in nitrogen and 3.61 per cent (22.41 ha) was medium in available nitrogen (Figure 2). Therefore, Farmers across Upparapalli village should prioritize nitrogen application, as low available N dominates the entire area. Split application of N is recommended in the central and eastern cultivated zones, while incorporation of organic manures and green manuring should be encouraged in upland and peripheral low-N areas.

The efficiency of applied nitrogen is generally low, primarily due to its loss through several pathways such as volatilization (especially in predominantly alkaline soils), nitrification, denitrification, chemical and microbial fixation, as well as leaching and sur-

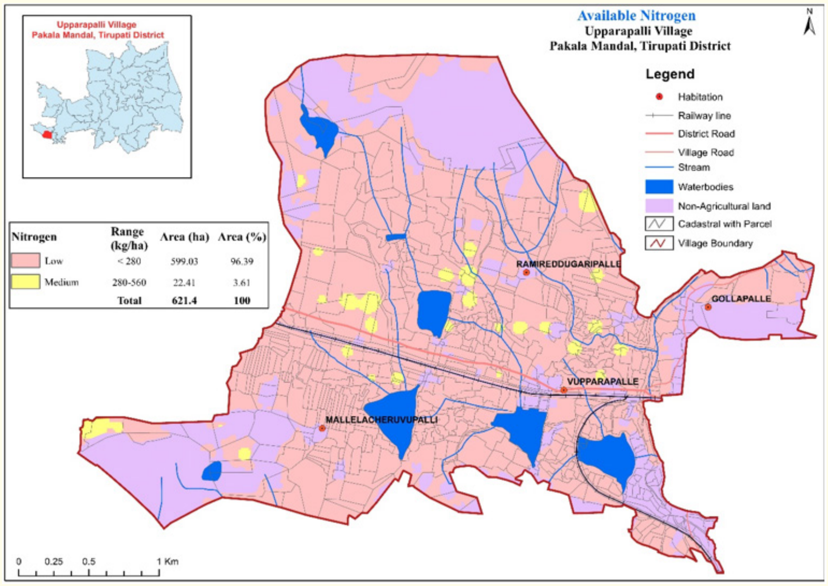

Figure 2: Spatial distribution of available nitrogen in soils of Upparapalli village.

face runoff [13]. The reduced availability of nitrogen in the samples may also be a result of the semi-arid climatic conditions, which likely accelerated the oxidation of nitrogen in the soil [14]. Another contributing factor could be the tropical climate, which accelerates the breakdown and depletion of organic matter, thereby leading to nitrogen deficiency [15]. In certain areas, a medium nitrogen status was observed, which may be attributed to the use of nitrogen fertilizers along with the presence of dense vegetative cover [16].

Available phosphorus

The available phosphorus (P_2O_5) content in the soils of Upparapalli village exhibited a wide range, varying from 11 to 87 kg ha^{-1}, with a mean value of 44.67 kg ha^{-1} and a standard deviation of 20.95 kg ha^{-1}. The coefficient of variation was calculated at 46.90%, indicating considerable spatial heterogeneity in phosphorus availability across the study area (Table 2). GIS-based spatial mapping of available phosphorus revealed that the majority of the village's land area (85.09%, equivalent to 528.77 ha) falls under the medium availability category. This was followed by areas categorized as high (12.27%, 76.28 ha) and low (2.64%, 16.39 ha) in available phosphorus, respectively, as depicted in the corresponding Figure 3. Therefore, Phosphorus application can be reduced or avoided in the central and western high-P zones, whereas localized low-P pockets require basal P application. Soil-test-based P management should be followed to prevent further phosphorus accumulation.

The observed low levels of available phosphorus in certain areas can be attributed to its fixation by clay minerals and oxides of iron and aluminium, which render it less accessible to plants. In soils, phosphorus predominantly exists in the solid phase, with limited solubility. Upon application, water-soluble phosphorus rapidly undergoes chemical reactions with soil constituents, leading to its transformation into more stable, less soluble forms. These transformations significantly influence the bioavailability of phosphorus, resulting in only a minor proportion remaining in the soil solution-this fraction is typically measured in standard soil tests [17].

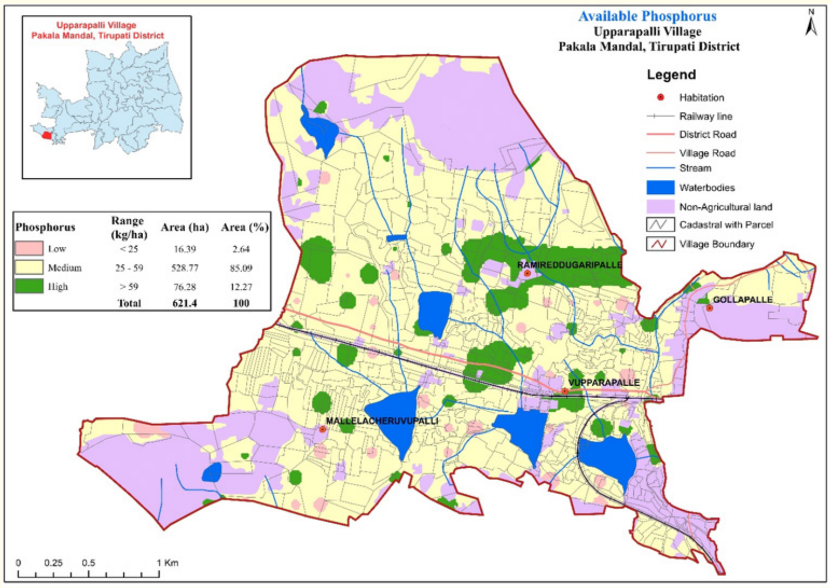

Figure 3: Spatial distribution of available phosphorus in soils of Upparapalli village.

Conversely, elevated levels of available phosphorus (P_2O_5) in certain soils have been associated with the accumulation of phosphorus from the indiscriminate and repeated application of diammonium phosphate (DAP) and other complex fertilizers [18]. In addition, elevated organic matter in surface horizons and the regular application of phosphorus-rich fertilizers contribute to higher phosphorus concentrations in the topsoil [19]. Another contributing factor to high P_2O_5 levels may be the restricted zone of crop cultivation within the rhizosphere, which, when coupled with continuous external phosphorus supplementation, leads to localized phosphorus buildup [20].

Available potassium

The available potassium (K) content in the soils of Upparapalli village exhibited substantial variability, ranging from 60 to 593 kg ha^{-1}, with a mean value of 302 kg ha^{-1} and a standard deviation of 134.18 kg ha^{-1} (Table 2). The coefficient of variation (CV) was 44.36%, indicating notable spatial heterogeneity in potassium availability across the study area. GIS-based spatial analysis revealed that the majority of the land area (65.78%, corresponding to 408.78 ha) was classified as medium in available potassium. This was followed by areas with high potassium availability (32.97%, 204.90 ha) and a small portion with low availability (1.25%, 7.76

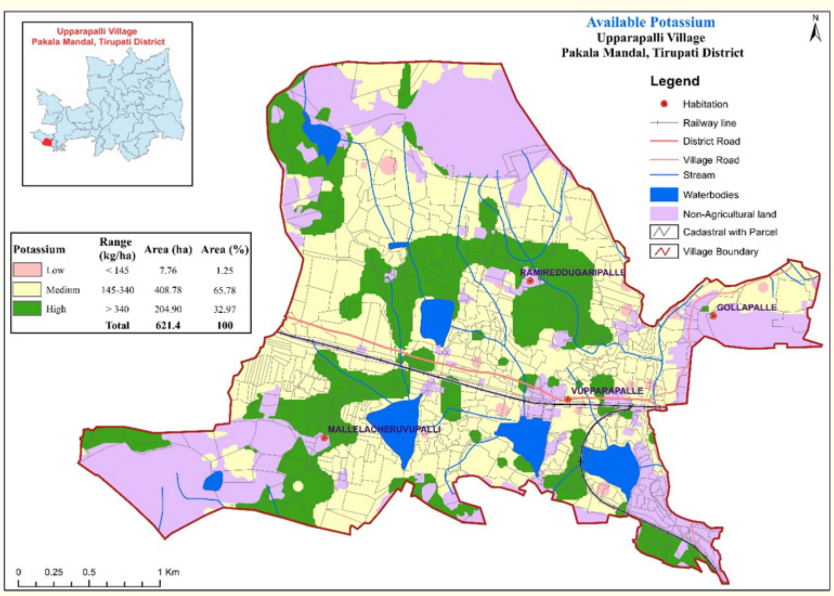

Figure 4: Spatial distribution of available potassium in soils of Upparapalli village.

ha) (Figure 4). Moreover, Farmers in the peripheral and upland zones should prioritize potassium application due to low K status, while K application can be reduced to maintenance doses in the central and southern high-K areas.

The variation in available potassium levels, ranging from low to high across the study area, can be largely attributed to the mineralogical composition of the parent material, particularly the dominance of potash-rich micaceous and feldspar minerals. Similar findings have been reported [21,22]. In addition, processes such as the accelerated weathering of potassium-bearing minerals, the release of exchangeable potassium through organic matter decomposition, and the capillary rise of potassium from subsoil layers influenced by groundwater dynamics contribute to elevated potassium levels in certain areas [23]. Furthermore, the excessive or continuous application of potassic fertilizers may also result in the accumulation of available K_2O in surface soils [24].

Available sulphur

The available sulphur content in the soils of Upparapalli village ranged from 1 to 64 mg kg^{-1}, with a mean value of 24.34 mg kg^{-1} and a standard deviation of 14.73 mg kg^{-1} (Table 2). The coefficient of variation was 60.51%, indicating a high degree of spatial variability in sulphur availability across the study area. Based on the critical threshold of 10.00 mg kg^{-1}, soil sulphur status ranged from deficient to sufficient. GIS-based spatial mapping of available sulphur showed that 96.64% of the area (600.57 ha) was classified as sufficient, while only 3.36% (20.87 ha) was identified as sulphur deficient (Figure 5). Therefore, Sulphur application should be targeted only in localized deficient patches, while S fertilization can be avoided in the majority of the village where sulphur is sufficient.

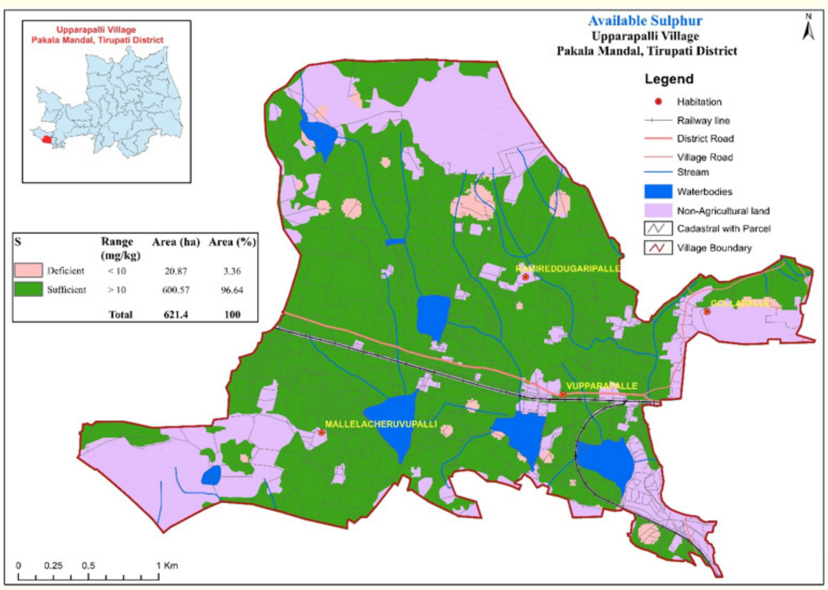

Figure 5: Spatial distribution of available sulphur in soils of Upparapalli village.

The higher sulphur concentrations observed in the surface soil horizons can be attributed primarily to the greater accumulation of organic matter in these upper layers, which enhances sulphur retention and availability [25]. In addition, the sustained application of sulphur-containing fertilizers, such as single super phosphate, has likely contributed to the increased sulphur content. Another contributing factor may be the presence of clay particles with negatively charged surfaces, which repel the sulphate anion (SO_4^{2-}), thereby limiting its leaching and enhancing its availability in the root zone. These findings are consistent with earlier reports [26,27].

Exchangeable calcium

The exchangeable calcium content in the soils of Upparapalli village ranged from 2.3 to 25 cmol(p$^+$) kg^{-1}, with a mean of 9.15 cmol(p$^+$) kg^{-1} and a standard deviation of 2.99 cmol(p$^+$) kg^{-1} (Table 2). The coefficient of variation (32.68%) indicates moderate spatial variability in exchangeable calcium across the study area. According to the critical threshold of 1.5 cmol(p$^+$) kg^{-1}, all soil samples were classified as sufficient in exchangeable calcium. GIS-based mapping confirmed that 100% of the area assessed (621.44 ha) fell within the sufficient range for this nutrient (Figure 6). Therefore, no calcium fertilization is required across Upparapalli village, as exchangeable Ca is sufficient throughout the study area.

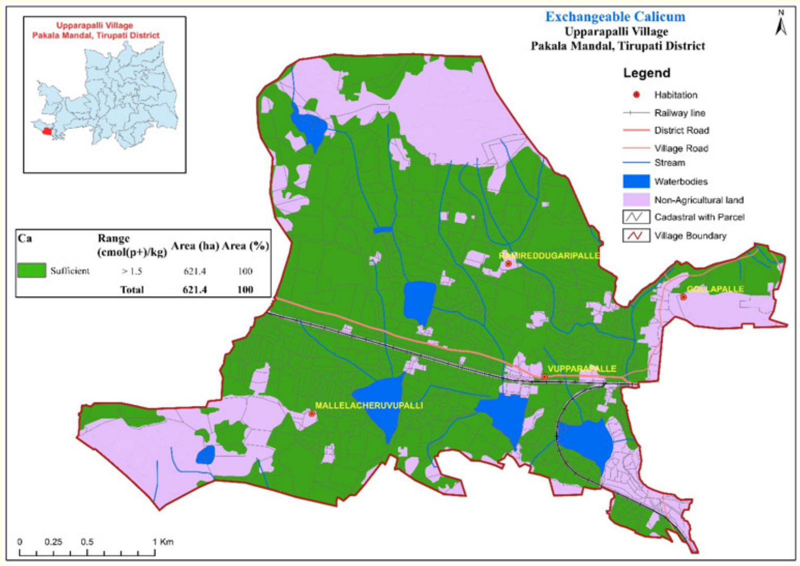

Figure 6: Spatial distribution of exchangeable calcium in soils of Upparapalli village.

This sufficiency in exchangeable calcium may be attributed to the calcium-rich nature of the parent material from which the soils have developed. In arid and semi-arid regions, limited precipitation results in minimal leaching of calcium from the soil profile, facilitating its gradual accumulation over time and often leading to the development of calcareous soils. Additionally, high evaporation rates in these regions can promote the upward movement of calcium-enriched groundwater through capillary rise, further contributing to calcium enrichment in the surface layers. These observations are consistent with the findings reported by [28] Comparable observations have been documented [29,30].

Exchangeable magnesium

Exchangeable magnesium content in the soils of Upparapalli village ranged from 1.0 to 10.5 cmol(p$^+$) kg^{-1}, with a mean value of 5.23 cmol(p$^+$) kg^{-1} and a standard deviation of 2.38 cmol(p$^+$) kg^{-1} (Table 2). The coefficient of variation was 45.50%, indicating considerable spatial variability in magnesium availability across the study area. Based on the critical threshold of 1.0 cmol(p$^+$) kg^{-1}, all soils were classified as sufficient in exchangeable magnesium. GIS-based spatial mapping confirmed that the entire study area (100%, 621.44 ha) fell within the sufficient range for this essential nutrient (Figure 7). Moreover, Magnesium application is not necessary in the village, since exchangeable Mg is sufficient in all mapped areas.

This adequate level of exchangeable magnesium may be attributed to the development of soils from magnesium-rich basic parent materials. Comparable results have been reported by [31]. The generally high levels of exchangeable magnesium in these soils may be attributed to the presence of magnesium-bearing clay minerals, particularly illite and chlorite, as suggested by [32].

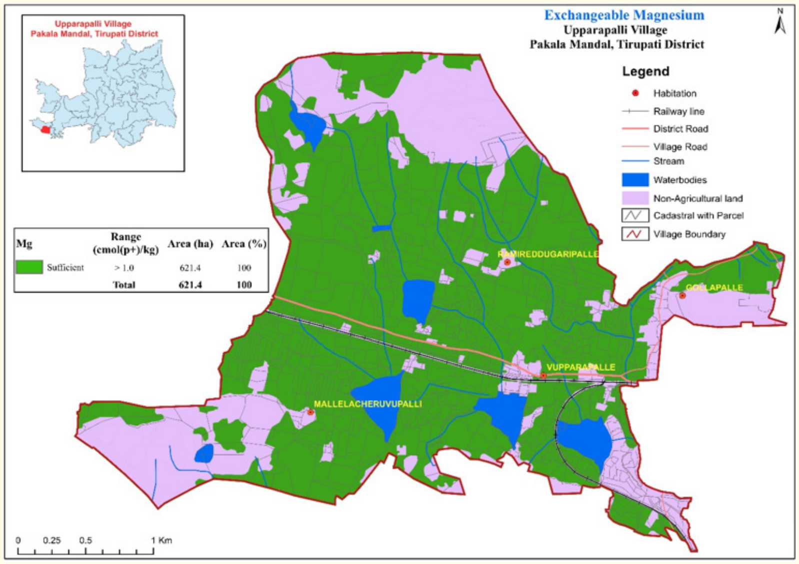

Figure 7: Spatial distribution of exchangeable magnesium in soils of Upparapalli village.

Conclusions

The geospatial evaluation of soil nutrient status in Upparapalli village revealed considerable spatial heterogeneity in the distribution of macronutrients. Nitrogen levels were predominantly low across the study area, whereas phosphorus and potassium were generally present at medium to high concentrations. Secondary nutrients such as sulphur, calcium, and magnesium were found to be largely sufficient, influenced by factors including organic matter content, inherent soil mineralogy, and fertilizer application practices. These results highlight the critical need for site-specific nutrient management and demonstrate the effectiveness of GIS-based soil mapping in formulating targeted fertilization strategies to support sustainable agricultural productivity.

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