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# Macronutrient Enrichment Patterns In Biosolid-Amended Soils: Evidence From PCA And Correlation Analysis In Tumkur District, Surrounded By Bangalore

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## ABSTRACT
Application of Sewage sludge in agriculture has gained significance role as a sustainable strategy for *nutrient recovery from urban waste streams while enhancing the soil fertility. The study assess the spatial variations of macronutrients of nitrogen (N), phosphorus ($P_2O_5$), and potassium ($K_2O$) in sludge-amended agricultural soils of selected taluks of Tumkur district. Surface soil samples (0–15 cm depth) were collected from sludge applied taluks and analyzed as per standard soil-testing protocols. The nutrient data were evaluated using violin plots, one-way ANOVA, principal component analysis (PCA), and correlation heatmaps. The mean value of N ranged from 361.7 to 470.3 kg ha ⁻¹, $P_2O_5$ from 104.9 to 150.9 kg ha ⁻¹, and $K_2O$ from 321.5 to 609.5 kg ha ⁻¹. Gubbi taluk consistently showed the highest nutrient enrichment followed by Tumkur, and Kunigal taluk displayed the lowest values of organic carbon concentrations. The results of ANOVA test confirmed statistically significant differences for N, $P_2O_5$, and $K_2O$ ($p < 0.05$). Strong positive correlations were observed between organic carbon and N ($r = 0.88$), $P_2O_5$ ($r = 0.81$), and $K_2O$ ($r = 0.79$). PCA was indicated a dominant nutrient enrichment gradient explaining 73.1% of total variance, strongly associated with organic carbon and macronutrients. Overall, the findings highlight the agronomic benefit of sewage sludge recycling and the importance of site-specific nutrient management to minimize environmental risks of long-term nutrient accumulation.*
***Keywords:*** *Sewage sludge*; Soil fertility; NPK dynamics; Principal Component Analysis; Correlation heatmap; Karnataka soils.

## INTRODUCTION
The use of municipal sewage sludge in agriculture land aligns with circular economy principles by transforming organic wastes into nutrient resources while reducing reliance on mineral fertilizers (Weldon & Bettiol, 2016). Sludge contains considerable amounts of nitrogen, phosphorus and potassium along with organic matter that enhances soil physical structure, microbial activity, and nutrient retention capacity (Kumar et al., 2017; Sharma et al., 2019). Numerous studies have shown that sludge application increases soil macronutrient availability and crop yields; however, responses often remain highly site-specific, influenced by interactions among soil texture, organic carbon, pH and management history (Zafar et al., 2021).

Organic carbon plays a major role in regulate the nutrient availability by stabilizing nitrogen through microbial incorporation and slowing phosphorus fixation through surface sorption processes (Larsen & Jensen, 2014). Field-scale investigations applying multivariate statistical approaches have demonstrated that nutrient accumulation under organic amendment systems frequently co-varies with organic carbon dynamics rather a single soil chemical parameter.

Despite growing interest, limited comprehensive evaluations exist for Karnataka soils integrating nutrient availability with multivariate assessment tools such as principal component analysis or correlation network mapping. The aim of this study was therefore to characterize taluk-wise nutrient enrichment in sludge-treated fields of Tumkur district using both classical statistics and advanced multivariate analyses.

## MATERIALS AND METHODS
Composite surface soil samples (0–15 cm depth) were collected from sludge-amended agricultural fields across the selected taluks of Tumkur district, Karnataka. Available nitrogen was estimated using the alkaline permanganate oxidation method (Subbiah & Asija, 1956). Olsen's sodium bicarbonate extraction was applied for the determination of available phosphorus ($P_2O_5$) (Olsen et al., 1954), while available potassium ($K_2O$) was measured following neutral ammonium acetate extraction using a flame

photometer (Jackson, 1973). Soil organic carbon content was determined by the (Walkley & Black, 1934). Nutrient variability was examined through distribution statistics and violin plots. One-way analysis of variance (ANOVA) was used to test taluk-wise differences. Correlation matrices were generated using Pearson correlation coefficients among soil variables. PCA was applied to explore nutrient interactions and dominant controlling factors.

## RESULTS AND DISCUSSION

The violin plot illustrates the field-scale distribution of available soil nitrogen (N) across the three sludge-amended taluks of Tumkur, Gubbi, and Kunigal. The width of each violin represents the density of samples at different nitrogen concentrations, where wider sections indicate values that occur more frequently. The central horizontal bar depicts the mean nitrogen concentration, providing a measure of central tendency for each taluk.

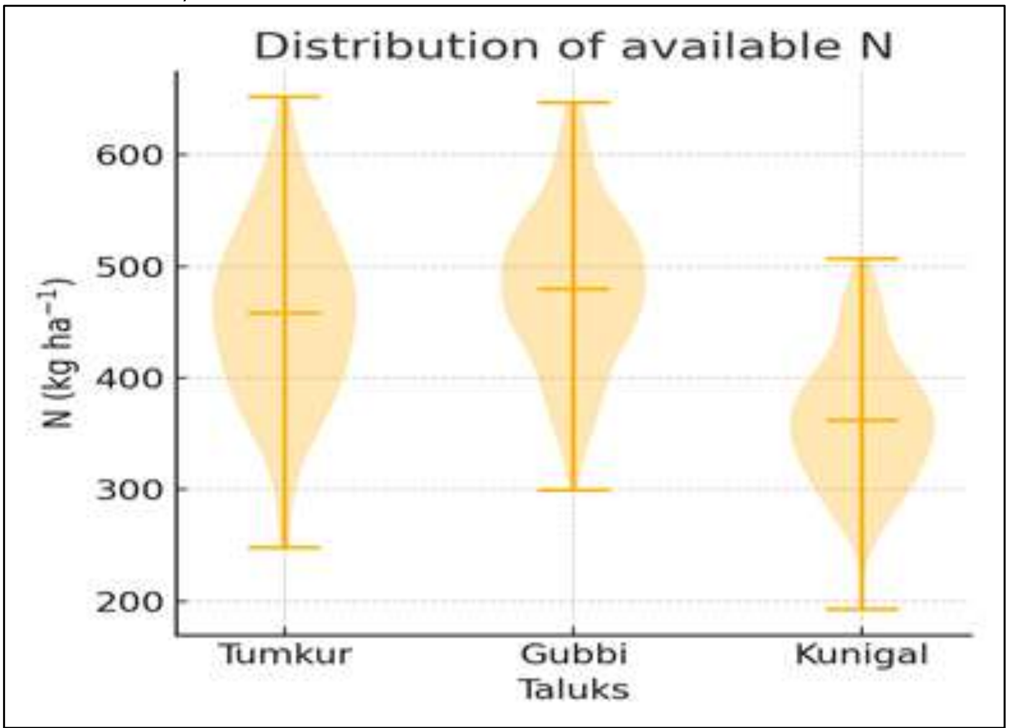


**Fig 1.** Taluk-wise Nitrogen Distribution

The violin plot illustrating the distribution of available nitrogen shows clear spatial variability among sludge-amended soils. Gubbi taluk shows the highest central tendency, with the density of values concentrated toward elevated nitrogen levels, indicating relatively uniform nitrogen enrichment. Tumkur soils display a broader spread of values, reflecting greater heterogeneity in nitrogen availability, likely associated with variability in sludge application intensity and soil organic carbon content influencing mineralization dynamics. Kunigal soils present a comparatively compact distribution centered at lower concentrations, shows the reduced nitrogen accumulation and stabilization capacity compared to the other taluks.

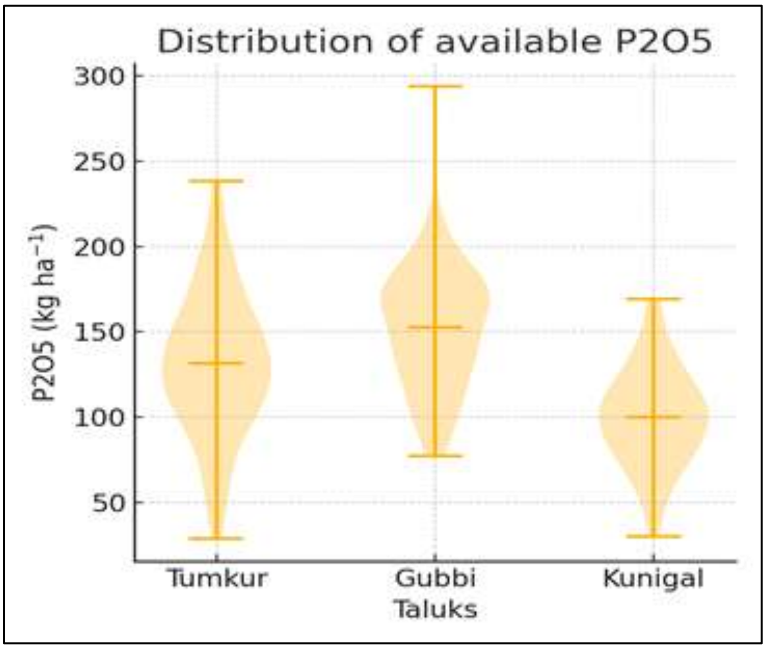


**Fig 2.** Taluk-wise Phosphorus Distribution

Phosphorus enrichment followed a similar trajectory (Fig. 2). The violin plot depicting the distribution of available phosphorus ($P_2O_5$) across taluks highlights distinct spatial patterns of phosphorus accumulation in sludge-amended soils. Gubbi taluk shows the highest central tendency, with the violin width concentrated in upper $P_2O_5$ ranges, indicating relatively uniform phosphorus enrichment across fields. Tumkur soils show a broader spread of values, indicate the varying phosphorus retention levels influenced by site-specific sludge inputs and differences in soil phosphorus fixation capacity. Kunigal soils display a comparatively compact violin centered at lower concentrations, reflecting both reduced phosphorus availability and limited variability. This pattern may arise from higher calcium-associated P fixation and lower organic carbon levels, which restrict phosphorus solubility and stabilization.

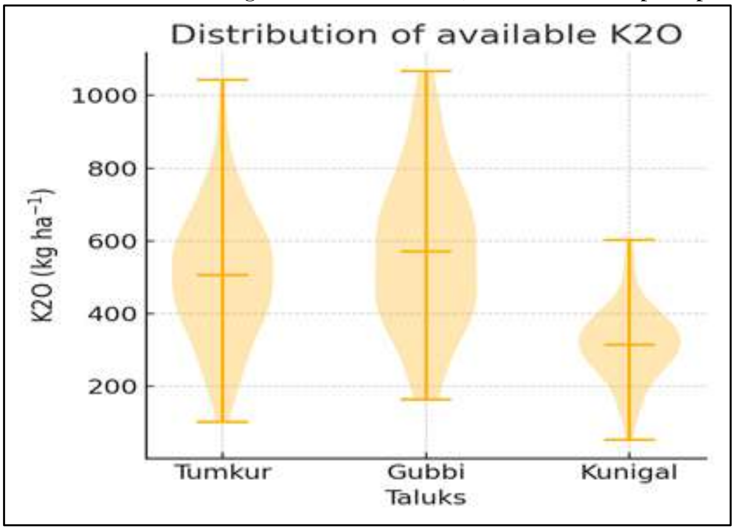


**Fig 3.** Taluk-wise Potassium Distribution

The violin plot for available potassium ($K_2O$) demonstrates the more variability among the nutrients, particularly in Tumkur and Gubbi taluks. Gubbi soils present both high median values and wide dispersion, reflecting strong potassium enrichment potentially derived from sludge inputs combined with underlying mineral weathering contributions. Tumkur soils also display pronounced variability, indicating heterogeneous K stabilization across fields. Kunigal soils exhibit narrower and lower-centered distributions, suggesting lower native potassium reserves and reduced organic matter-mediated K retention. These results illustrate that potassium dynamics are driven by both sludge amendment intensity and inherent soil mineralogical properties. The taluk-wise mean concentrations of available nitrogen (N), phosphorus ($P_2O_5$), and potassium ($K_2O$) differed across sludge-amended soils. Gubbi taluk consistently recorded the highest macronutrient levels, followed by Tumkur and Kunigal. This trend highlights the role of site-specific soil properties and sludge management practices to regulate nutrient retention and stabilization.

**Table 1.** Descriptive statistics of soil available macronutrients across taluks

| Taluk | Available N (kg $ha^{-1}$) | Available $P_2O_5$ (kg $ha^{-1}$) | Available $K_2O$ (kg $ha^{-1}$) | pH (mean) | Organic Carbon (%) |
|---|---|---|---|---|---|
| Tumkur | 456.50 ± 52.14 | 135.72 ± 21.18 | 476.39 ± 137.22 | 6.64 | 1.15 |
| Gubbi | 470.32 ± 41.56 | 150.87 ± 19.44 | 609.46 ± 201.37 | 6.38 | 1.14 |
| Kunigal | 361.71 ± 38.67 | 104.89 ± 16.35 | 321.51 ± 82.64 | 6.64 | 0.88 |

**Table 2.** Soil fertility classification (ICAR, 2011)

| Parameter | ICAR Fertility Class | Threshold levels (kg $ha^{-1}$) | Taluk Status |
|---|---|---|---|
| Available N | High | > 280 | All taluks – High fertility |
| Available $P_2O_5$ | High | > 25 | All taluks – High fertility |
| Available $K_2O$ | High | > 280 | Tumkur & Gubbi – Very High Kunigal – High |

(ICAR soil fertility standards, Indian Council of Agricultural Research soil testing guidelines)
Taluk-wise macronutrient accumulation patterns were influenced by organic carbon and soil chemical properties significantly. Higher OC levels in Gubbi corresponded with increased nutrient retention and stabilization, especially nitrogen. In Kunigal, the soils consistently showed a lower macronutrient levels linked to reduced OC and potential nutrient immobilization processes.
Relative phosphorus accumulation suggests long-term buildup risks that may accelerate eutrophication if unmanaged. Potassium data highlight the fertiliser replacement value of sludge where mineral K reserves are sufficient to support retention. Across taluks, data reinforce that sludge functions as a valuable partial substitute for inorganic fertilizers but must be regulated through nutrient budget systems.
Taluk-wise mean concentrations demonstrated consistent nutrient enrichment in the order Gubbi > Tumkur > Kunigal for N, $P_2O_5$ and $K_2O$ respectively. The nutrient levels observed in Gubbi soils exceeded ranges typically reported from sludge-amended Indian agricultural soils, where available nitrogen values were ranged between 250–350 $kgha^{-1}$ and phosphorus between 40–80 kg $ha^{-1}$ (Kumar et al., 2017; Sharma et al., 2019). European long-term sludge studies reported the similar enrichment patterns but caution against potential phosphorus accumulation when application rates exceed crop uptake capacity (European Commission, 1986).

**Table 3**. Statistical significance of taluk-wise differences in soil macronutrients (ANOVA)

| Parameter | F-value | p-value |
|---|---|---|
| **Nitrogen (N)** | 3.14 | **0.049** |
| **Phosphorus ($P_2O_5$)** | 3.49 | **0.036** |
| **Potassium ($K_2O$)** | 4.60 | **0.013** |

ANOVA indicated statistically significant taluk-wise variation across all measured macronutrients: nitrogen ($p = 0.049$), phosphorus ($p = 0.036$) and potassium ($p = 0.013$). Violin plot analyses revealed wider distribution ranges for potassium relative to nitrogen and phosphorus, particularly within Tumkur and Gubbi taluks. This variability may reflect heterogeneous sludge distribution patterns, differences in mineral weathering potential, or variation in exchangeable potassium stabilization mechanisms.

**Soil Property Controls on Nutrient Retention**

**Table 4.** Principal Component Analysis (PCA) summary statistics

| Principal Component | Eigenvalue (%) | Cumulative variance (%) | Variables with high loadings |
|---|---|---|---|
| PC1 | 73.1 | 73.1 | N, $P_2O_5$, $K_2O$, Organic Carbon |
| PC2 | 17.7 | 90.8 | pH |

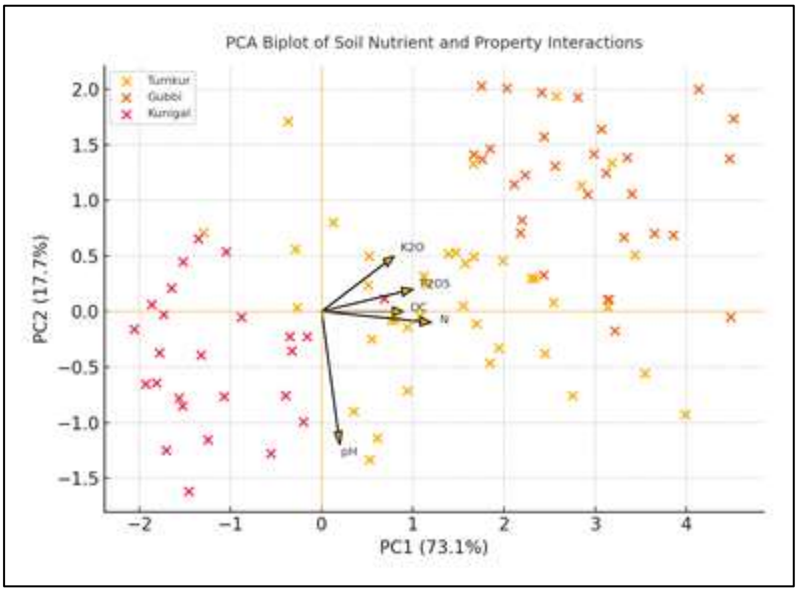


**Fig 4.** Multivariate Analysis of Nutrient Interactions (PCA)

The PCA biplot summarizes complex nutrient interrelationships by projecting the soil samples and nutrient load onto two principal axes that collectively explain 90.8% of total variability. PC1 eigen value of 73.1% represents a macronutrient enrichment gradient driven jointly by strong positive load of N, $P_2O_5$, $K_2O$, and organic carbon, highlights the role of sludge-derived carbon in nutrient stabilization. Samples from Gubbi cluster along the positive PC1 axis, confirming consistently higher nutrient accumulation, whereas Kunigal samples cluster with negative PC1 values, correspond to lower nutrient enrichment and organic carbon limitation, whereas, the Tumkur samples cluster scattered broadly across PC1, reflecting heterogeneous soil response to sludge application.
PC2 with a Eigen value of 17.7% is primarily influenced by soil pH, indicate a secondary control of nutrient solubility, particularly for phosphorus, rather a dominant nutrient enrichment.

**Table 5.** Pearson correlation coefficients between soil organic carbon, pH, and Macronutrients

| Parameters | N | $P_2O_5$ | $K_2O$ | OC | pH |
|---|---|---|---|---|---|
| N | 1.00 | 0.83 | 0.75 | 0.88 | 0.47 |
| $P_2O_5$ | 0.83 | 1.00 | 0.89 | 0.81 | 0.32 |
| $K_2O$ | 0.75 | 0.89 | 1.00 | 0.79 | 0.20 |
| Organic Carbon (OC) | 0.88 | 0.81 | 0.79 | 1.00 | 0.44 |
| pH | 0.47 | 0.32 | 0.20 | 0.44 | 1.00 |

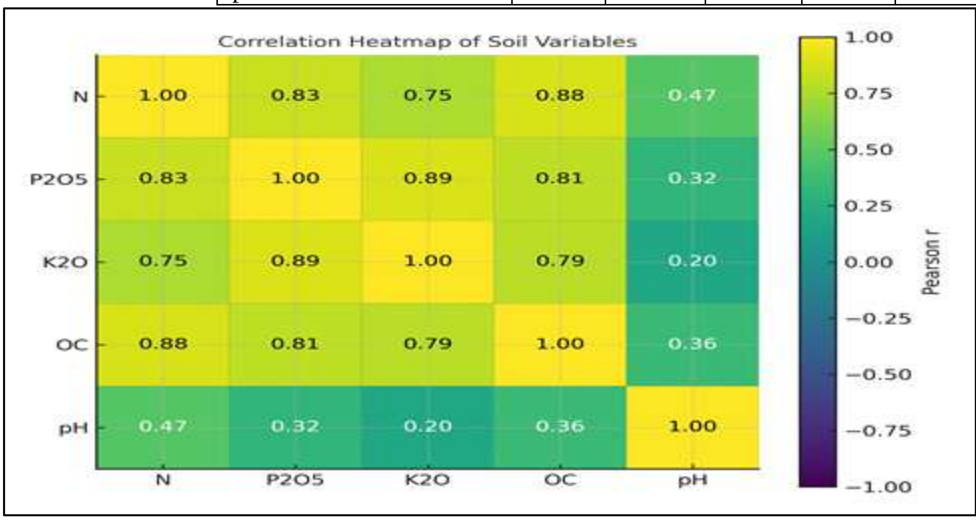


**Fig 5.** Correlation Heatmap of Soil Variables

The correlation heatmap shows the relationships among the soil macronutrients, demonstrating strong positive linkage between organic carbon and nutrient availability (OC–N = 0.88; OC–$P_2O_5$ = 0.81; OC–

$K_2O$ = 0.79). These robust correlations confirm the central role of organic matter in nutrient immobilization and stabilization, which enhances the nutrient retention in sludge-amended soils. Further, the strong cross-nutrient correlation of N–$P_2O_5$ and $P_2O_5$–$K_2O$ validate that the sludge acts as a multi-nutrient source, rather supply of nutrients independently. The soil pH is comparatively weaker, emphasizing that pH exerts a influence on nutrient solubility, particularly for phosphorus, but it is not as a primary driver of nutrient enrichment.

Nutrient levels recorded in the present investigation were exceeded with reported studies for Indian sludge-amended soils (Kumar et al., 2017; Sharma et al., 2019), where average nitrogen levels ranged between 250–350 kg $ha^{-1}$ and phosphorus exceeds (90 kg $ha^{-1}$) in few samples, whereas in Gubbi the nutrients concentrations were found within the upper limit of European long-term sludge reuse trials (European Commission, 1986), emphasizing both agronomic benefits and nutrient budget strategies to prevent environmental risks. The international guidelines emphasize nutrient-based sludge application limits to minimize risks of groundwater contamination and eutrophication (USEPA, 1995; European Commission, 1986).

## CONCLUSION

Sewage sludge application substantially increased the availability of N, $P_2O_5$ and $K_2O$, with organic carbon emerged as the primary driver of nutrient stabilization. Multivariate PCA and correlation analyses were highlighted the coupled nature of nutrient dynamics in sludge amendment. While agronomic benefits are evident, considering the high phosphorus concentrations and introduction of nutrient budget frameworks in Karnataka, it is recommended to regulate sludge dose based on soil fertility status and crop nutrient requirements to meet sustainable utilization of sludge.

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