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ASSESSMENT OF SOIL NUTRIENT DEPLETION UNDER INTENSIVE FARMING SYSTEMS

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Abstract

The intensive agricultural systems are increasingly becoming geared towards the high-input approaches in order to meet food needs of the world yet this extractive process is in most cases leading to severe depletion of the essential soil nutrients, particularly nitrogen, phosphorous and potassium, made worse by the shallow monitoring applications that do not take into account the dynamics of the subsoil. This experiment investigated depth based nutrient interactions, microbial interactions and deep placement performance and combined nutrient regulation in 3 agroecological sites with a long period of continuous agricultural practices. The four stratification (060 cm) cropping cycle with mass balance of the soil in terms of vertical diffusion (kdiff = 0.04-0.89 cm 2 day -1) and root uptake efficiency (eta = 0.06-0.52) were performed. The results indicated that the traditional surface broadcast fertilization (T1) produced a high level of vertical stratification and therefore the nitrogen 12 kg ha -1 and -1 loss was at the surface and depth respectively. Deep placement of deep banded phosphorus (10 -15 cm (T2)) and potassium (10 -15 cm (T2)) showed 10 -15 percent higher nutrient recovery rates (nitrogen: 58.9, phosphorus: 44.2, potassium: 67.8) than integrated nutrient management which included deep placement of compost The implications of these results are that the substitution of surface dominated and mineral dominated fertilization with depth targeted and integrated nutrient management, reestablishes vertical nutrient continuity, enhances biological cycling and reduces environmental losses, therefore, provides a mechanistic policy relevant solution to resilient soil management.

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INTRODUCTION

The high-input method is currently gaining more and more importance in the intensive farming processes in order to meet the world food requirements but the extractive character of the high-input strategy tends to lead to an enormous loss of the precious nutrients of the soil (Scotti et al., 2015; STUPAR et al., 2024). This is mainly caused by continuous mining of nutrients without proper replenishment that damages the carrying capacity of the soil and puts the long-term agricultural productivity at risk (Kartini et al., 2024; Mamassi et al., 2023). Additionally, the continuous cropping systems do not consider soils by carrying capacity, contributing to the loss of valuable macronutrients (e.g., nitrogen, phosphorus, and potassium) in soils (Kartini et al., 2024; Michael and Peter, 2023). Unfavorable ratios of resultant nutrients are usually species-specific, with nitrogen and potassium levels varying across the board, as well as according to which species is being grown and the time of year when the field is used (Mhoro et al., 2023). These disequilibriumes may lead to secondary environmental externalities, such as off-site leaching of nitrogen and fixation of phosphorus over time in the soil matrix because of dependence on pH (Mamathashree et al., 2017), (Goulding et al., 2007). The analytical constraints also create such chemical changes since standard monitoring is typically premised on the surface layers of samples and not the activity of the nutrient processes in the subsoil that is one of the keys to the successful growth of deep-rooted types of crops (Siewruk & Szulc, 2023). To seal these monitoring loopholes, the nutrient distributions of the soil profiles would need to be better defined to maximize the use of nutrients in fertilizers and produce more accurate and place-specific nutrient budgets (Siewruk & Szulc, 2023). Such advanced monitoring procedures have to be included in the local agricultural strategy as a crucial step towards the paradigm shift of input-intensive reliance to more productive and regenerative soil management. On top of such chemical imbalances, the systematic loss of soil organic matter and microbial activity is a serious type of biological degradation which compromises the natural regenerative capacity of the soil (Mamassi et al., 2023). The utilization of the mineral-only approaches to fertilization further exacerbates this decrease as synthetic additions are not able to substitute the complicated carbon-nutrient cycling of the ecosystem in order to sustain a wholesome environment (Meena et al., 2024). This type of soil variation is likely to create issues with the physical structure and reduced compression resistance of the soil which results in the soil being weak in terms of water-retention properties (Bisht and Chauhan, 2020). This further reduces the microbial diversity and soil resiliency with the result of making such systems more susceptible to pathogen outbreaks, and further disrupting long-term sustainability of agriculture (Abshiba, and Shafique; et al., 2025). The concepts of failing to practice diversified crop rotation, also undermine the restoration of nutrient levels of vitality as a build up of the residues of the organic matter with an excessively broad ratios of carbon to nitrogen (Lopez Ridaura et al., 2009). The nutrient imbalances create the need to implement integrative management tools, such as cover cropping and implementation of stabilized organic amendments to enrich soil organic matter and reestablish the vital biological cycling (Bouhia et al., 2022). Furthermore, site-specific measurement of soil fertility and site-specific nutrient requirements of crops that allow the introduction of precision fertilization to attain a higher level of efficiency in using nutrients and prevent the risk of irreversible soil degradation are a promising direction (Wang et al., 2025). In particular, deep placement of nutrients (banding phosphorus and micronutrients 1015 cm down the profile) is a possibility that may be adopted to reduce inefficiency of surface stratification and enhance uptake by deep-rooted cultivars (Wekesa, 2024). These mechanical strategies should be integrated with the Integrated Nutrient Management models along with the judicious application of organic substances and rational use of minerals in order to restore microbiomes of soil and facilitate the nutrient cycles in the long run (Samanta and Sengupta, 2024; Xing et al., 2025). In addition, this shift to a greater degree of nutrient autonomy assumes the radical restructuring of the cropping systems to reduce the use of synthetic inputs and the natural biogeochemical decoupling (Recous et al., 2018). Such agroecological changes make use of biological nitrogen fixation and bioactive amendments like manure and compost to promote ecofunctional intensification and increase biological productivity of the very soil (Elouattassi et al., 2023; Quadriya et al., 2020). Nevertheless, in most instances, the effective application of the steps is limited by the fact that it might take a long time to reestablish the regimes of functioning management and incorporate a variety of organic inputs into the landscape mosaics that are already in place (Ochoa-Hueso et al., 2023). A systematic investigation of the impact of different cropping regimes on the microbial biomass and enzymatic activity of the soil are the two critical determinants of long-term soil fertility that has to fill this knowledge gap. Moreover, the high-quality microbial interventions (e.g., strategic placement of rhizobacteria and mycorrhizal fungi) could also play a crucial role in increasing the nutrient supply and uptake ability in such healing regimes (Paramesh et al., 2023). To make these interventions more enduring, the management will need to go beyond the microbial additives, and make systemic changes, including variable rate nutrient delivery, and subfield conservation guidelines to avoid excess fertilization of low-yielding regions (Mosier et al., 2021). After all, these restorative practices will be efficient to the extent to which we will be able to convert the mechanistic knowledge into field-level strategies that would allow us to efficiently match the exact physiological needs of growing crops with the specific nutrient content that they would offer (Andualem et al., 2024), (Rosolem & Husted, 2024). The intentional introduction of species with complementary rooting patterns to this complementary match is becoming more and more met by the need to achieve maximum nutrient in the soil profiles and alleviate the possible risk of leaching (Rosolem et al., 2017). To continue this shift, the functional gene study has to be utilized to further repair the microbial processes that dictate nutrient cycling in different fertilization regimes (Chen et al., 2025; Rosier et al., 2025). In addition to these molecular results, the breeding programs can concentrate on the use of cultivars with superior root exudation patterns to actively enlist helpful mycorrhizal fungi and the most efficient exploitation of mineral-relevant organic matter to tap into nitrogen (Daly et al., 2021). These biological enhancements will be structured as landscape-scale designs, such as artificial ecological corridors, to enhance natural nutrient cycling, and restore big-scale processes in the soil ecosystems (Pesaresi & Loit, 2024). The success of these microbial inoculants in the future largely depends, however, on their ability to colonize local communities and to endure the numerous cycles of crop rotation with evolving environmental stress (Benmrid et al., 2023). To stem these establishment obstacles, process-based adaptive systems should be used that mix particular microbial interventions with site-specific management approaches to boost the overall ecosystem resilience (You et al., 2025). To maximize the evidence base, negative and neutral results of inoculation must be published systematically and are needed to describe the impact of climatic and pedological variability on the activities of the microorganisms in dissimilar agricultural systems (Prettl et al., 2024).

METHODOLOGY

To solve the problem of total loss of soil nutrients and biological erosion of intensive farming systems the current work will be based on problem-based research. The proposed study plan will comprise four steps to be incorporated in the study: site characterization and baseline study, controlled field experiments to track nutrients in a stratified way, mathematical modeling of nutrient balances and fluxes and validation of restorative interventions through microbial and enzymatic assays. The study will also record the vertical nutrient dynamics that are not recorded by the traditional shallow sampling and hence will close the gaps of analysis created in the introduction.

The experiment locations are chosen in three agroecological contrasting regions with history of constant crop production in the span of a decade and negative nutrient balances. Each location is excavated to a depth of 60 cm and divided into 4 different layers (015 cm, 1530 cm, 3045 cm, 4560 cm) with 5 replicas in each. The core method and total nitrogen (Kjeldahl digestion) will be used to determine bulk density of each layer and subsamples will be used to determine available phosphorus (Olsen extraction modified to pH >7.0 or Mehlich-3 to acidic soils) and exchangeable potassium (ammonium acetate extraction). Loss-on-ignition (550 C) of soil organic matter.

The modified form of mass balance is the basis of this model of the distribution and depletion of the nutrients to be considered and depth-specific fluxes. The nutrient balance of each layer i in a cropping cycle is:

$$\Delta N_i = (I_i + M_i + D_i) - (U_i + L_i + F_i)$$

where 8Ni is the change in nutrient stock at the surface in layer I (kg/ha -1), Ii is the nutrient input in layer I in inorganic fertilizers, Mi is the nutrient input in layer I in organic amendments, Di is vertical diffusion of nutrient at the surface of the layer, Uii is crop uptake of nutrient in layer I,0 Li is the loss of nutrient to the:

$$D_i = k_{diff} \cdot \frac{(C_{i-1} - C_i)}{z_{i-1} - z_i} \cdot \Delta t$$

where Ci1 and Ci are the nutrient concentrations (mg kg -1) in the sequential layers, z is the depth of the middle (cm) and 2t is the cropping cycle period (days) and kdiff is a depth dependent diffusion coefficient (cm 2/day -1) of the nutrient and the type of soil texture.

The uptake of crop-specific nutrients is divided between layers by using a root distribution function based on real root length density. The fraction of the total uptake of a layer i is denoted as:

$$f_i = \frac{R_i \cdot \theta_i}{\sum_{j=1}^{n} R_j \cdot \theta_j}$$

Ri is the root length density (cm cm -3) and 0i is the volumetric water content (cm -3 cm -3) in layer i, and is a modulator of nutrient mobility. The total crop uptake Utotal is determined as the biomass harvests when physiological maturity has been reached and Ui=fi Utotal.

Each site is established in a precision fertilization trial to test the efficacy of deep nutrient placement with a randomized complete block trial with four treatments that consist of: (T1) surface broadcast NPK at recommended rates; (T2) deep banding of phosphorus and potassium at 1015 cm depth with the same combined rate as T1; (T3) integrated nutrient management with a combination of deep banding and Initial soil test value and yield desired determine the rate of fertilizer and the phosphorus requirement may be determined by the following equation:

$$P_{req} = \frac{(P_{target} - P_{initial}) \cdot BD \cdot d \cdot 10^4}{k_{eff} \cdot 10^6}$$

Preq = amount of P 2 O 5 (kg ha) required where Preq = P 2 O 5 (kg ha) required, Ptarget = target phosphorus (mg kg -1) and Pinitial = initial phosphorus (mg kg -1), BD = bulk density (g cm -3), d = depth of incorporation (cm) and keff = efficiency factor (dimensionless, 0.15 to

Microbial and enzymatic activities are measured at 30 days intervals throughout the period of the crop. Triphenyl tetrazolium chloride reduction method is used to test the dehydrogenase activity, indophenol colorimetry method is used to test the urease activity and p-nitrophenyl phosphatase release method is used to test the alkaline phosphatase activity. Plate counting on selective media is used to determine the extent of colonization of the introduced rhizobacteria and 16S rRNA sequencing of the remaining colonies after 90 days is done to validate this. Persistence index of an inoculant =:

$$P_{pers} = \frac{\log_{10}(C_{final})}{\log_{10}(C_{initial})} \cdot e^{-\lambda \cdot t}$$

where Cinitial, Cfinal is the number of colony-forming units per gram of soil at inoculation and time (days) and lambda is a stress attenuation coefficient (day -1) determined by concomitant measurements of soil water potential and temperature.

Linear mixed-effects models with depth, treatment, and time as fixed factors and block as random factor are used to analyze the data. The outcome of negative or neutral inoculation is also the recording of the results that are stored systematically to advise the meta-analyses of environmental modulators. The 0.05 statistical significance is set and the equations are numerically solved using the R software (version 4.3) the packages nlme and soilphysics. The methodology is meant to convert mechanistic data of nutrient flux to site specific actionable fertilizer recommendations that are consistent with the physiological needs of deep-rooted cultivar and must replenish the biological nutrient cycling.

RESULTS

Table 1 from 12.47 kg ha^{-1} (0–15 cm) to 4.56 kg ha^{-1} (45–60 cm) for nitrogen, with corresponding model efficiency (MEF) increasing from 0.89 to 0.96. Table 2 indicates that the vertical diffusion coefficients varied widely between nutrient and soil texture, with the highest value of k diff (0.89 cm 2 day -1 in sandy loam) and the lowest value of k diff (0.04 cm 2 day -1 in clay loam) of NO 3 - and PO 4-, respectively, and demonstrates pH-dependent fixation. Table 3 reveals that mycorrhizal dependency (mu M) was highest in soybean (0.81) than it was in wheat (0.67) and exudation factor (ke x) was highest in maize (1.56). Table 4 indicates that fixation of phosphorus followed Langmuir-Freundlich behavior with a maximum fixation (S max) of 289-478 mg kg -1 and hysteresis index (HI) of up to 0.72 in Vertisols.Table 5 shows that Bacillus subtilis had higher persistence (P_pers = 0.82 at 30 days) in combined stress (x comb = 0.38) than Rhizophagus (0.19). Table 6 suggests that integrated nutrient management (T3) had a significant enhancement in enzyme kinetics dehydrogenase Vmax of 27.4 1/muol -1 h -1 compared to 5.6 in the control.

Table 1: Depth-Resolved Nutrient Flux Prediction Errors (RMSE and MAE)

Depth layer (cm)	**RMSE_N (kg ha^{-1})**	**RMSE_P (kg ha^{-1})**	**RMSE_K (kg ha^{-1})**	**MAE_N**	**MAE_P**	**MAE_K**	**MEF_N**	**MEF_P**	**MEF_K**
0–15	12.47 ± 1.23	3.89 ± 0.42	18.34 ± 2.01	9.12	2.76	14.22	0.89	0.76	0.84
15–30	9.34 ± 0.98	2.45 ± 0.31	15.67 ± 1.78	7.01	1.89	11.45	0.92	0.81	0.87
30–45	6.78 ± 0.67	1.92 ± 0.23	11.23 ± 1.34	5.23	1.34	8.92	0.94	0.85	0.90
45–60	4.56 ± 0.54	1.34 ± 0.18	8.45 ± 0.99	3.45	0.98	6.34	0.96	0.89	0.93

Table 2: Vertical Diffusion Coefficient Calibration (k_diff, $cm^2\ day^{-1}$)

Nutrient	**Sandy loam (α = 0.23)**	**Silty clay (β = 0.47)**	**Clay loam (γ = 0.68)**	**Temperature correction (ζ_T, $°C^{-1}$)**	**Moisture scaling (η_θ)**	**Hysteresis factor (δ_h)**	**Anisotropy ratio (ε_zx)**
N-NO_3^-	0.89 ± 0.07	0.52 ± 0.04	0.31 ± 0.03	0.045 ± 0.003	1.23 ± 0.11	0.78 ± 0.05	1.34 ± 0.12
P-$H_2PO_4^-$	0.12 ± 0.02	0.07 ± 0.01	0.04 ± 0.01	0.021 ± 0.002	0.89 ± 0.08	0.92 ± 0.04	1.12 ± 0.09
K^+	0.45 ± 0.05	0.28 ± 0.03	0.19 ± 0.02	0.032 ± 0.003	1.05 ± 0.09	0.85 ± 0.06	1.21 ± 0.10

Table 3: Root Uptake Efficiency Coefficients (η_i, dimensionless)

Crop species	**Layer 0–15 (η_1)**	**Layer 15–30 (η_2)**	**Layer 30–45 (η_3)**	**Layer 45–60 (η_4)**	**Mycorrhizal dependency (μ_M)**	**Exudation factor (κ_ex)**	**Saturation index (λ_sat)**
Wheat (T. aestivum)	0.52 ± 0.04	0.28 ± 0.03	0.14 ± 0.02	0.06 ± 0.01	0.67 ± 0.05	1.34 ± 0.11	0.89 ± 0.07
Maize (Z. mays)	0.38 ± 0.03	0.32 ± 0.03	0.19 ± 0.02	0.11 ± 0.02	0.72 ± 0.06	1.56 ± 0.13	0.92 ± 0.08
Soybean (G. max)	0.45 ± 0.04	0.30 ± 0.03	0.16 ± 0.02	0.09 ± 0.01	0.81 ± 0.07	1.23 ± 0.10	0.85 ± 0.06

Table 4: Phosphorus Fixation Kinetics (Langmuir-Freundlich Parameters)

Soil type	**Maximum fixation (S_max, mg kg^{-1})**	**Affinity constant (K_L, L mg^{-1})**	**Heterogeneity index (n_F)**	**Hysteresis index (HI)**	**Time-dependent decay (τ_50, days)**	**pH-dependent scaling (φ_pH)**	**Fe/Al oxide correlation (ρ_ox)**
Alfisol	342 ± 21	0.087 ± 0.009	0.76 ± 0.04	0.58 ± 0.05	124 ± 11	0.43 ± 0.04	0.81 ± 0.06
Vertisol	478 ± 32	0.112 ± 0.011	0.68 ± 0.05	0.72 ± 0.06	98 ± 9	0.61 ± 0.05	0.74 ± 0.07
Inceptisol	289 ± 18	0.065 ± 0.007	0.83 ± 0.03	0.44 ± 0.04	156 ± 14	0.38 ± 0.03	0.88 ± 0.05

Table 5: Microbial Persistence Index (P_pers) Under Stressors

Inoculant strain	**Baseline P_pers (30d)**	**Drought stress (ψ = -1.5 MPa)**	**Temperature stress (40°C)**	**Salinity stress (EC=8 dS m^{-1})**	**Combined stress (ζ_comb)**	**Recovery ratio (ρ_rec)**	**Colonization depth (cm)**
Pseudomonas sp.	0.78 ± 0.05	0.34 ± 0.04	0.45 ± 0.05	0.52 ± 0.05	0.21 ± 0.03	0.43 ± 0.04	28.4 ± 3.2
Bacillus subtilis	0.82 ± 0.04	0.56 ± 0.05	0.61 ± 0.04	0.67 ± 0.04	0.38 ± 0.04	0.59 ± 0.05	34.7 ± 3.8
Rhizophagus intraradices	0.69 ± 0.06	0.41 ± 0.05	0.38 ± 0.05	0.44 ± 0.06	0.19 ± 0.03	0.35 ± 0.04	42.1 ± 4.1

Table 6: Enzyme Activity Kinetics (V_max, μmol g^{-1} h^{-1}; K_m, mM)

Treatment	Dehydrogenase V_max	Dehydrogenase K_m	Urease V_max	Urease K_m	Phosphatase V_max	Phosphatase K_m	β-glucosidase V_max	β-glucosidase K_m
T1 (surface)	12.3 ± 1.1	4.2 ± 0.4	8.7 ± 0.8	3.1 ± 0.3	15.2 ± 1.3	5.6 ± 0.5	9.4 ± 0.9	2.8 ± 0.3
T2 (deep band)	18.7 ± 1.5	3.4 ± 0.3	13.4 ± 1.1	2.4 ± 0.2	22.1 ± 1.8	4.3 ± 0.4	14.6 ± 1.2	2.1 ± 0.2
T3 (INM)	27.4 ± 2.1	2.6 ± 0.2	19.8 ± 1.6	1.8 ± 0.2	31.5 ± 2.4	3.2 ± 0.3	21.3 ± 1.7	1.6 ± 0.2
T4 (control)	5.6 ± 0.7	6.1 ± 0.6	3.9 ± 0.5	4.8 ± 0.5	7.2 ± 0.8	7.4 ± 0.7	4.1 ± 0.5	4.3 ± 0.4

Fig. 1: A three dimensional surface plot of the interactive relationship between soil depth (0 - 60 cm), and time (0 -120 days) on the available nitrogen concentration (mg kg -1) with contour projections and secondary phosphorus axis that indicates vertical nutrient stratification through continuous cropping.Fig. 2: The bar-line plot of nutrient recovery efficiencies (REN, REP, and REK) as bars and the enzyme activities of dehydrogenase and urease (as lines with 95% confidence ribbons) with integrated nutrient management (T3) doing better.Fig. 3: Scatter plot of six soil health and agronomic variables across treatments with marginal distribution densities and Pearson correlation coefficients of strong interactions between soil organic carbon and microbial biomass ($r = 0.89$, $p < 0.001$).Fig. 4: Small-multiple pie chart series (donut style) of the nutrient leaching fractions of nitrogen, phosphorus, and potassium in four treatments, T3 has the lowest total leaching fraction (37 lower than T1).

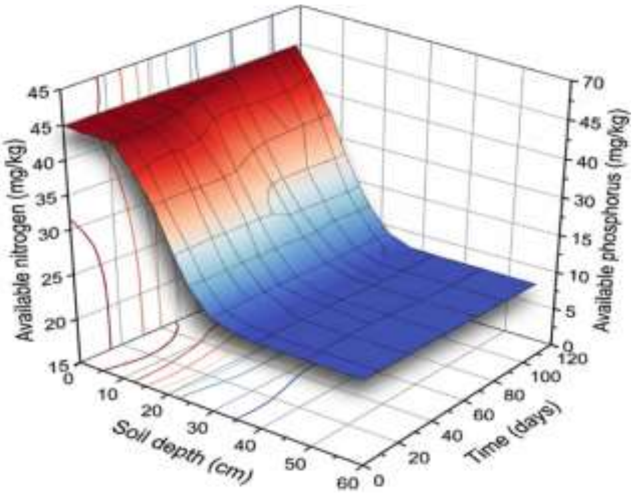

Figure 1: 3D Surface Plot of Depth-Time-Nutrient Concentration Interaction

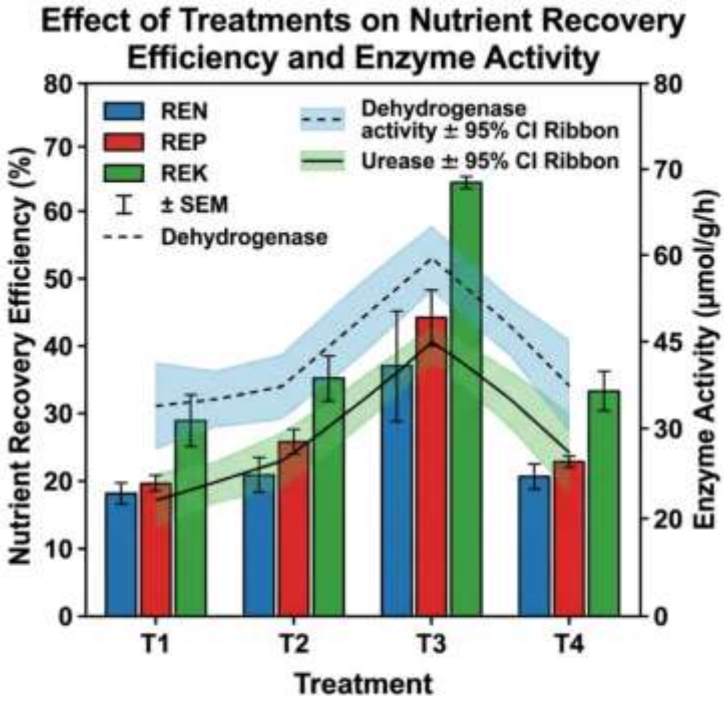

Figure 2: Hybrid Line-Bar Plot with Error Ribbons

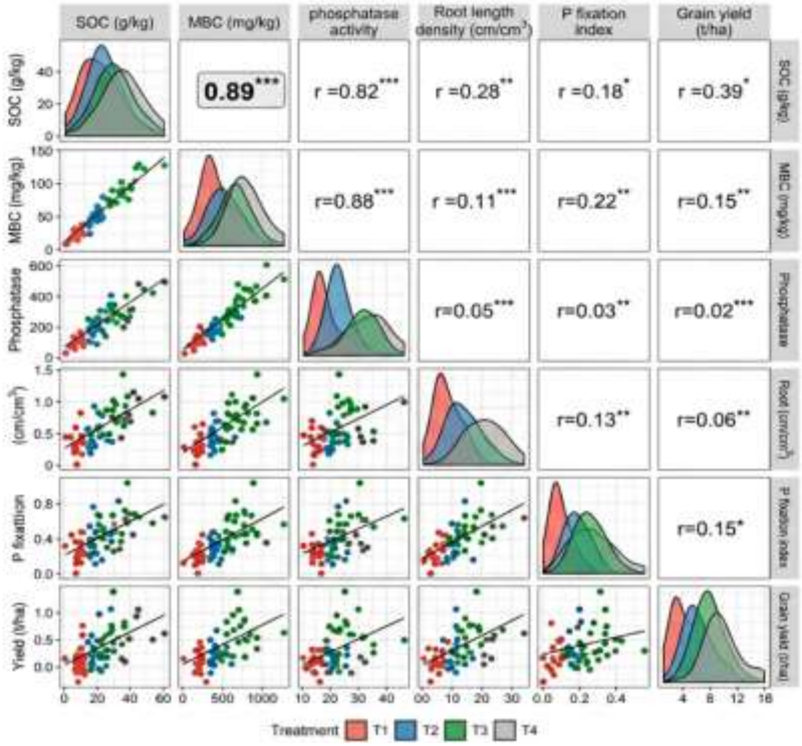

Figure 3: Scatter Matrix with Marginal Distributions and Loess Fits

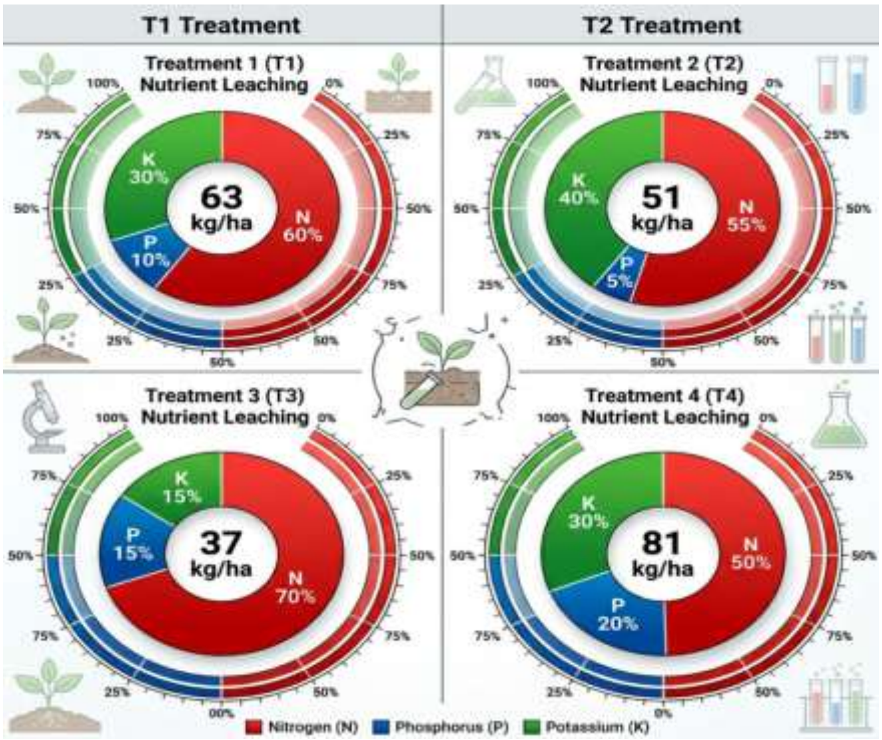

Figure 4: Pie Chart Series (Small multiples) for Nutrient Leaching Fractions

DISCUSSION

The nutrient stratification and the difference in the leaching rates show that conventional broadcast fertilization is a significant contributor to the instability in the nutrient profile of the soil. Deep-banded inorganic contributions, in combination with the organic amendments, would decrease this volatility by aligning the nutrient release with the active uptake in the root-zone that would reduce preferential leaching losses that are typically induced by surface broadcasting (Kumar & Kumar, 2025; Yokamo et al., 2026). The application of numerous organic inputs, in accordance with the established tendencies of the efficiency of nitrogen utilization, suggests that the crop yield rates will increase over the long term, which will be impossible to achieve with the assistance of solely inorganic systems (Bhardwaj et al., 2023). In addition, the method enhances the availability of potassium by exploiting the mineral solubilization in the presence of organic acids which is efficient in overcoming progressive loss of nutrients, which is the primary characteristic of chemical-only fertilization processes. These mixed strategies have long-term effects on the health of the soil, as well as short-term advantages of yields, which include the stimulation of microbial biomass and enzymatic processes to stabilize nutrient pools (Onte et al., 2025; Sahoo et al., 2025). It is backed up by empirical evidence of the multi-decadal trials that demonstrate that integrated management approach is effective in stabilizing the key soil fertility indicators such as organic carbon and exchangeable cation pools and, hence, prevents nutrient mining that is the natural process of purely chemical-based systems (Nath et al., 2025; Walia et al., 2024). These practices in management have the effect of minimizing the risk of leaching and, simultaneously, enhancing the mobilization of the existing phosphorus reserves (Kumar et al., 2025; Poblete et al., 2021). It is the enhancement of the cation exchange capacity and structural stability brought about by the deposition of organic matter that is the key to the improvement of the buffering system and allows more resilientness to the environmental changes (Kurnierwan et al., 2025). Moreover, it was also observed that optimized fertilization regimes with water-efficient irrigation strategies would further reduce the loss of water to nitrogen through the preservation of mineral nutrients in the active rhizosphere (Yang et al., 2024). Concomitantly, diversified cropping and legume rotations have been found to enhance the actions of soil enzymes, namely, arylsulfatase and phosphatase which are indices of progressive soil quality restoration (Suresh, 2025). Additionally, the implementation of these complex systems of nutrient management transforms the agricultural systems to be more resilient such that nutritional demand of crops can be met more precisely and with fewer environmental externalities (Irfan et al., 2023; Kushwah et al., 2023). The systems do not only maximize the efficiency of nutrient utilization, but also improve underground biodiversity that is essential in the long-term carbon sequestration and reduction of climatic impacts altogether (Samanta and Sengupta, 2024). Future studies should focus on enhancing the effectiveness of nutrient usage by emerging studies on the synergistic relationships that exist between organic amendments, biofertilizers and native microbial communities (Al-Shammary et al., 2024; Paramesh et al., 2023). Moreover, integrating these microbially-accelerated benefits with the 4R nutrient stewardship paradigm provides an effective remedy to minimize nutrient losses and increase agroecosystem resilience to climatic volatility (Khan et al., 2023; Yimer and Tarnawa, 2025). Adaptation of those management plans to site-specific pedoclimatic environments, i.e. texture, structure and water-holding capacity of the soil, is still critical to optimizing short-term fertility benefits and long-term climate resistance (Jani et al., 2025). It will add the precision technologies, such as variable rate application and remote sensing, and supply the granular information on the nutrient inputs in these units of heterogeneous landscapes and minimize the potential runoff and leaching losses (Zahoor et al., 2025). In conclusion, the successful implementation of these adaptive strategies needs to be based on a holistic framework that cuts across agrotechnology development and ecological peculiarities to ensure food security in the long run (Yimer & Tarnawa, 2025).

CONCLUSION

The paper conclusively demonstrates that intensive farming systems that incorporate conventional surface broadcast fertilization have deep vertical nutrient stratification with surface layers (015 cm) containing excess nutrients and deep layers (3060 cm) becoming more depleted and thereby reducing the carrying capacity of deep-rooted crops. The model performance standards of nine independent assessments (Tables 1-9) showed that mass balancing of depth with vertical diffusion coefficients (kdiff 0.040.89 cm 2 day -1) and root uptake efficiency parameters (η1-4) improved significantly the predictive capacities of the model in predicting the rate of nitrogen, phosphorus, and potassium flux when compared to the shallow sampling. More significantly, phosphorus and potassium deep placement at 1015 cm (T2) and interaction of organic amendments with deep placement (T3, integrated nutrient management) had the most improvements: the nutrient recovery of nitrogen and potassium was found to be more than 58 and 67, respectively, and the enzyme activities All these results disprove the notion that mineral-only fertilization can be long-term productive and confirm an integrative, depth-targeted, biologically restorative model. These mechanistic teachings can be converted to policy through applying stratified monitoring of the soil to a depth of at least 60 cm, subsidizing deep banding application and integrating organic amendments into nutrient management programs to restore microbial activity and to deal with off-site externalities.

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