



RESEARCH ARTICLE

Assessment of variability and soil–plant nutrient interactions for crop yield prediction in semi-arid Alfisols using regression analysis

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Received: 05 August 2025; Accepted: 01 February 2026; Available online: Version 1.0: 18 March 2026

Cite this article: Sathish A, Siddu M. Assessment of variability and soil–plant nutrient interactions for crop yield prediction in semi-arid Alfisols using regression analysis. *Plant Science Today*. 2026; 13(sp1): 1-14. <https://doi.org/10.14719/pst.11117>

Abstract

Precision nutrient management is essential for improving crop productivity in semi-arid Alfisols, where soil variability strongly influences yield. This study evaluated the relationships among soil properties, plant nutrient uptake namely nitrogen (N), phosphorus (P), potassium (K) and crop yields of finger millet, maize, field bean, tomato and brinjal under improved practices (IP) and farmers' practices (FP) across the North and South Transects of Bengaluru. Multivariate regression models were developed to identify the key predictors of yield under both management systems. Finger millet in the North Transect showed strong associations with plant N, P and K, as well as with soil N and pH. The IP models significantly predicted finger millet yield using plant N, P and K, whereas FP models were primarily driven by plant K and soil K. In the South Transect, maize yield was mainly influenced by plant N and soil N, with IP models significant for P and K uptake in the North and N uptake in the South; FP models were significant only for N uptake in the South. Tomato yield under IP was significantly associated with P uptake, while field bean showed significant FP-based predictions for N uptake. Brinjal showed no significant relationships across nutrients and transects. Micronutrient-based models provided additional predictive power for field bean (North) and maize (South), whereas macronutrient-based soil models remained largely non-significant. Overall, the regression analysis highlighted nutrient–yield linkages and underscored the role of plant nutrient uptake as a reliable predictor for site-specific recommendations in semi-arid Alfisols.

Keywords: alfisols; nutrient uptake; regression models; variability

Introduction

Urban farming plays a critical role in enhancing ecosystem services, particularly at the rural–urban interface. Systematic evaluation of production efficiency across diverse agricultural systems with varying management intensities and species compositions is vital, as these factors influence soil fertility, environmental sustainability and crop quality. This study investigates the variability and interrelationships among soil fertility indicators, plant nutrient uptake and crop yields under field conditions. It further develops multivariate regression models for yield prediction and input management strategies.

Rainfed agriculture supports global food security and, in India, occupies nearly 85 million hectares 60 % of the net cultivated area-sustaining 40 % of the population. However, these regions experience various forms of soil degradation-physical, chemical and biological. Common issues include low organic matter content, surface crusting, hard-setting behaviour, poor structural stability and nutrient imbalances, particularly deficiencies in nitrogen (N), phosphorus (P), sulfur (S) and micronutrients. In addition, isolated areas face salinity–sodicity hazards and reduced microbial activity, which are characteristic problems of semi-arid Alfisols (1-3).

Unsustainable land-use practices exacerbate this degradation, affecting soil structure, water balance, biodiversity and ecosystem services. In peri-urban Kumasi, Ghana, intensified vegetable cultivation and shortened fallow periods near water bodies prompted the adoption of integrated organic waste recycling to support nutrient cycling, sanitation and food production (4). However, data on the ecological impacts of urban agriculture in Bengaluru remain limited.

Globally, about 827 million tons of compostable biomass are produced annually, yet only 17 % is composted (5). Compostable agricultural waste-urban refuse, crop residues and food-industry by-products can enhance soil fertility. Municipal solid waste compost application has improved yields (6–8). Continued cultivation without replenishment depletes nutrients, especially micronutrients such as zinc (Zn), boron (B), iron (Fe) and occasionally S and manganese (Mn), which are commonly deficient in semi-arid Alfisols due to low organic matter, coarse texture and leaching under intermittent rainfall, ultimately affecting both crop productivity and human nutrition. While organic matter can be restored over time, micronutrient recovery is more challenging (9). Sustainable land use requires resource audits and geospatial assessments (10).

Geostatistical tools, such as kriging, enable spatial analysis of parameters such as soil organic carbon (11, 12). Balanced nutrient application based on soil fertility has improved productivity of finger millet and groundnut in Karnataka (13). GIS-based fertilizer recommendations have proven effective in semi-arid Alfisols (14). Soil quality indicators viz., soil organic carbon, available nutrient status (N, P, K and micronutrients) assessed at the micro-watershed scale are essential for site-specific management (15–17). Building on this, the present study applies robust regression techniques (18, 19) to model yields of finger millet, maize, field bean, tomato and brinjal across semi-arid Alfisols in the North and South Transects of Bengaluru.

Materials and Methods

Study area description

This study was conducted across selected farmers' fields in semi-arid Alfisols of southern India, specifically in the North and South Transects of Bengaluru. In 2017, 31 and 29 fields were surveyed in the North and South Transects, respectively, followed by 37 and 32 fields in 2018. The transects were classified into rural, transitional and urban zones using Vidhana Soudha as the central reference. The study region (12.15°–13.35° N, 77.04°–78.02° E) lies within the hot, moist semi-arid eco-subregion of the Southern Karnataka Plateau, with an elevation range of 667–992 m above MSL and average annual rainfall of 859 mm. The landscape is characterized by rocky uplands, flat-topped hills and plateaus formed over Archaean crystalline rocks, including Peninsular Gneissic Complex and Closepet granite. Dominant soils include loamy and gravelly lateritic types, derived from acidic granitic parent material. Rainfall variability across five taluks (Devanahalli, Hosakote, Nelamangala, Doddaballapura, Kanakapura) between 2014–2017 ranged from 520 to 1254 mm, with deviations between -33 % and +61 % (Table 1).

Survey and field selection

A baseline survey was conducted in 14 selected villages from both transects. Farmers were stratified by rural and transitional zones and interviewed using a structured questionnaire to collect data on cropping systems, demographics, land use, irrigation, fertilization and income. Based on the 2017 baseline, sixty suitable farmers were selected for demonstration trials in finger millet and other major crops based on land quality, accessibility and willingness to participate.

Soil and plant analysis

Pre-sowing soil samples were collected from a 0–20 cm depth and processed by air-drying, sieving and homogenizing. Soil pH and electrical conductivity (EC) were determined using a 1:2.5 soil-to-water ratio (20) and organic carbon was measured using standardized protocol (21). Available nitrogen was analysed using

alkaline permanganate (22), phosphorus by Bray's or Olsen's method depending on pH (23, 24) and potassium using 1N ammonium acetate (NH₄OAc) followed by flame photometry (20). Calcium, magnesium and sulphur were determined by titration and turbidometry, respectively (25, 26). While micronutrients (Zn, Fe, Mn, Cu) were measured by atomic absorption spectrophotometry (27). Corresponding whole plant samples collected at harvest were analysed for N (micro-Kjeldahl), P (vanadomolybdate), K (flame photometry), Ca and Mg (titration) and S and micronutrients using standard methods (28).

Statistical analysis

Descriptive statistics namely minimum, maximum, mean, standard deviation (SD), Coefficient of Variation (CV) % were computed to capture variability. Pearson correlation analysis was employed to determine relationships between soil properties, plant uptake and yield. Significant variables were used to develop multivariate regression models, with significance set at $p < 0.05$, following standardized procedures (18, 19). Linear regression models estimated crop yield (Y) based on nutrient uptake using:

$$Y = \pm \alpha \pm \beta_1(\text{UN}) \pm \beta_2(\text{UP}) \pm \beta_3(\text{UK}) \quad (\text{Eqn. 1})$$

where α is the intercept and β_1 – β_3 are coefficients representing change in yield per unit nutrient uptake. Model performance was assessed using R² values. Regression models were also used to estimate yield based on soil macro and micronutrients, pH and EC from the North and South Transects.

Results and Discussion

Crop yield differences under improved and farmers' practices across transects

Field experiments conducted in both North and South Transects demonstrated clear yield advantages for crops under Improved Practices (IP) compared to Farmers' Practices (FP), indicating the impact of enhanced nutrient and crop management strategies. In the North Transect (Table 2), IP resulted in substantial yield advantages across all evaluated crops, with gains ranging from 11.5 % to 15.2 % . Finger millet grown in 27 fields recorded a mean yield of 2,747 kg/ha under IP compared to 2,359 kg/ha under FP, representing a 15.2 % increase, despite comparable variability (CV ≈ 22 %). Maize yields increased by 11.5 % under IP (8,398 kg ha⁻¹) over FP (7,101 kg ha⁻¹), with yield variability influenced by soil-type differences across locations. Vegetable crops also showed marked improvements: tomato yields increased by 14.1 %, field bean by 13.3 % and brinjal by 15.2 % under IP. These improvements can be attributed to balanced fertilization, improved nutrient availability and better crop management, consistent with findings of previous studies (29, 30) which reported enhanced crop performance through integrated nutrient and resource management practices (29, 30).

Table 1. Annual rainfall received in different taluks of rural Bengaluru from 2014 to 2017

| Taluk | Normal (mm) | 2014 | | 2015 | | 2016 | | 2017 | |
|----------------|-------------|-------------|-------|-------------|-------|-------------|-------|-------------|-------|
| | | Actual (mm) | D (%) | Actual (mm) | D (%) | Actual (mm) | D (%) | Actual (mm) | D (%) |
| Devanahalli | 788 | 667 | -15 | 1061 | 35 | 682 | -13 | 952 | 21 |
| Doddaballapura | 752 | 938 | 25 | 1144 | 52 | 735 | -2 | 1114 | 48 |
| Hosakote | 813 | 688 | -15 | 1061 | 31 | 720 | -11 | 1081 | 33 |
| Nelamangala | 925 | 983 | 6 | 1145 | 24 | 743 | -20 | 1124 | 21 |
| Kanakapura | 780 | 758 | -3 | 1060 | 36 | 520 | -33 | 1254 | 61 |

D: Deviation (%)

Table 2. Descriptive statistics of yield attained by improved practice and farmers practice in the north transect of Bengaluru

| Parameter | Minimum | Maximum | Mean | SEM | SD | CV (%) |
|-----------------------------------|---------|---------|-------|--------|--------|--------|
| Finger millet (27 farmers) | | | | | | |
| IP yield (kg ha ⁻¹) | 1730 | 3500 | 2747 | 116.0 | 602.8 | 21.9 |
| FP yield (kg ha ⁻¹) | 1530 | 3151 | 2359 | 100.3 | 521.4 | 22.1 |
| Increase in yield (%) | 6.9 | 21.3 | 15.2 | 0.7 | 3.7 | 24.2 |
| Maize (9 farmers) | | | | | | |
| IP yield (kg ha ⁻¹) | 7410 | 9880 | 8398 | 342.9 | 1028.7 | 12.2 |
| FP yield (kg ha ⁻¹) | 6180 | 8150 | 7101 | 226.7 | 680.2 | 9.6 |
| Increase in yield (%) | 3.2 | 21.2 | 11.5 | 2.1 | 6.2 | 53.9 |
| Tomato (14 farmers) | | | | | | |
| IP yield (kg ha ⁻¹) | 37070 | 69160 | 53609 | 2121 | 7935 | 14.8 |
| FP yield (kg ha ⁻¹) | 32120 | 58070 | 46601 | 1800 | 6735 | 14.5 |
| Increase in yield (%) | 9.5 | 21.7 | 14.1 | 1.0 | 3.9 | 27.5 |
| Field bean (7 farmers) | | | | | | |
| IP yield (kg ha ⁻¹) | 2720 | 3250 | 2937 | 67.9 | 179.6 | 6.1 |
| FP yield (kg ha ⁻¹) | 2372 | 2720 | 2586 | 52.8 | 139.7 | 5.4 |
| Increase in yield (%) | 9.1 | 17.5 | 13.3 | 1.4 | 3.8 | 28.9 |
| Brinjal (4 farmers) | | | | | | |
| IP yield (kg ha ⁻¹) | 34590 | 49420 | 40888 | 3096.6 | 6193.2 | 15.1 |
| FP yield (kg ha ⁻¹) | 30890 | 42010 | 35315 | 2386.1 | 4772.3 | 13.5 |
| Increase in yield (%) | 12.0 | 18.5 | 15.2 | 1.7 | 3.4 | 22.3 |

CV: Coefficient of variation (%); SD: Standard deviation; SEM: Standard error mean.

Similar yield benefits were observed in the South Transect (Table 3), with IP increasing productivity by 10.4–16.4 % despite higher site variability. Finger millet showed the maximum gain in this transect, with yields increasing from 2,474 kg ha⁻¹ under FP to 3,038 kg ha⁻¹ under IP (16.4 %). Although the coefficient of variation was high (48.1 %), this variability likely reflects soil heterogeneity, differences in farmer practices and minor climatic fluctuations rather than inconsistencies in IP performance. Maize yields increased by 10.4 %, while field bean recorded a 13.9 % gain under IP. Tomato and brinjal also showed yield increases of 11.3 % and 10.6 %, respectively. These trends corroborate reports of earlier studies which demonstrated that site-specific and soil-test-based nutrient recommendations enhance yield stability and nutrient-use efficiency (31, 32). Overall, the consistent yield gains summarized in Fig. 1 confirm that IP offers a robust pathway for sustainable productivity enhancement across diverse agro-ecological conditions. These findings confirm the effectiveness of IP in achieving sustainable yield improvements and is at par with a previously conducted study (33).

Associations between yield, nutrient uptake and soil parameters

Correlation analyses (Table 4) revealed significant positive relationships between yield and plant nutrient uptake across most crops. In the North Transect, finger millet yields correlated strongly with the uptake of N ($r = 0.943$), P ($r = 0.864$) and K ($r = 0.660$) and negatively with soil pH ($r = -0.434$), indicating a preference for slightly acidic soils. Maize showed a negative correlation with soil B (-0.677), while tomato yield correlated with P (0.589) and K (0.888) uptake. Field bean and brinjal exhibited strong correlations between nutrient pairs (e.g., N–P, N–K, P–K), supporting the principle of nutrient synergy.

In the South Transect, similar nutrient relationships were observed. For finger millet, nutrient uptake correlations were high between N–P (0.818) and N–K (0.666). In maize, yield showed high correlation with N uptake (0.757) and soil N (0.862). Nutrient interactions such as P–K (0.988) indicated that crop performance was heavily dependent on balanced nutrient availability and uptake. These relationships agree with findings of the previous studies which examined nutrient interactions in semi-arid and nutrient synergy

Table 3. Descriptive statistics of yield attained by improved practice and farmers practice in the south transect of Bengaluru

| Parameter | Minimum | Maximum | Mean | SEM | SD | CV (%) |
|-----------------------------------|---------|---------|--------|---------|---------|--------|
| Finger millet (37 farmers) | | | | | | |
| IP yield (kg ha ⁻¹) | 1853 | 10000 | 3038.4 | 240.5 | 1462.7 | 48.1 |
| FP yield (kg ha ⁻¹) | 1853 | 3459 | 2474.1 | 69.9 | 425.0 | 17.2 |
| Increase in yield (%) | 9.1 | 25.7 | 16.4 | 0.6 | 3.9 | 24.0 |
| Maize (8 farmers) | | | | | | |
| IP yield (kg ha ⁻¹) | 2348 | 10000 | 8419 | 911.7 | 2578.6 | 30.6 |
| FP yield (kg ha ⁻¹) | 2630 | 9000 | 7444 | 741.4 | 2096.9 | 28.2 |
| Increase in yield (%) | 6.6 | 14.3 | 10.4 | 1.0 | 2.7 | 26.4 |
| Tomato (2 farmers) | | | | | | |
| IP yield (kg ha ⁻¹) | 24711 | 55000 | 39855 | 15144.5 | 21417.6 | 53.7 |
| FP yield (kg ha ⁻¹) | 44479 | 47500 | 45989 | 1510.5 | 2136.2 | 4.6 |
| Increase in yield (%) | 8.9 | 13.6 | 11.3 | 2.4 | 3.3 | 29.5 |
| Field bean (7 farmers) | | | | | | |
| IP yield (kg ha ⁻¹) | 2100 | 4479 | 3150 | 288.5 | 763.2 | 24.2 |
| FP yield (kg ha ⁻¹) | 2100 | 3000 | 2608 | 124.2 | 328.5 | 12.6 |
| Increase in yield (%) | 10.0 | 17.9 | 13.9 | 1.2 | 3.1 | 22.2 |
| Brinjal (2 farmers) | | | | | | |
| IP yield (kg ha ⁻¹) | 27182 | 45000 | 36091 | 8909.0 | 12599.2 | 34.9 |
| FP yield (kg ha ⁻¹) | 24711 | 40000 | 32356 | 7644.5 | 10811.0 | 33.4 |
| Increase in yield (%) | 10.0 | 11.1 | 10.6 | 0.6 | 0.8 | 7.4 |

CV: Coefficient of variation (%); SD: Standard deviation; SEM: Standard error mean

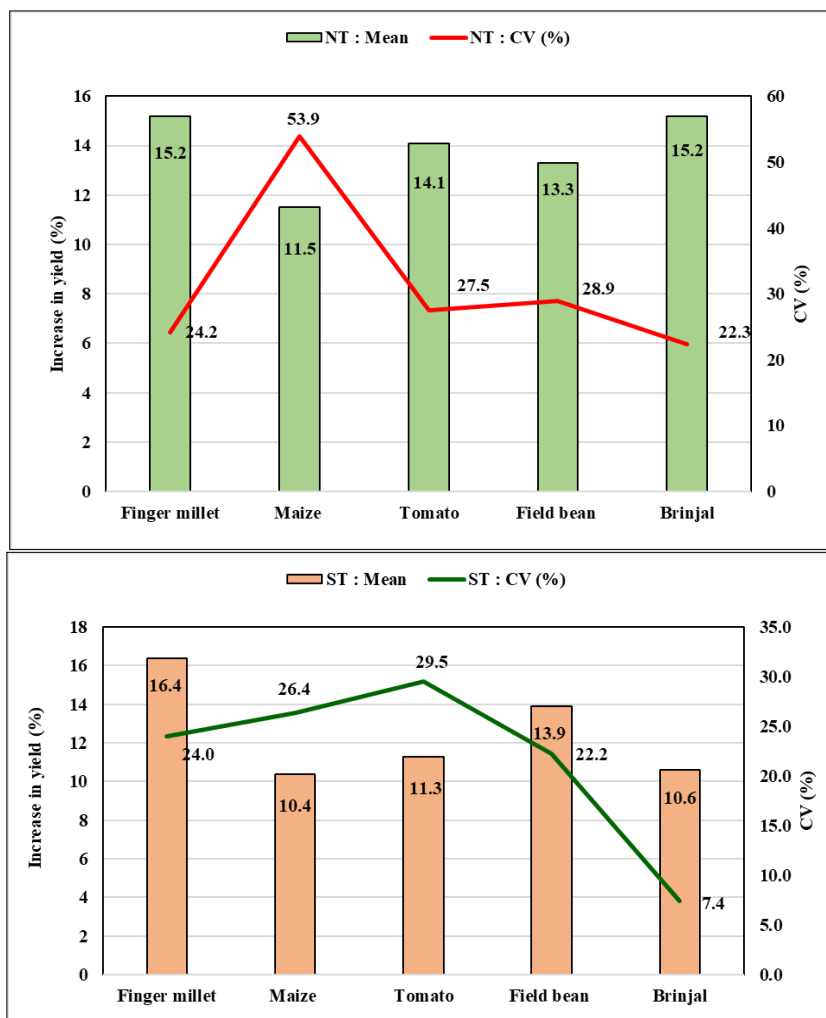


Fig. 1. Yield increase (%) of improved practice and its coefficient of variation (%) over farmers practice of crops under north transect (top) and south transect (bottom).

Table 4. Relationship between parameters in different crops in the north and south transects of Bengaluru

| Parameter 1 | Parameter 2 | North transect | | | | | South transect | | |
|-------------|----------------|--------------------|-----------|-------------|----------------|-------------|--------------------|-----------|----------------|
| | | Finger millet (27) | Maize (9) | Tomato (14) | Field bean (7) | Brinjal (4) | Finger millet (37) | Maize (8) | Field bean (7) |
| IP Yield | IP Uptake N | 0.943** | 0.623 | 0.398 | -0.099 | 0.901 | 0.186 | 0.757* | -0.426 |
| IP Yield | IP Uptake P | 0.864** | 0.072 | 0.589* | 0.438 | 0.937 | 0.116 | 0.387 | -0.332 |
| IP Yield | IP Uptake K | 0.660** | -0.196 | 0.888** | 0.714 | 0.721 | 0.159 | 0.291 | -0.603 |
| IP Yield | Yield increase | 0.047 | 0.193 | 0.183 | 0.598 | 0.615 | -0.262 | -0.369 | 0.537 |
| IP Yield | Soil pH | -0.434* | -0.107 | 0.295 | -0.641 | 0.142 | 0.122 | -0.424 | 0.027 |
| IP Yield | EC | 0.263 | -0.327 | -0.218 | 0.025 | -0.212 | 0.143 | -0.013 | -0.250 |
| IP Yield | Nitrogen | 0.411* | -0.166 | -0.085 | 0.036 | 0.196 | -0.017 | 0.862** | -0.380 |
| IP Yield | Phosphorus | 0.048 | 0.269 | -0.052 | 0.453 | -0.092 | -0.051 | -0.264 | -0.487 |
| IP Yield | Potassium | 0.222 | -0.216 | -0.137 | 0.187 | 0.144 | -0.092 | -0.037 | -0.033 |
| IP Yield | Iron | 0.101 | -0.060 | -0.126 | -0.223 | 0.439 | -0.074 | 0.560 | -0.393 |
| IP Yield | Zinc | -0.157 | -0.190 | 0.229 | 0.568 | -0.399 | 0.229 | -0.603 | -0.202 |
| IP Yield | Copper | -0.125 | -0.274 | -0.096 | 0.188 | -0.170 | -0.152 | -0.261 | 0.056 |
| IP Yield | Manganese | 0.291 | 0.114 | 0.358 | -0.110 | -0.760 | -0.174 | 0.357 | -0.318 |
| IP Yield | Boron | 0.056 | -0.677* | 0.352 | 0.024 | -0.764 | -0.161 | 0.553 | 0.060 |
| IP Uptake N | IP Uptake P | 0.867** | 0.572 | 0.841** | 0.813* | 0.985* | 0.818** | 0.840** | 0.660 |
| IP Uptake N | IP Uptake K | 0.616** | 0.356 | 0.667** | 0.532 | 0.931 | 0.666** | 0.784* | 0.907** |
| IP Uptake N | Nitrogen | 0.364 | -0.502 | -0.413 | -0.722 | -0.156 | 0.294 | 0.702 | 0.260 |
| IP Uptake P | IP Uptake K | 0.680** | 0.936** | 0.753** | 0.890** | 0.856 | 0.633** | 0.988** | 0.433 |
| IP Uptake P | Phosphorus | -0.002 | -0.122 | -0.265 | -0.047 | -0.094 | -0.061 | 0.319 | 0.313 |
| IP Uptake K | Potassium | 0.193 | -0.383 | -0.230 | -0.155 | 0.539 | 0.001 | -0.049 | -0.094 |

FP: Farmers practice; IP: Improved practice, Critical correlation value with 25 degrees of freedom at 5 % level = 0.381 and 1 % level of significance = 0.487

Critical correlation value with 7 degrees of freedom at 5 % level = 0.666 and 1 % level of significance = 0.798

Critical correlation value with 12 degrees of freedom at 5 % level = 0.532 and 1 % level of significance = 0.661

Critical correlation value with 5 degrees of freedom at 5 % level = 0.754 and 1 % level of significance = 0.874

Critical correlation value with 2 degrees of freedom at 5 % level = 0.950 and 1 % level of significance = 0.990

Critical correlation value with 35 degrees of freedom at 5 % level = 0.325 and 1 % level of significance = 0.418

Critical correlation value with 6 degrees of freedom at 5 % level = 0.707 and 1 % level of significance = 0.834

trends reported earlier (34–37).

Predicting plant nutrient uptake from soil nutrient levels

Regression analysis (Table 5 and 6) demonstrated that plant nutrient uptake could be predicted more reliably from soil test values under IP than under FP, reflecting better nutrient–soil synchrony. Crop yield is fundamentally driven by nutrient uptake, which varies with native soil fertility and high-nutrient soils often exhibit lower fertilizer response due to diminished marginal returns (37–39). Under IP in the North Transect, prediction models showed moderate to strong explanatory power, particularly for P uptake in finger millet and maize (R^2 often > 0.75), while N and K uptake were predicted with moderate accuracy. Vegetable crops and pulses exhibited moderate predictability, indicating crop-specific differences in nutrient demand and uptake dynamics. In contrast, FP models showed markedly weaker relationships, with few exceptions and in some cases, negative regression slopes suggested nutrient oversupply and inefficient utilization. In the South Transect, IP-based models again outperformed FP models with strong predictability for finger millet nutrient uptake and moderate predictability for maize, whereas FP models were largely non-significant, except in isolated cases. Overall, the higher R^2 values and consistency of IP-based models confirm that soil test-based nutrient prediction is more robust under improved nutrient management. These observations are consistent with a previous study which reported that soil N and P levels are effective predictors of plant nutrient uptake in dryland cropping systems (40).

Yield prediction through plant nutrient uptake

Regression models based on plant nutrient uptake (Table 7) indicated higher predictability of yield under IP than under FP. In the North Transect, IP-based models showed strong explanatory power for finger millet, tomato and brinjal ($R^2 > 0.8$), indicating a strong link between nutrient uptake and yield. Maize and field bean exhibited moderate model performance. Under FP, predictability improved mainly for maize and field bean, with yield largely driven by N uptake. The relatively better performance of farmer practice for maize may be due to the crop's response to high-input conditions, where in field bean, traditional sowing and organic amendments used by farmers often favour better nodulation and biological N fixation compared to the standardized inputs applied under improved practice.

Fig. 2–Fig. 6 depict clear positive relationships between crop yield and nutrient uptake across management practices. Under IP in the North Transect, finger millet yield showed a strong positive response to N uptake, indicating efficient conversion of absorbed N into yield. Brinjal yield was consistently influenced by both N and P under IP and FP, reflecting its high demand for balanced nutrition. In contrast, tomato yield under IP was more strongly driven by K uptake, highlighting the role of K in fruit development and yield formation. These results reinforce earlier findings, demonstrating the strong predictive influence of plant nutrient uptake on crop yields in Alfisol environments (29, 41).

Yield prediction through soil nutrients

Yield prediction based on soil nutrient status (Table 8 and 9) showed variable performance across crops and management practices, with micronutrients emerging as stronger predictors than macronutrients. In the North Transect under IP, yield predictability from macronutrients was generally weak, whereas field bean yield showed strong dependence on soil micronutrient status, indicating the importance of Zn, Fe, B and Mn in legume productivity. Under FP, modest improvements in predictability for maize and field bean suggested partial alignment between farmer-managed inputs and soil nutrient availability. In the South Transect, soil-based models performed better, particularly for maize, where both macro- and micronutrients explained a large proportion of yield variability under IP and even stronger relationships were observed under FP. Overall, these results highlight the critical role of soil micronutrients in yield determination and support earlier findings emphasizing their contribution to crop productivity in Alfisol environments (42).

Influence of soil pH and EC on yield prediction

Regression models based on soil pH and EC (Table 10) indicated limited predictive capability for most crops. In the North Transect, finger millet yield showed moderate prediction under IP ($R^2 = 0.384$) and FP ($R^2 = 0.339$), with positive associations with EC and negative associations with pH. This pattern may reflect the crop's favourable response to moderate soluble salt concentrations that enhance nutrient availability, while slightly higher pH levels can reduce micronutrient solubility and buffering capacity, thereby limiting plant uptake and yield. In the South, only finger millet under FP had a weakly significant model ($R^2 = 0.119$), suggesting marginal utility of these parameters in yield forecasting.

Table 5. Regression models for predicting plant uptake through soil nutrients in North Transect of Bengaluru

| Crop (No. of farmers) | IP regression model | R^2 | PE | FP regression model | R^2 | PE |
|-----------------------|-----------------------------|-------|------|------------------------------|---------|-------|
| Finger millet (27) | UN = 91.837** + 0.051* (SN) | 0.142 | 14.7 | UN = 90.540** + 0.013 (SN) | 0.016 | 11.9 |
| | UP = 13.745** + 0.001 (SP) | 0.001 | 2.6 | UP = 11.968** - 0.002 (SP) | 0.016 | 1.1 |
| | UK = 80.615** + 0.013 (SK) | 0.031 | 9.6 | UK = 69.814** + 0.033** (SK) | 0.222** | 8.4 |
| Maize (9) | UN = 164.921** - 0.040 (SN) | 0.252 | 9.1 | UN = 136.362** - 0.007 (SN) | 0.012 | 8.6 |
| | UP = 38.700** - 0.009 (SP) | 0.015 | 4.7 | UP = 33.672** + 0.005 (SP) | 0.024 | 2.1 |
| | UK = 139.984** - 0.097 (SK) | 0.147 | 20.2 | UK = 182.687 + 0.163 (SK) | 0.002 | 324.8 |
| Tomato (14) | UN = 144.877** - 0.081 (SN) | 0.170 | 16.6 | UN = 128.263** - 0.066 (SN) | 0.149 | 14.7 |
| | UP = 10.495** - 0.008 (SP) | 0.070 | 0.8 | UP = 10.127** - 0.011 (SP) | 0.206 | 0.6 |
| | UK = 100.026** - 0.039 (SK) | 0.053 | 9.8 | UK = 96.220** - 0.050 (SK) | 0.125 | 7.7 |
| Field bean (7) | UN = 83.935** - 0.020 (SN) | 0.521 | 3.0 | UN = 83.337** - 0.032 (SN) | 0.450 | 5.4 |
| | UP = 12.669** - 0.001 (SP) | 0.002 | 1.7 | UP = 9.749** + 0.008 (SP) | 0.249 | 0.8 |
| | UK = 42.672** - 0.002 (SK) | 0.024 | 3.0 | UK = 38.296** + 0.001 (SK) | 0.001 | 3.3 |
| Brinjal (4) | UN = 167.568 - 0.070 (SN) | 0.024 | 22.6 | UN = 130.829 - 0.014 (SN) | 0.002 | 17.9 |
| | UP = 48.249 - 0.088 (SP) | 0.009 | 11.2 | UP = 37.404 + 0.058 (SP) | 0.014 | 5.7 |
| | UK = 77.145 + 0.849 (SK) | 0.291 | 22.9 | UK = 75.910 + 0.605 (SK) | 0.253 | 17.9 |

* and ** indicate significance at 5 % and 1 % level of significance respectively

FP: Farmers practice; IP: Improved practice; PE: Prediction error; R2: Coefficient of determination; SK: Soil potassium; SN: Soil nitrogen; SP: Soil phosphorus; UK: Uptake of potassium; UN: Uptake of nitrogen; UP: Uptake of phosphorus.

Table 6. Regression models for predicting plant uptake through soil nutrients in the south transect of Bengaluru

| Crop (No. of farmers) | IP regression model | R ² | PE | FP regression model | R ² | PE |
|-----------------------|------------------------------|----------------|------|-------------------------------|----------------|------|
| Finger millet (37) | UN = 92.516** + 0.032 (SN) | 0.087 | 12.1 | UN = 96.888** - 0.009 (SN) | 0.023 | 6.9 |
| | UP = 13.326** - 0.003 (SP) | 0.004 | 2.6 | UP = 11.500** + 0.003 (SP) | 0.012 | 1.5 |
| | UK = 75.733** + 0.001 (SK) | 0.001 | 7.7 | UK = 71.608** + 0.003 (SK) | 0.009 | 7.3 |
| Maize (8) | UN = 131.270** + 0.054* (SN) | 0.493* | 5.7 | UN = 109.746** + 0.074** (SN) | 0.743** | 4.5 |
| | UP = 35.623** + 0.025 (SP) | 0.102 | 3.9 | UP = 33.647** + 0.018 (SP) | 0.073 | 3.4 |
| | UK = 128.246** - 0.004 (SK) | 0.002 | 13.5 | UK = 108.487** + 0.004 (SK) | 0.004 | 10.9 |
| Field bean (7) | UN = 71.100** + 0.006 (SN) | 0.068 | 2.8 | UN = 96.732** - 0.002 (SN) | 0.003 | 3.5 |
| | UP = 11.457** + 0.018 (SP) | 0.098 | 1.7 | UP = 10.296** + 0.004 (SP) | 0.053 | 0.6 |
| | UK = 43.941** - 0.002 (SK) | 0.009 | 3.9 | UK = 36.799** - 0.003 (SK) | 0.032 | 2.6 |

* and ** indicate significance at 5 % and 1 % level of significance, respectively

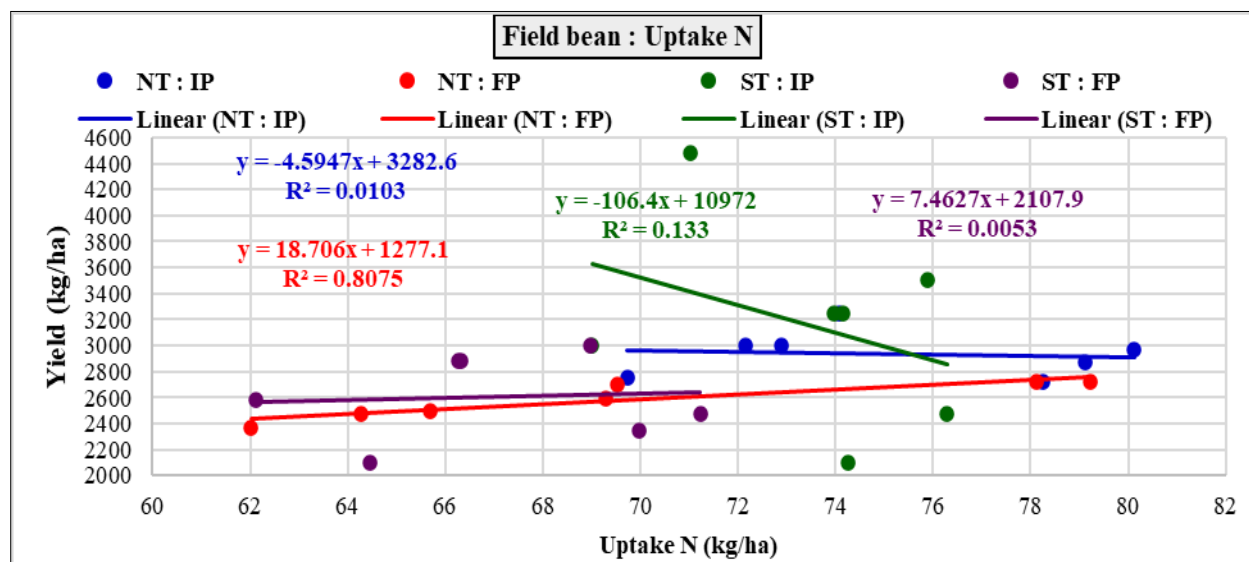
FP: Farmers practice; IP: Improved practice; PE: Prediction error; R²: Coefficient of determination; SK: Soil potassium; SN: Soil nitrogen; SP: Soil phosphorus; UK: Uptake of potassium; UN: Uptake of nitrogen; UP: Uptake of phosphorus.

Table 7. Regression models for predicting yield through plant N, P and K in North and South Transects of Bengaluru

| Crop (No. of farmers) | IP regression model | R ² | PE | FP regression model | R ² | PE |
|-----------------------|---|----------------|---------|---|----------------|--------|
| North transect | | | | | | |
| Finger millet (27) | IPY = -1529.15** + 30.91** (UN) + 23.28 (UP) + 6.617 (UK) | 0.908** | 194.1 | FPY = -2050.9** + 16.839* (UN) + 89.11 (UP) + 23.21** (UK) | 0.791** | 253.2 |
| Maize (9) | IPY = -5.043 + 51.481 (UN) + 256.752 (UP) - 70.703 (UK) | 0.660 | 758.1 | FPY = -1102.25 + 101.15** (UN) - 158.43 (UP) + 0.519 (UK) | 0.825* | 359.8 |
| Tomato (14) | IPY = -21042.672 - 205.266 (UN) + 1659.430 (UP) + 870.739** (UK) | 0.862** | 3356.2 | FPY = -5997.56 - 161.998 (UN) + 689.368 (UP) + 712.629 (UK) | 0.288 | 6477.8 |
| Field bean (7) | IPY = 3473.790 - 43.689 (UN) + 72.572 (UP) + 43.710 (UK) | 0.847* | 99.3 | FPY = 1837.19* + 29.636* (UN) - 95.441 (UP) - 7.590 (UK) | 0.908* | 59.8 |
| Brinjal (4) | IPY = -1748.945 + 298.679 (UN) | 0.812* | 3288.4 | FPY = -3172.30 + 305.639* (UN) | 0.885* | 1979.0 |
| | IPY = 12660.683 + 631.472 (UP) | 0.878* | 2645.4 | FPY = -212.543 + 894.343 (UP) | 0.782* | 2731.3 |
| | IPY = 7943.596 + 201.399 (UK) | 0.520 | 5253.7 | FPY = 5718.331 + 215.368 (UK) | 0.583 | 3775.9 |
| South transect | | | | | | |
| Finger millet (37) | IPY = -487.702 + 29.119 (UN) - 100.233 (UP) + 23.327 (UK) | 0.045 | 1492.6 | FPY = -2182.49** + 26.93** (UN) + 165.43** (UP) + 2.94 (UK) | 0.821** | 187.9 |
| Maize (8) | IPY = -42257.7 + 436.96* (UN) + 465.85 (UP) - 282.89 (UK) | 0.815 | 1469.1 | FPY = -3741.591 - 33.972 (UN) + 248.989 (UP) + 67.546 (UK) | 0.285 | 2345.3 |
| Field bean (7) | IPY = -289247.373 + 9670.893 (UN) - 5878.834 (UP) - 7818.457 (UK) | 0.603 | 14000.9 | FPY = 2960.503 + 165.898 (UN) - 1289.489 (UP) + 59.228 (UK) | 0.760 | 227.5 |

* and ** indicate significance at 5 % and 1 % level of significance respectively

FP: Farmers practice; FPY: Farmers practice yield; IP: Improved practice; IPY: Improved practice yield; PE: Prediction error; R²: Coefficient of determination; UK: Uptake of potassium; UN: Uptake of nitrogen; UP: Uptake of phosphorus.



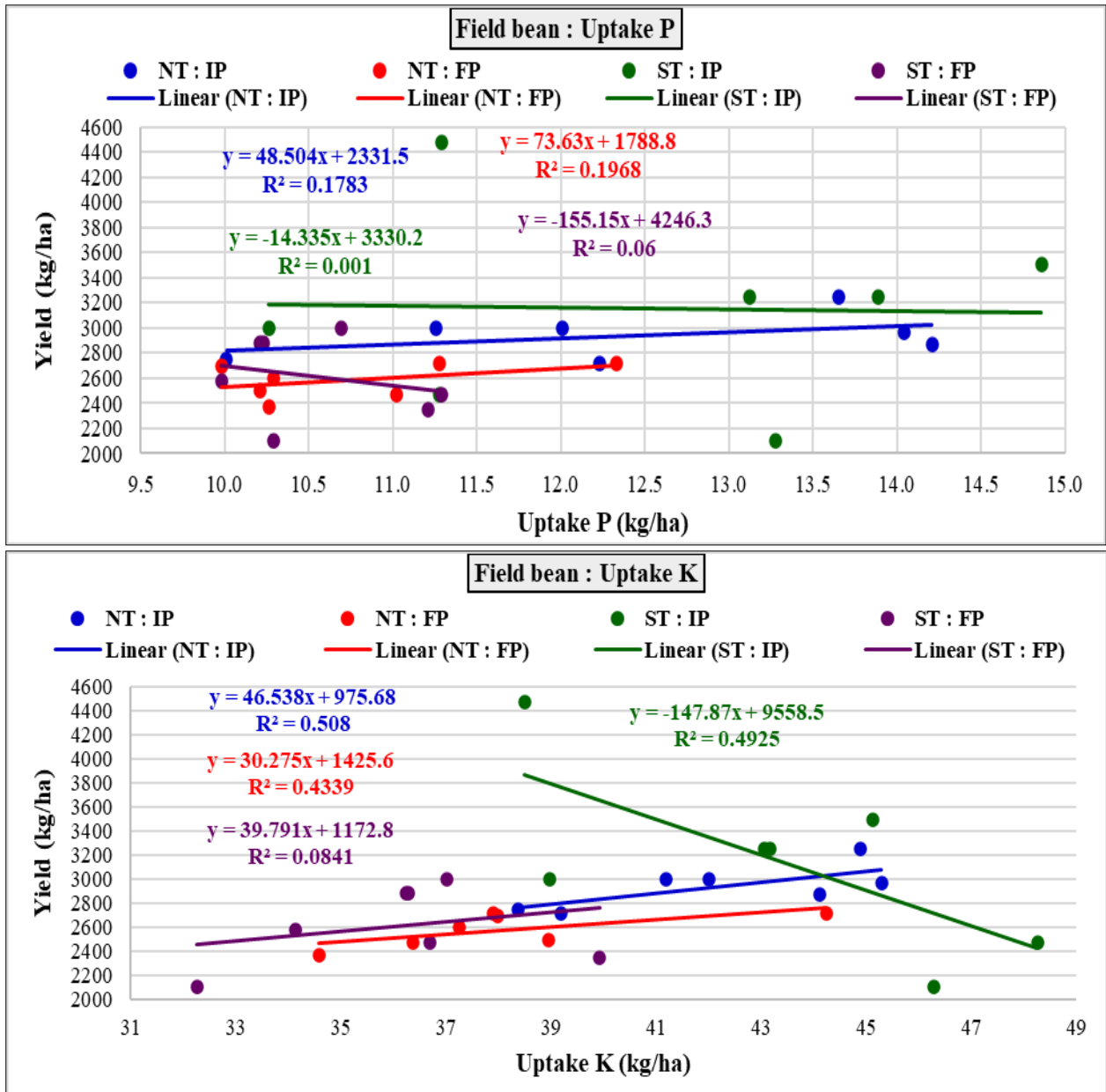
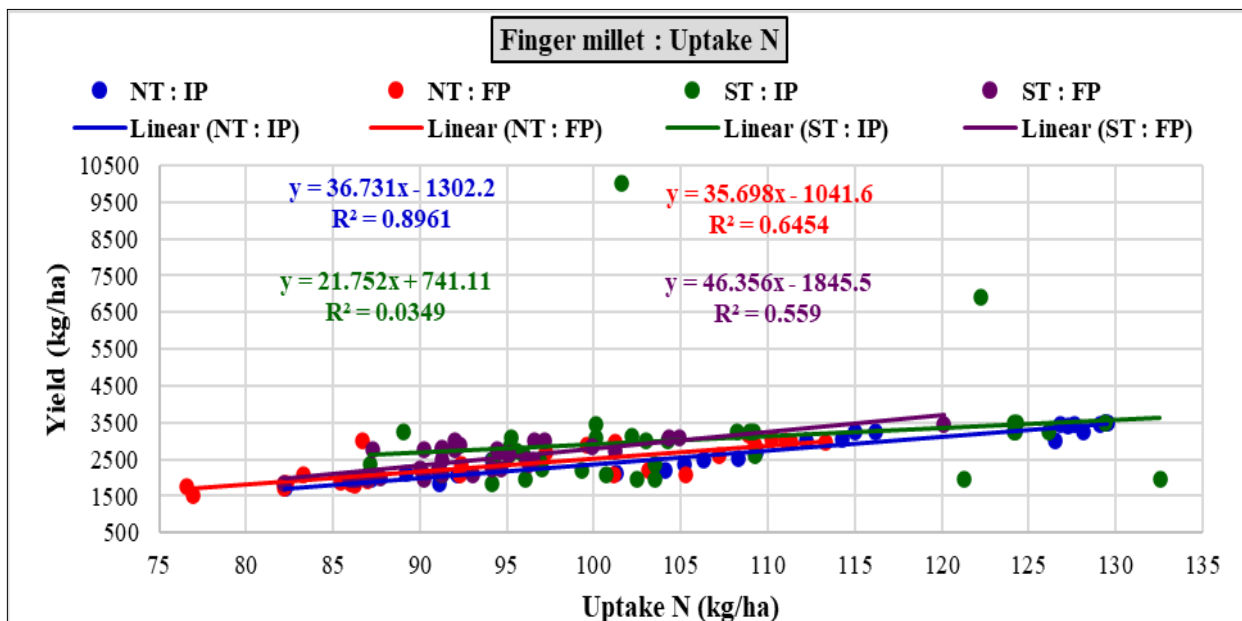


Fig. 2. Effect of plant N, P and K on the yield of field bean in farmers' fields of the North and South Transects.



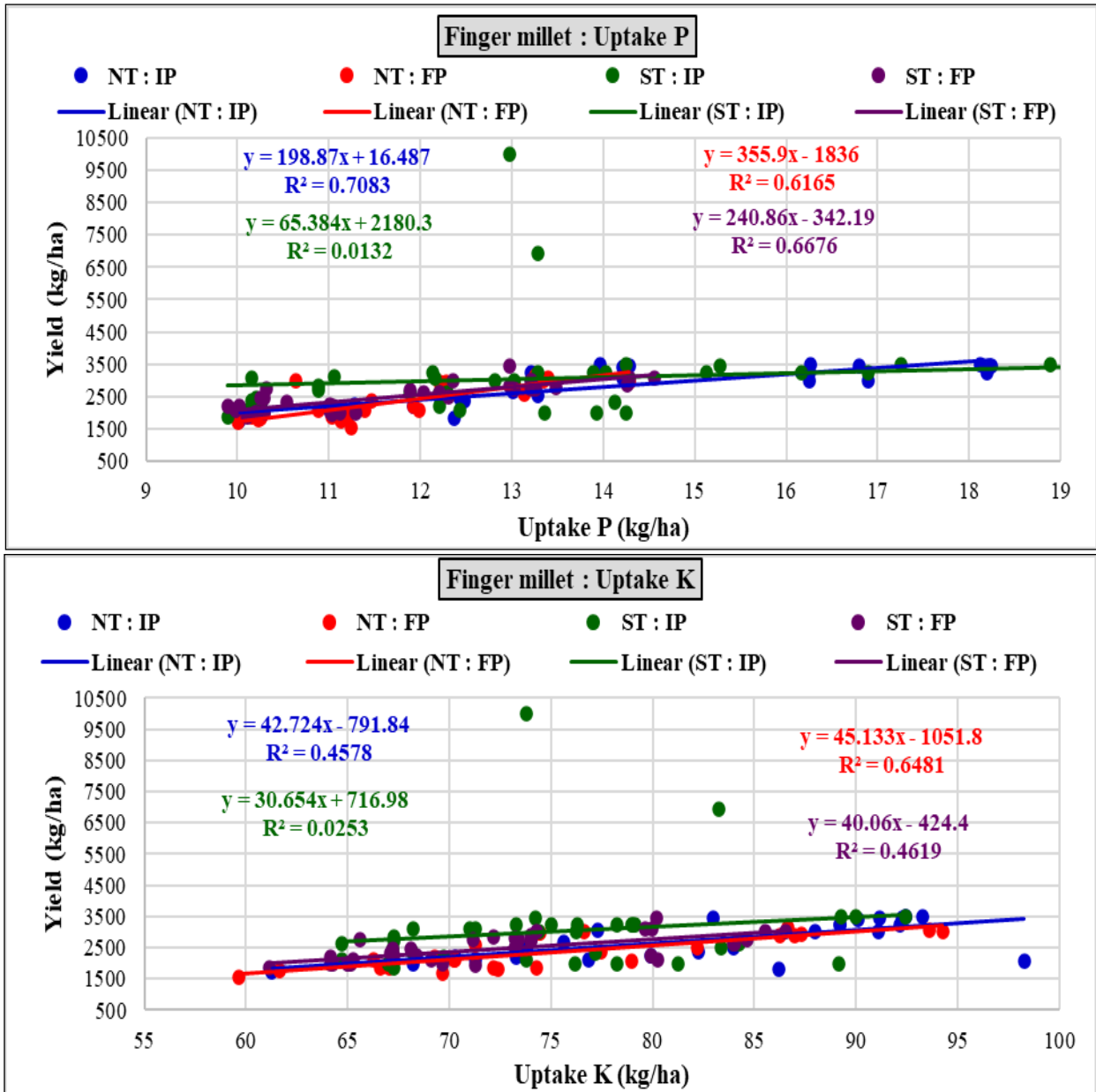
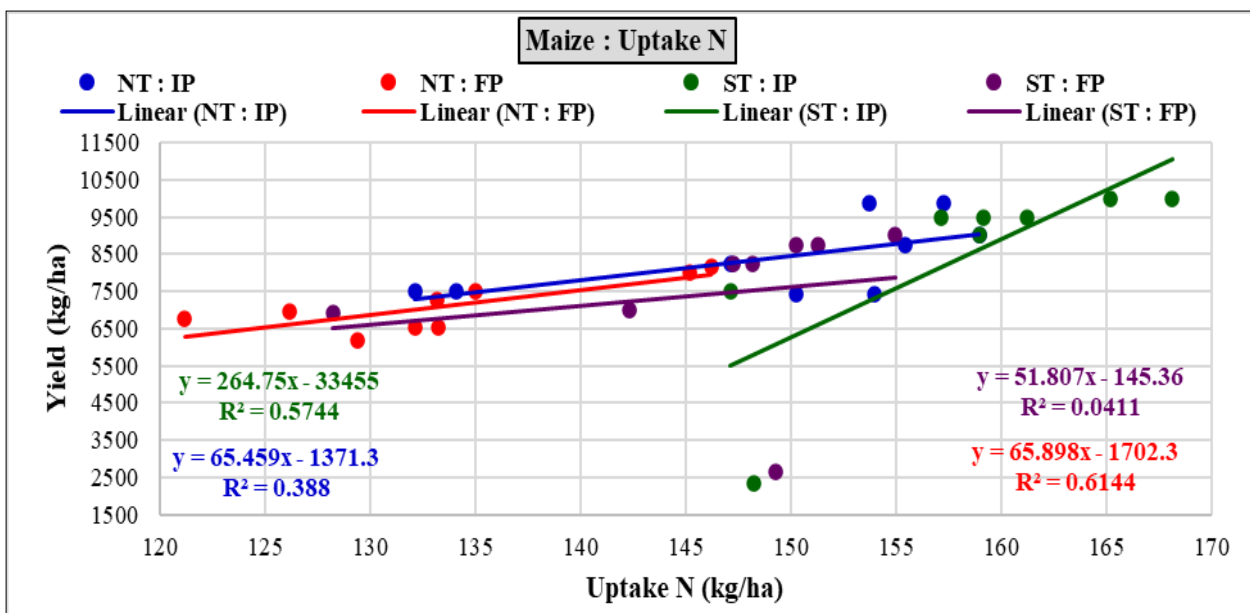


Fig. 3. Effect of plant N, P and K on finger millet yield in farmers' fields of North and South Transects.



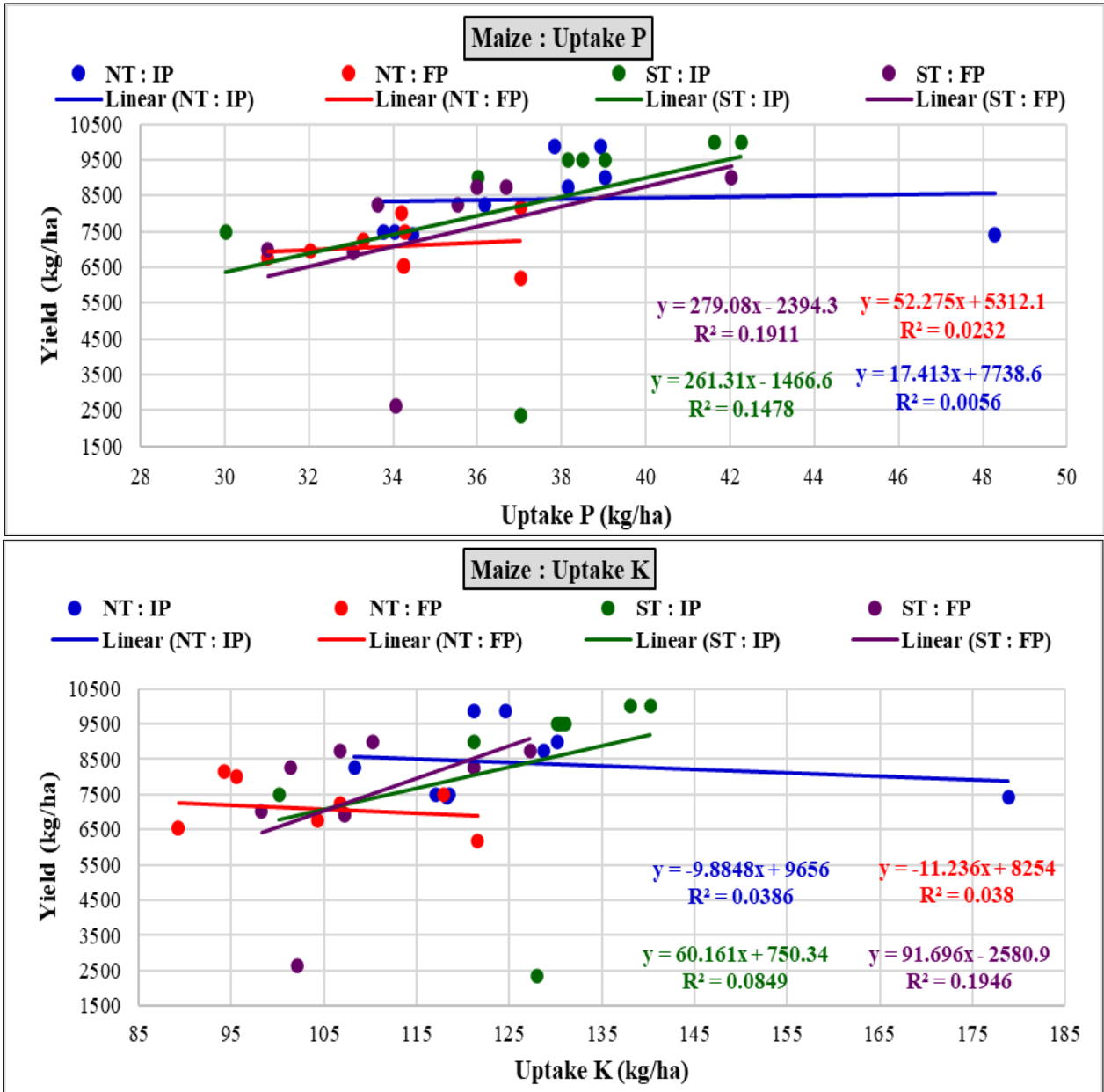
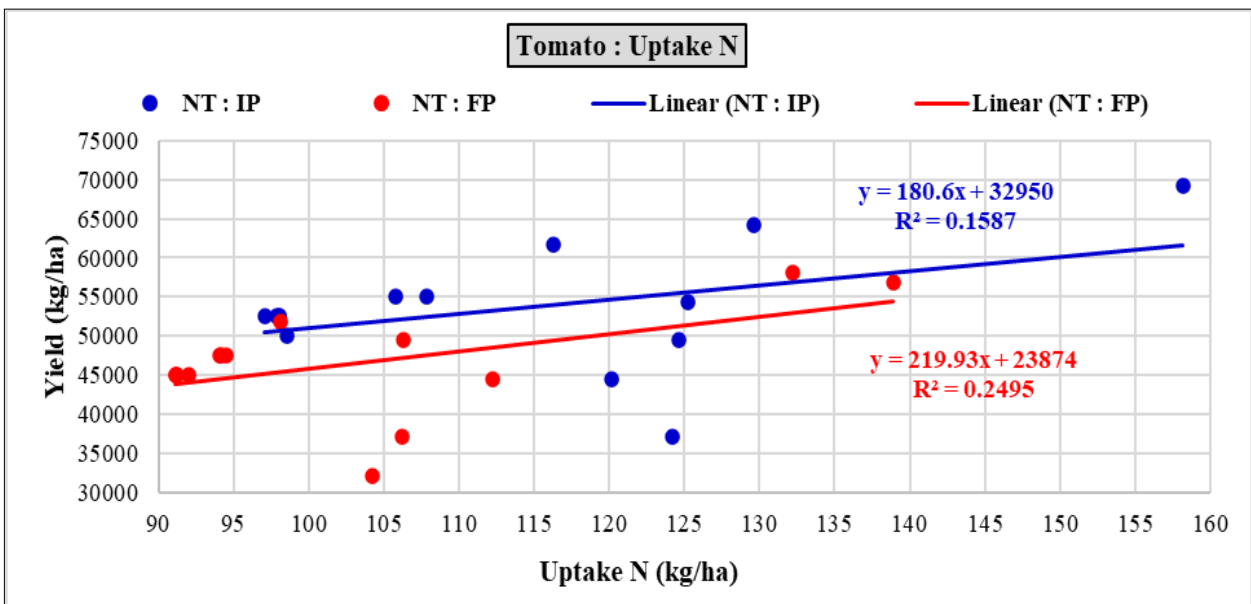


Fig. 4. Effect of plant N, P and K on maize yield in farmers' fields of North and South Transects.



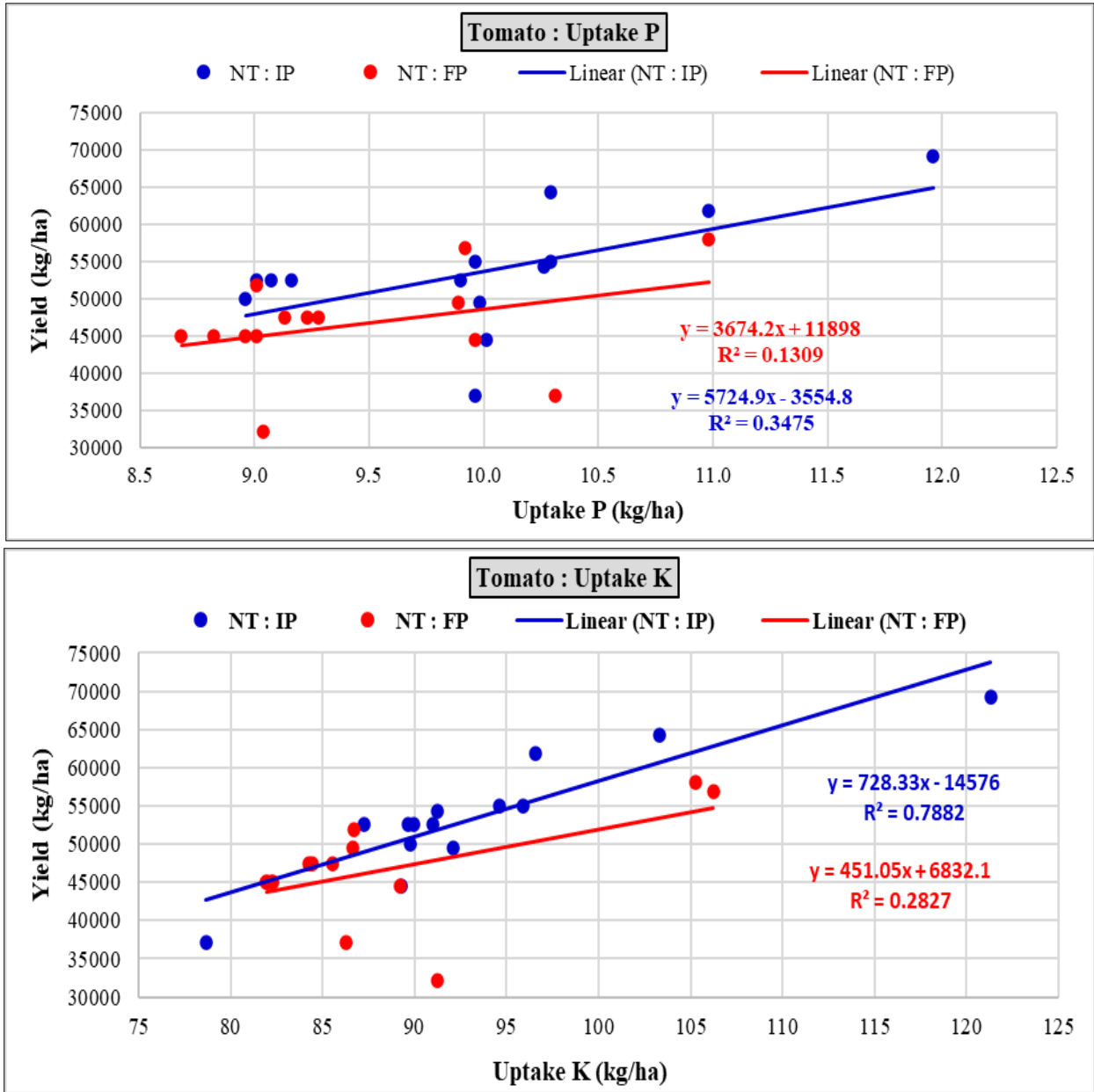
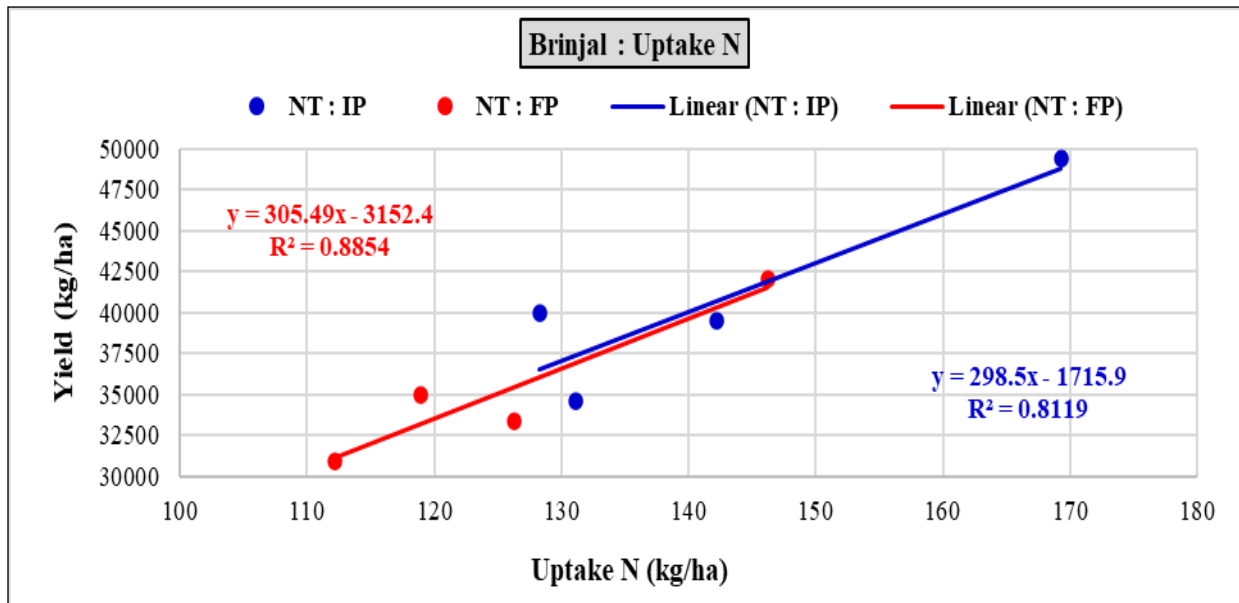


Fig. 5. Effect of plant N, P and K on tomato yield in farmers' fields of North Transect (NT).



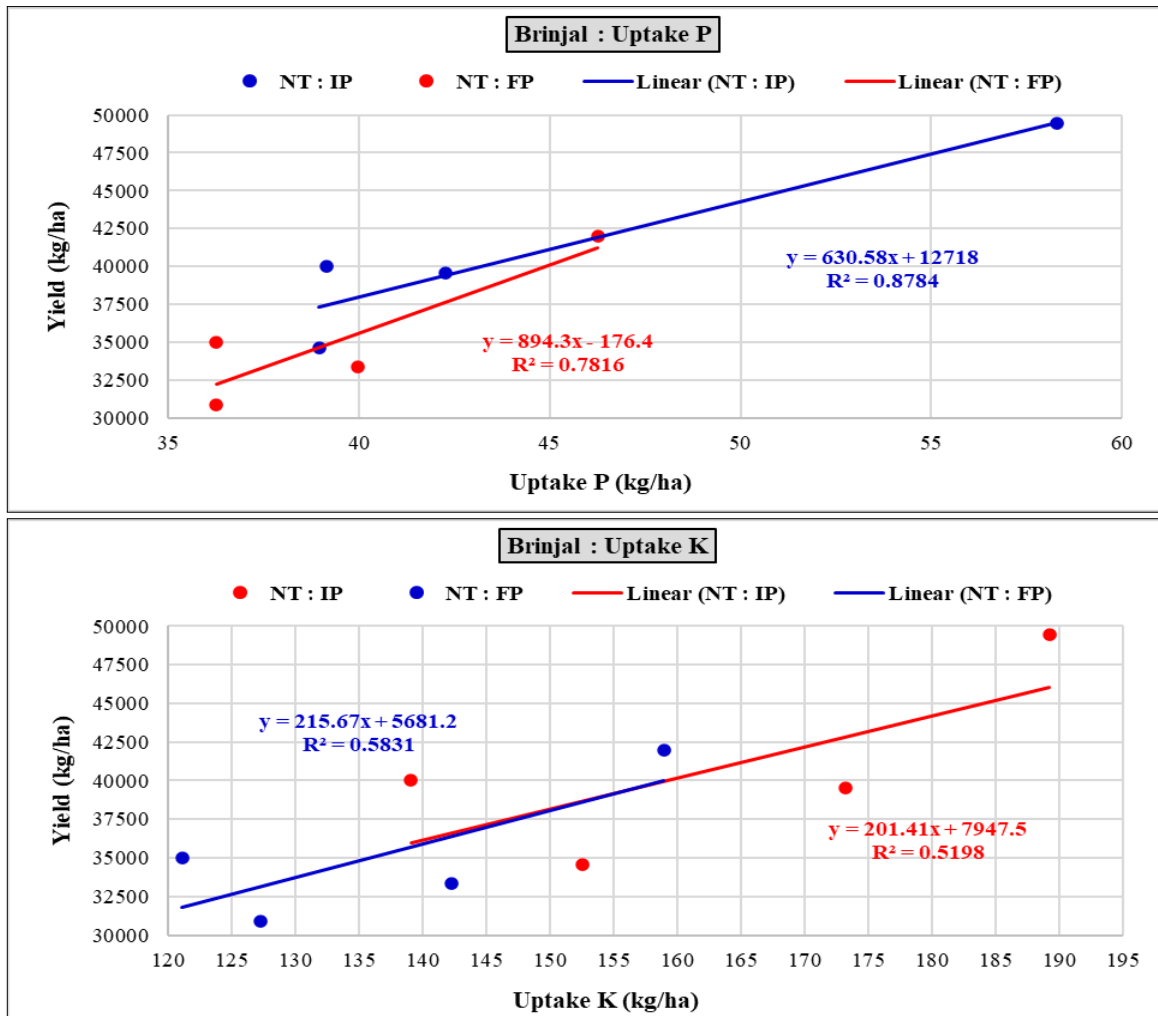


Fig. 6. Effect of plant N, P and K on brinjal yield in farmers’ fields of North Transect.

Table 8. Regression models for predicting yield through soil nutrients in the North Transect of Bengaluru

| Crop (No. of farmers) | IP regression model | R ² | PE | FP regression model | R ² | PE |
|-----------------------|---|----------------|--------|---|----------------|--------|
| Finger millet (27) | IPY = 1862.700** + 2.221* (SN) – 0.467 (SP) + 0.715 (SK) | 0.206 | 571.0 | FPY = 1570.809** + 1.821* (SN) + 0.056 (SP) + 0.739 (SK) | 0.209 | 493.1 |
| | IPY = 2525.660** + 10.657 (Fe) – 69.086 (Zn) – 420.650 (Cu) + 54.539 (Mn) + 163.865 (B) | 0.118 | 629.9 | FPY = 2341.355** + 11.757 (Fe) – 97.180 (Zn) – 483.823 (Cu) + 37.096 (Mn) + 193.877 (B) | 0.147 | 535.9 |
| | IPY = 2126.008** + 2.246 (SN) – 0.953 (SP) + 0.522 (SK) + 3.645 (Fe) – 33.010 (Zn) – 569.450 (Cu) + 23.028 (Mn) + 122.493 (B) | 0.518 | 619.7 | FPY = 1956.003** + 1.891 (SN) – 0.562 (SP) + 0.602 (SK) + 6.031 (Fe) – 48.558 (Zn) – 613.269 (Cu) + 8.863 (Mn) + 120.478 (B) | 0.298 | 525.2 |
| Maize (9) | IPY = 8186.824** + 0.641 (SN) + 11.162 (SP) – 8.594 (SK) | 0.315 | 1076.6 | FPY = 6041.370** + 1.804 (SN) + 8.372 (SP) – 3.557 (SK) | 0.408 | 661.9 |
| | IPY = 10786.280** – 71.266 (Fe) – 130.766 (Zn) + 721.355 (Cu) + 3.028 (Mn) – 5755.848 (B) | 0.727 | 877.2 | FPY = 8404.878** + 27.217 (Fe) + 334.789 (Zn) – 1046.169 (Cu) – 73.280 (Mn) – 1859.007 (B) | 0.791 | 507.2 |
| Tomato (14) | IPY = 60084.532** – 7.046 (SN) – 16.122 (SP) – 17.508 (SK) | 0.027 | 8926.6 | FPY = 50776.758** – 5.311 (SN) – 16.670 (SP) – 7.137 (SK) | 0.013 | 7628.7 |
| | IPY = 36198.430** – 600.932 (Fe) + 379.678 (Zn) + 5277.700 (Cu) + 1480.216 (Mn) + 18963.740 (B) | 0.482 | 7278.2 | FPY = 31519.899** – 387.687 (Fe) + 745.710 (Zn) + 3086.703 (Cu) + 1164.142 (Mn) + 15426.870 (B) | 0.501 | 6065.6 |
| | IPY = 41019.130 – 39.536 (SN) + 10.190 (SP) + 19.367 (SK) – 318.567 (Fe) + 545.104 (Zn) + 7394.965 (Cu) + 1224.080 (Mn) + 31555.830 (B) | 0.553 | 8550.4 | FPY = 30968.218 – 24.808 (SN) 12.028 (SP) + 25.088 (SK) – 225.646 (Fe) + 937.455 (Zn) + 5016.373 (Cu) + 1043.197 (Mn) + 24296.162 (B) | 0.563 | 7182.3 |
| Field bean (7) | IPY = 2770.272** – 0.107 (SN) + 1.713 (SP) + 0.013 (SK) | 0.211 | 225.6 | FPY = 2815.744** – 0.512 (SN) + 0.241 (SP) – 0.191 (SK) | 0.395 | 153.6 |
| | IPY = 2737.199* – 40.090 (Fe) + 685.784 (Zn) – 1428.411 (Cu) + 106.241 (Mn) – 729.189 (B) | 0.984 | 56.1 | FPY = 2576.472 – 36.509 (Fe) + 89.137 (Zn) – 485.922 (Cu) + 76.164 (Mn) – 241.071 (B) | 0.614 | 212.5 |
| Brinjal (4) | IPY = 30585.357 + 29.071 (SN) | 0.038 | 7438.2 | FPY = 23140.655 + 34.355 (SN) | 0.090 | 5575.1 |
| | IPY = 43220.622 – 57.908 (SP) | 0.008 | 7553.1 | FPY = 39651.332 – 107.622 (SP) | 0.049 | 5700.4 |
| | IPY = 34430.378 + 63.464 (SK) | 0.021 | 7505.7 | FPY = 29386.283 + 58.273 (SK) | 0.030 | 5757.9 |

* and ** indicate significance at 5 % and 1 % level of significance respectively

FPY: Farmers practice yield; IPY: Improved practice yield; PE: Prediction error; R²: Coefficient of determination; SK: Soil potassium; SN: Soil nitrogen; SP: Soil phosphorus.

Table 9. Regression models for predicting yield through soil nutrients in the South Transect of Bengaluru

| Crop (No. of farmers) | IP regression model | R ² | PE | FP regression model | R ² | PE |
|-----------------------|--|----------------|---------|--|----------------|--------|
| Finger millet (37) | IPY = 3174.236** + 0.303 (SN) – 1.584 (SP) – 0.576 (SK) | 0.011 | 1518.9 | FPY = 2117.321** + 1.001 (SN) – 0.856 (SP) + 0.027 (SK) | 0.067 | 428.8 |
| | IPY = 3645.936* + 61.411 (Fe) + 675.824 (Zn) – 1118.218 (Cu) – 107.888 (Mn) – 2097.185 (B) | 0.125 | 1474.1 | FPY = 1905.606** + 10.687 (Fe) + 179.890 (Zn) + 154.483 (Cu) – 16.642 (Mn) + 1290.838 (B) | 0.113 | 431.3 |
| | IPY = 3551.813* – 0.966 (SN) + 0.900 (SP) – 0.841 (SK) + 94.478 (Fe) + 888.043 (Zn) – 830.818 (Cu) – 140.326 (Mn) – 1483.048 (B) | 0.144 | 1534.0 | FPY = 1727.230** + 1.446 (SN) – 1.481 (SP) – 0.127 (SK) – 12.442 (Fe) + 80.868 (Zn) + 224.162 (Cu) – 6.446 (Mn) + 1164.018 (B) | 0.177 | 437.1 |
| Maize (8) | IPY = –2239.375 + 22.584* (SN) – 5.948 (SP) – 0.443 (SK) | 0.757 | 1681.9 | FPY = 1985.391 + 5.988 (SN) + 21.812 (SP) + 2.517 (SK) | 0.374 | 2195.4 |
| | IPY = –6762.318 + 287.655 (Fe) + 7778.833 (Zn) – 16074.140 (Cu) + 627.515 (Mn) + 37662.456 (B) | 0.921* | 1351.9 | FPY = 5271.083 – 36.134 (Fe) + 6681.277 (Zn) – 17501.718 (Cu) + 1378.760 (Mn) – 14721.147 (B) | 0.978* | 586.2 |
| Field bean (7) | IPY = 41819.788 – 47.793 (SN) – 394.931 (SP) + 43.564 (SK) | 0.467 | 16217.8 | FPY = 1396.286** + 2.424* (SN) + 2.504 (SP) + 0.166 (SK) | 0.871 | 167.1 |
| | IPY = –841.038 – 3967.832 (Fe) – 30012.307 (Zn) + 45586.313 (Cu) + 2908.760 (Mn) + 207397.530 (B) | 0.659 | 22463.8 | FPY = 1911.070 + 90.481 (Fe) + 240.128 (Zn) + 803.120 (Cu) – 90.474 (Mn) – 1820.447 (B) | 0.893 | 262.7 |

* and ** indicate significance at 5 % and 1 % level of significance, respectively

FPY: Farmers practice yield; IPY: Improved practice yield; PE: Prediction error; R²: Coefficient of determination; SK: Soil potassium; SN: Soil nitrogen; SP: Soil phosphorus.

Table 10. Regression models for predicting yield through pH and EC in the North and South Transects of Bengaluru

| Crop (No. of farmers) | IP regression model | R ² | PE | FP regression model | R ² | PE |
|-----------------------|--|----------------|---------|---|----------------|--------|
| North Transect | | | | | | |
| Finger millet (27) | IPY = 4947.565** – 464.992** (pH) + 3246.815** (EC) | 0.384** | 492.6 | FPY = 4111.212** – 373.466** (Soil pH) + 2715.242* (EC) | 0.339** | 441.3 |
| Maize (9) | IPY = 8776.464* + 18.088 (Soil pH) – 2954.738 (EC) | 0.107 | 1122.5 | FPY = 8889.854** – 291.273 (Soil pH) + 259.528 (EC) | 0.143 | 727.0 |
| Tomato (14) | IPY = 43470.569* + 2005.537 (pH) – 10534.084 (EC) | 0.102 | 8176.6 | FPY = 40255.602* + 1369.052 (Soil pH) – 9900.140 (EC) | 0.081 | 7019.3 |
| Field bean (7) | IPY = 4197.696** – 214.952 (Soil pH) + 153.061 (EC) | 0.445 | 163.9 | FPY = 2293.824* + 56.121 (Soil pH) – 218.434 (EC) | 0.137 | 158.9 |
| Brinjal (4) | IPY = 44044.610 + 198.934 (Soil pH) – 27714.162 (EC) | 0.046 | 10479.6 | FPY = 31567.103 + 687.814 (Soil pH) – 4172.615 (EC) | 0.029 | 8144.8 |
| South Transect | | | | | | |
| Finger millet (37) | IPY = 1152.567 + 205.372 (pH) + 3167.520 (EC) | 0.029 | 1483.4 | FPY = 960.746 + 221.214* (Soil pH) – 41.499 (EC) | 0.119 | 410.4 |
| Maize (8) | IPY = 17655.016** – 1804.978 (pH) + 19923.127 (EC) | 0.287 | 2576.1 | FPY = 11943.744 – 774.279 (Soil pH) + 4669.319 (EC) | 0.091 | 2364.9 |
| Field bean (7) | IPY = 87664.430 – 9010.067 (pH) – 28319.770 (EC) | 0.088 | 18380.9 | FPY = 3059.327 – 79.344 (Soil pH) + 618.060 (EC) | 0.199 | 360.0 |

* and ** indicate significance at 5 % and 1 % level of significance respectively

EC: Electrical conductivity (ds m⁻¹); FPY: Farmers practice yield; IPY: Improved practice yield; PE: Prediction error; R²: Coefficient of determination.

Integrated understanding of yield drivers

Overall, the findings support the hypothesis that IP significantly enhance both crop yield and the predictability of plant and soil nutrient dynamics. Yield benefits were greatest in finger millet and maize, which showed the highest correlations with nutrient uptake and soil fertility. The regression models consistently performed better under IP than FP, affirming the role of integrated nutrient management in stabilizing yield outcomes. Plant nutrient uptake proved to be a more robust predictor of yield than soil nutrient concentrations, especially under improved management regimes. These findings corroborate previous studies (31, 32, 42), which highlight the importance of synchronizing nutrient supply with crop demand to optimize productivity in semi-arid Alfisol systems.

Conclusion

Study shows that plant nutrient uptake-based regression models provide stronger yield predictions than soil macronutrient models in semi-arid Alfisols. Improved Practices (IP) gave better prediction performance for finger millet (North Transect), maize (both transects) and tomato (North), mainly through plant N, P and K uptake. Micronutrient-based models enhanced prediction for field bean (North) and maize (South), underscoring the role of secondary nutrients in yield variability.

Acknowledgements

The authors thank the Vice Chancellor, University of Agricultural Sciences, Bangalore, for research facilities and Department of

Biotechnology, Govt. of India, for funding under the Indo-German project to conduct experiments.

Authors' contributions

SA planned, supervised and corrected the manuscript. SM wrote the original draft, created visualizations, developed the methodology, conducted the investigation, collected and curated the data and conceptualized the study. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors do not have any conflicts of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used the ChatGPT and GIMINI in order for grammar and writing assistance, ensuring clarity and coherence in presentation. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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