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RESEARCH ARTICLE

A comprehensive analysis of the effects of balanced NPK fertilization on maize quality, nutrient uptake and soil sustainability using hierarchical cluster dendrogram techniques

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Abstract

In modern agriculture, fertilizer application is critical for improving crop yields and addressing soil nutrient deficiencies, yet it often presents environmental and sustainability challenges. This study investigated the effects of varying nitrogen (N), phosphorus (P) and potassium (K) fertilization levels on maize (*Zea mays* L.), focusing on quality, nutrient uptake and soil sustainability. Field experiments were conducted on *Alfisols* at the Zonal Agricultural Research Station, Bengaluru, during 2022-23 and 2023-24, utilizing Soil Test Crop Response (STCR) fertilization strategies. The objective was to evaluate maize yield, nutrient partitioning and soil nutrient dynamics under different NPK regimes. Structural improvements, including higher crude fibre content and reduced moisture levels, improved kernel and fodder integrity and storage potential. Nutrient uptake studies revealed that optimal fertilizer levels promoted nutrient assimilation during vegetative growth and efficient translocation to kernels in reproductive stages, leading to higher yields. Precision fertilization minimized nutrient wastage by aligning applications with crop demand, reducing environmental risks. This study emphasizes stage-specific nutrient management and balanced NPK fertilization to achieve improved maize quality, optimal nutrient use efficiency and sustainable soil health, providing critical insights for enhancing agricultural productivity while maintaining

Introduction

Maize (*Zea mays* L.) is one of the most widely cultivated cereal crops globally, playing a critical role in food security, economic stability and agricultural systems. It is a staple food for billions of people, particularly in developing regions such as Sub-Saharan Africa, Latin America and parts of Asia (1). Maize is consumed in various forms, including as a primary source of carbohydrates, animal feed and industrial raw material for biofuels and other products. The significance of maize in food security stems from its high productivity, adaptability to diverse agro-climatic conditions and nutritional value (2). It serves as a vital calorie source, providing energy for millions and its by-products contribute to dietary protein through livestock feed. In many countries, maize-based diets are integral to combating hunger and malnutrition.

Nitrogen, phosphorus and potassium are vital macronutrients for plant growth, supporting key physiological and biochemical processes. Nitrogen is crucial for chlorophyll synthesis, photosynthesis and protein formation, driving vegetative growth and yield potential. Phosphorus facilitates energy transfer, root development and flowering, enhancing resilience and productivity. Potassium regulates water balance, enzyme activation and carbohydrate metabolism, improving stress tolerance, nutrient utilization and crop quality (3). A balanced supply of these nutrients ensures optimal growth, prevents physiological disruptions and maintains soil health. These macronutrients are the foundation of fertilization strategies for meeting crop demands and promoting sustainable agriculture. Fertilizers replenish essential nutrients like nitrogen, phosphorus and potassium that are often depleted in soils, supporting plant growth (4). By addressing nutrient deficiencies, fertilizers enhance vegetative growth, root development, flowering and stress tolerance. This results in improved crop yields, quality and soil fertility, ensuring sustainable agricultural productivity.

Fertilizer use, while crucial for enhancing crop yields and addressing soil nutrient deficiencies, presents several challenges in modern agriculture. One of the most significant issues is over-fertilization, which occurs when excessive amounts of nutrients, particularly nitrogen, phosphorus and potassium, are applied to crops (5). Over-fertilization can lead to nutrient imbalances, where certain nutrients are available in excess while others become deficient, disrupting plant growth and leading to suboptimal crop quality. This imbalance can also reduce the efficiency of nutrient uptake, leading to higher costs and decreased overall farm productivity (6).

Another major concern is nutrient leaching, particularly for nitrogen and phosphorus. Leaching occurs when excess nutrients are washed away by rainfall or irrigation, eventually reaching groundwater or surface water bodies. This can contaminate drinking water, contribute to eutrophication and disrupt aquatic ecosystems, causing harmful algal bloom (7). Additionally, the excess nutrients in the environment contribute to greenhouse gas emissions, particularly nitrous oxide, a potent greenhouse gas produced by soil microbes in the presence of excess nitrogen fertilizers. This exacerbates climate change, further complicating the environmental impact of fertilizer use (8).

Despite the widespread application of fertilizers, there is a lack of sufficient studies that specifically correlate NPK fertilization with both maize qualities, such as its nutritional content and the sustainability of soil nutrients. While much research has focused on optimizing fertilizer rates for yield maximization, less attention has been given to how these practices affect the nutritional quality of maize, including its protein, mineral content and overall food security value (9). Similarly, the long-term effects of fertilizer use on soil nutrient sustainability remain underexplored. Research is needed to understand how varying NPK levels influence both immediate crop quality and the long-term health of soils, ensuring that fertilization strategies are both efficient and sustainable for future agricultural practices (10).

Precision fertilization is crucial for balancing crop productivity and environmental sustainability. By applying the right amount of nutrients at the right time, precision fertilization optimizes crop growth while minimizing nutrient waste and environmental harm. It reduces the risks of over-fertilization, nutrient imbalances and leaching, which can harm ecosystems and contribute to greenhouse gas emissions (11). This approach improves nutrient use efficiency, ensuring that crops receive the necessary nutrients without excess application. Ultimately, precision fertilization supports both high agricultural productivity and long-term soil health, contributing to sustainable farming practices that protect the environment while meeting global food demands (12).

The primary objective of this study is to assess the impact of varying NPK fertilization levels on maize quality, focusing on yield, nutrient composition and overall nutritional attributes of the maize crop. The research also seeks to evaluate the residual effects of different NPK fertilization treatments on soil nutrient availability after harvest, examining how fertilization influences the replenishment and sustainability of soil nutrients for future cropping cycles.

Materials and Methods

Experimental site

The field experiments were carried out on *Alfisols* of the Vijaypura series, classified as a fine mixed Isohyperthermic family of *typic Kandic Paleustalfs*, at the Zonal Agricultural Research Station (Block No. F12A), University of Agricultural Sciences, Gandhi Krishi Vignyan Kendra, Bengaluru. The station is located in the Eastern Dry Zone of Karnataka at coordinates 13° 04' 55.2'' N latitude and 77° 34' 10.0'' E longitude, with an elevation of 930 m above sea level. The total rainfall recorded during the crop period in 2022-23 and 2023-24 was 68.6 mm. To mitigate water stress and promote nutrient uptake, supplemental irrigation was provided during critical growth stages. The average maximum and minimum temperatures during the crop period were 29.7 °C and 18.6 °C, respectively (Fig. 1).

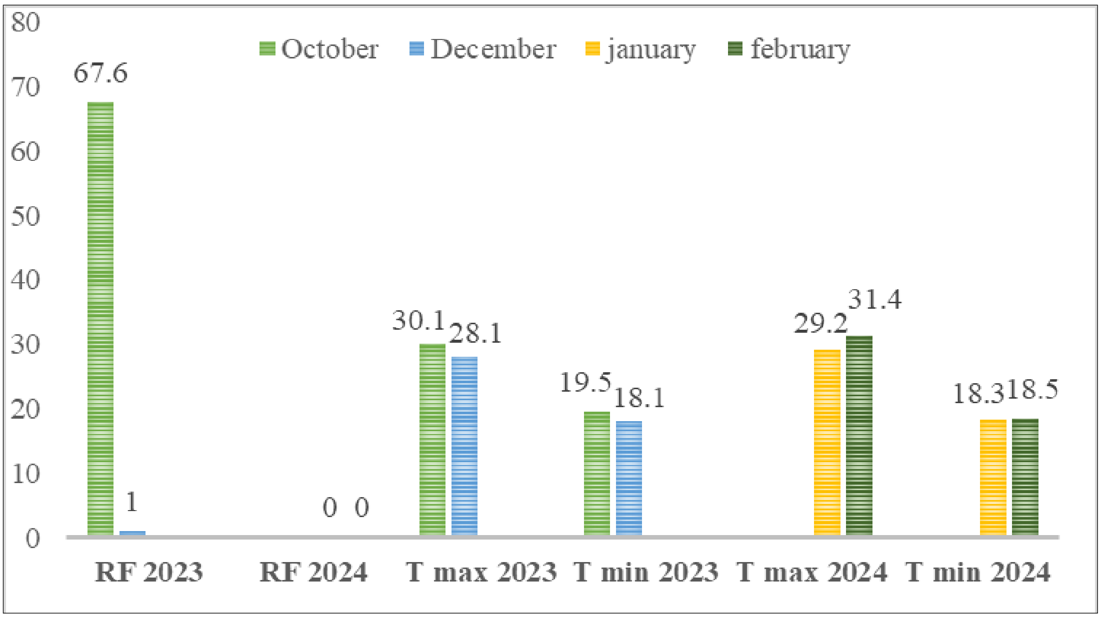

Fig. 1. Variation in rainfall, maximum temperature and minimum temperature during the field experiments (RF: rainfall; T max: Temperature maximum; T min: Temperature minimum).

The experiment was conducted in two phases: Phase 1, a fertility gradient experiment with fodder maize from February to April 2023-24 and Phase 2, the main experiment with maize from October to February 2023-24. The surface soil (0-20 cm depth) of the experimental field was red, well-drained and sandy clay loam in texture, with a pH of 6.13, electrical conductivity of 0.23 dS m^{-1} and organic carbon content of 5.1 g kg^{-1}. Prior to the gradient experiment, the available nitrogen, phosphorus and potassium levels in the soil were 239.96, 137.12 and 267.24 kg ha^{-1}, respectively.

Fertility gradient experiment with fodder maize

In 2023, a fertility gradient experiment was conducted to eliminate prior soil fertility effects and create an artificial fertility gradient for available NPK (13) (Fig. 2). Three uniform strips were established, each receiving three different N, P and K fertilizer levels: 0-0-0, 150-135-200 and 300-270-400 kg ha^{-1}, respectively. The nitrogen dose applied was based on the recommended rate for fodder maize (150 kg ha^{-1}), while phosphorus and potassium doses were selected based on the soil's capacity to fix these nutrients (135 and 200 kg ha^{-1}, respectively). Fodder maize (variety: African Tall) was grown to stabilize soil fertility. After 60 days, the maize was harvested and surface soil samples were collected from each strip to access the development of fertility gradient. The soil samples were air-dried, gently ground and sieved through a 2 mm mesh. Available nitrogen was measured using the alkaline $KMnO_4$ method (14), available phosphorus was extracted with Bray's extractant (0.025 M HCl and 0.03 M NH_4F) and measured using the ascorbic acid method (15), while available potassium was extracted with 1 N ammonium acetate (pH 7.0) and quantified using a flame photometer (16).

Test crop experiment with maize

The experimental study was conducted during the *Rabi* season of 2023, aiming to analyze the nutrient composition (NPK) of different maize parts during growth under various NPK fertilization regimes. Each fertility strip was divided into three blocks based on farmyard manure (FYM) application: F0 (no FYM), F1 (recommended FYM dose) and F2 (double the recommended FYM dose). Each block was further subdivided into 9 plots, including 7 NPK-treated plots, 1 plot with only nano fertilizer and 1 absolute control plot, resulting in 27 treatments per block. The NPK treatments were applied at three levels for each nutrient, leading to 21 combinations. These treatments, along with the nano fertilizer and control plots, were replicated across the remaining two strips through randomization. A total of 81 treatments (27 × 3 = 81) were implemented. Maize was grown following standard agricultural practices, excluding the fertilizer doses. Detailed treatment layouts and nutrient applications are provided in Supplementary data (17).

The 75 % of RDN (Recommended Dose of Nitrogen), (50 % of 75 % RDN at sowing, 25 % of 75 % RDN at 45 DAS and the remaining 25 % of 75 % RDN at 75 DAS), 75 % of RDP (Recommended Dose of Phosphorus) and 100 % of RDK (Recommended Dose of Potassium) was supplied through conventional fertilizers at basal through urea, single super phosphate and muriate of potash respectively. Further Nano DAP @4 mL L^{-1} at 30 DAS and 60 DAS was supplied through foliar application. The farmyard manure (FYM) was applied 15 days in advance to sowing.

Pre-soak irrigation was provided 3-4 days before sowing and seeds were dibbled at 60 × 30 cm spacing. Moisture was maintained around the root zone and regular shallow cultivation was done to control weeds, promote soil aeration and encourage root growth. Pest and disease control measures were also implemented. Soil and plant samples were collected at various growth stages, including vegetative emergence (VE as 15 DAS), early vegetative stages (VS as 30 DAS), early vegetative stage (EVS as 45 DAS), mid vegetative stage (MVS as 60 DAS), late vegetative stage (LVS as 75 DAS), reproductive stage (R1 as 90 DAS) and reproductive stage (R6 as harvest), following the experimental design. These

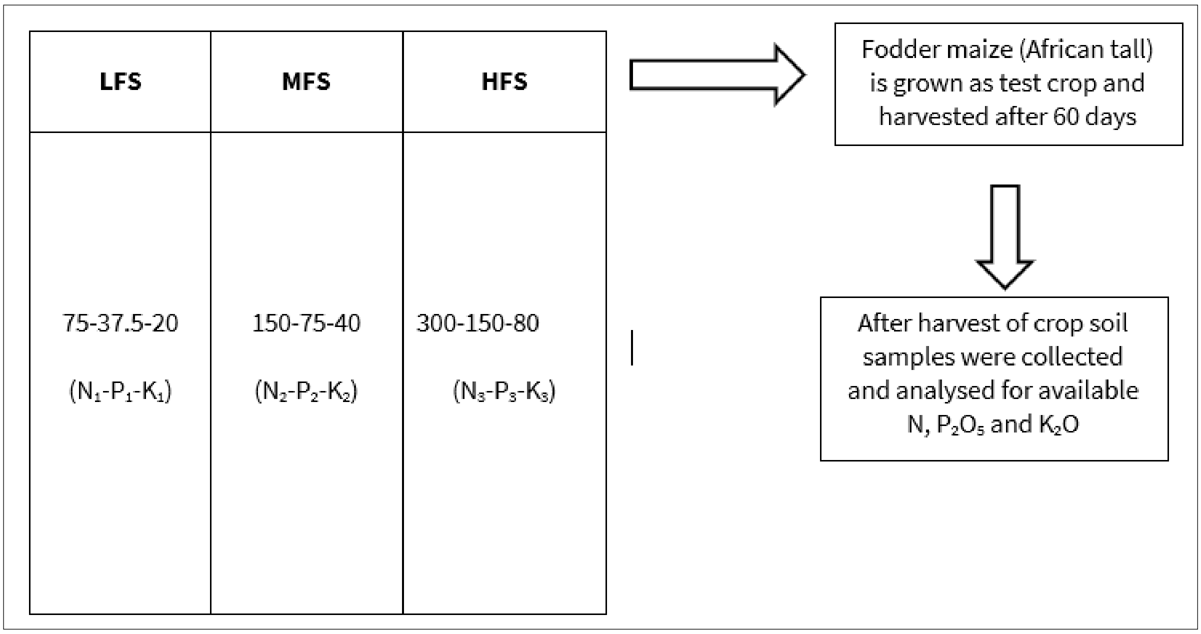

Fig. 2. Layout and details of fertility gradient experiment of fodder maize crop. Note: Low Fertility Strip (LFS): 50 % of Recommended dose of fertilizer; Medium Fertility Strip (MFS): 100 % Recommended dose of fertilizer; High Fertility Strip (HFS): 150 % Recommended dose of fertilizer.

samples were analyzed to assess the availability of NPK in the soil and determine the NPK uptake pattern during different crop growth stages. At harvest, the crop yield from each plot was recorded and expressed as tons per hectare (t ha^{-1}) for analysis.

Plant analysis

Plant samples were collected from each plot and subjected to a systematic drying process. Initially, they were air-dried in the shade, then placed in a hot air oven set to 65 °C for complete drying. After drying, the samples were finely ground using a Willey mill. Nitrogen content was determined using the micro Kjeldahl method (18). To prepare a di-acid extract for phosphorus and potassium analysis, a mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a 9:4 ratio was used (19). A pre-digestion step involved adding 10 mL of HNO_3 per gram of plant sample. The di-acid extract was then used to determine phosphorus and potassium levels. Phosphorus was measured spectrophotometrically using the vanadomolybdate method, while potassium content was determined using a flame photometer (19).

From the chemical analytical data, the uptake of each nutrient was calculated as shown below:

$$\text{Nutrient uptake (kg ha}^{-1} = \frac{[\text{Nutrient content(\%) x Dry weight (kg ha}^{-1})]}{100}$$

Quality parameters of maize

Crude protein content (%)

The crude protein (CP) content of dried samples was calculated by multiplying nitrogen per cent with 6.25 (20)

$$\text{Crude protein (\%) = Nitrogen (\%) X 6.25}$$

Ash content

Five grams oven dried sample grounded in Willey mill using a 2 mm sieve was de-smoked on a heater and ignited at 550°C in muffle furnace for 2 hr and cooled in desiccator (21). The weight of residual ash in previously weighed crucible was taken as total mineral. The mineral content was calculated and expressed in per cent as follows;

$$\text{Total ash (\%) = } \frac{\text{Weight of ash}}{\text{Weight of sample taken for ashing}} \text{ X 100}$$

Moisture content (%)

A known weight of powdered sample was taken in moisture cups and subjected to 90 °C (±5 °C) temperature in a well-ventilated hot air oven for 5-6 hr and cooled in desiccator. The weight of sample in moisture cups was taken and calculated the moisture percentage by determining the loss in weight of the sample during drying by using the following formula;

$$\text{Moisture (\%) = } \frac{\text{Original weight of sample (g) - Final weight of sample (g)}}{\text{Original weight of sample (g)}} \text{ X 100}$$

Ether extractable fat or crude fat (%)

The ether extractable fat was estimated by petroleum ether extraction method. The crude fat was calculated by using the formula (22) and expressed in percentage.

$$\text{Ether extractable fat (\%) = } \frac{\text{Weight of ether extract}}{\text{Weight of the dried plant sample taken}} \text{ X 100}$$

Crude fibre content (%)

Crude fibre (CF) content in grain was estimated by acid-alkali digestion method. The crude fibre was calculated by using the formula (22) and expressed in percentage.

$$\text{CF (\%) = } \frac{\text{(Weight of sample before ashing) - (Weight of sample after ashing)}}{\text{Weight of the dried plant sample tak-}} \text{ X 100}$$

Carbohydrate content (%)

Carbohydrate (CHO) content was calculated by using the following formula and expressed in percentage (23).

$$\text{CHO (\%) = 100 - [CP(\%)+Crude fat(\%)+CF(\%)+Ash(\%)+Moisture(\%)}$$

Statistical analysis using R software

The R software (version 4.4.1) was used for all statistical analyses. Heat maps were generated with the 'pheatmap' package. Hierarchical clustering and dendrograms were created with the 'hclust' function to identify patterns in nutrient uptake.

Results

Soil available nutrient status

Heat map

The heat map of soil available nitrogen (Fig. 3A) shows distinct temporal and treatment-specific variations. At the initial stage, nitrogen levels were relatively uniform across all treatments. However, by 15 DAS, significant differentiation was observed, with higher nitrogen availability in treatments receiving higher nitrogen doses. At 60 DAS, a pronounced peak in soil available nitrogen was evident in treatments with higher fertilizer application rates, as indicated by the intense red zones. This trend suggests a build-up of nitrogen in the soil at this stage. Toward the final stage, nitrogen levels decreased across most treatments, reflecting plant uptake during active growth phases.

The heat map for soil available phosphorus demonstrates temporal and treatment-specific variations (Fig. 3B). At the initial stage, phosphorus levels were moderately uniform across treatments. By 15 DAS, a distinct peak in phosphorus availability was observed in treatments with higher fertilizer applications, as indicated by the red zones on the map. Over time, phosphorus availability gradually decreased, particularly from 30 DAS onward, with most treatments showing a transition to green zones by the final stage. This decline suggests a steady reduction in soil phosphorus levels due to plant uptake and possible immobilization processes.

The heat map of soil available potassium over time reveals notable patterns in its distribution across treatments and stages of crop growth (Fig. 3C). Potassium levels were generally high during the initial stage and 15 DAS (Days After Sowing) but gradually declined as the crop progressed through the growing season, with the lowest values observed around 90 DAS and the final stage. Treatments varied in their ability to maintain potassium levels, with some showing consistently higher values throughout the timeline, indicating effective nutrient retention. Other treatments exhibited steep declines in potassium availability, particularly after 45 DAS, suggesting rapid uptake by plants or insufficient initial reserves. By the final stage, most treatments converged to similar potassium levels, although a few treatments retained marginally higher values, indicating slower uptake or residual nutrient availability.

Hierarchical cluster dendrogram

The cluster dendrogram of soil available nitrogen reveals distinct groupings among the treatments based on their similarity in nitrogen availability patterns (Fig. 4A). The dendrogram is divided into several clusters, each representing treatments with comparable nitrogen dynamics. At a higher hierarchical level, the treatments are grouped into major branches, indicating broader similarities. Within these major clusters, smaller subclusters are evident, suggesting nuanced variations in nitrogen availability among specific treatments. Treatments within the same cluster exhibit similar soil nitrogen availability, while those in different clusters demonstrate significant differences. This hierarchical structure provides a clear representation of the relationships among treatments based on soil available nitrogen.

The cluster dendrogram for soil available phosphorus highlights the grouping of treatments based on similarities in phosphorus availability (Fig. 4B). The dendrogram splits the treatments into several major clusters, each representing treatments with comparable patterns of soil phosphorus levels. At higher hierarchical levels, broad groupings emerge, distinguishing treatments with significantly different phosphorus dynamics. Within these major groups, smaller subclusters reveal subtle variations among treatments, reflecting differences in phosphorus retention, release or uptake. Treatments that are positioned closer together in the dendrogram exhibit more similar soil phosphorus characteristics, while those located in separate clusters demonstrate substantial variability.

The dendrogram illustrates the hierarchical clustering of soil available potassium levels based on their similarity (Fig. 4C). The clustering process divides the soil samples into distinct groups, represented by coloured branches in the dendrogram. The height at which two clusters merge indicates the dissimilarity between them, with higher merging points showing greater differences. The dendrogram identifies a total of 81 clusters, where samples within the same cluster are more similar in terms of available potassium than those in different clusters. Each cluster represents soil samples with comparable K levels, enabling the grouping of soil into categories based on nutrient availability.

Nitrogen partitioning of maize in selected treatments

The nitrogen uptake by different parts of maize during the growth stages varied differently across the control (0-0-0) and 100 % PK (0-2-2) treatments in the LFS, MFS and HFS, represented in Fig. 5.

Control (0-0-0)

In the control treatment (0-0-0), nitrogen uptake by maize differed across the low, medium and high fertility strips. In the low fertility strip, nitrogen uptake reached its maximum at the R1 stage, with the kernel accounting for 24.47 kg ha^{-1}, the leaf 21.85 kg ha^{-1} and the stem 7.28 kg ha^{-1}. The root, rind and cob sheath each contributed 4.73 kg ha^{-1}. In the medium fertility strip, nitrogen uptake was slightly higher, with the kernel absorbing 27.07 kg ha^{-1}, the leaf 21.06 kg ha^{-1} and the stem 6.02 kg ha^{-1}, while the root, rind and cob sheath collectively absorbed 6.01 kg ha^{-1}. The high fertility strip showed the greatest nitrogen uptake, with the kernel absorbing 28.30 kg ha^{-1}, the leaf 22.01 kg ha^{-1} and the stem 6.29 kg ha^{-1}, while the root, rind and cob sheath each contributed 6.30 kg ha^{-1}. This trend highlights the improved conditions in the HFS, which facilitated greater nitrogen absorption across all plant components compared to the LFS and MFS.

100 % PK (0-2-2)

The nutrient uptake by different plant parts varied significantly across growth stages and fertilizer levels (LFS, MFS and HFS). During the vegetative emergence stage, nutrient uptake by the leaf was 0.118 kg ha^{-1} under LFS, 0.136 kg ha^{-1} under MFS and 0.203 kg ha^{-1} under HFS. Stem and root uptake followed a similar trend, with HFS showing the highest values of 0.084 kg ha^{-1} for the stem and 0.061 kg ha^{-1} for the root. By the vegetative stage, leaf uptake increased substantially, reaching 2.250 kg ha^{-1} in LFS, 4.405 kg ha^{-1} in MFS and 5.906 kg ha^{-1} in HFS. Similarly, stem and root uptakes were highest in HFS, recording 3.007 and 1.933 kg ha^{-1}, respectively. In the early vegetative stage, nutrient uptake further increased, with the leaf, stem and root reaching 7.258, 5.080 and 2.177 kg ha^{-1} in LFS; 11.800, 8.260 and 3.540 kg ha^{-1} in MFS; and 12.739, 8.917 and 3.822 kg ha^{-1} in HFS, respectively. Uptake peaked during the mid-vegetative stage, where the leaf, stem and root uptake under HFS reached 23.921, 17.442 and 6.229 kg ha^{-1}, respectively, compared to 22.325, 16.278 and 5.814 kg ha^{-1} under MFS and 22.162, 16.160 and 5.771 kg ha^{-1} under LFS. The late vegetative stage showed a decline in vegetative part uptake, while kernel uptake became significant, recording 12.773 kg ha^{-1} under LFS, 13.038 kg ha^{-1} under MFS and 13.619 kg ha^{-1} under HFS. In the reproductive stages, kernel uptake dominated nutrient distribution. At R1, kernel uptake was 19.438, 20.569 and 22.058 kg ha^{-1} under LFS, MFS and HFS, respectively. By R6, kernel uptake increased further to 21.230 kg ha^{-1} in LFS, 22.871 kg ha^{-1} in MFS and 25.336 kg ha^{-1} in HFS. Simultaneously, uptake by vegetative parts (leaf, stem and root) decreased substantially, reflecting nutrient translocation to the kernel.

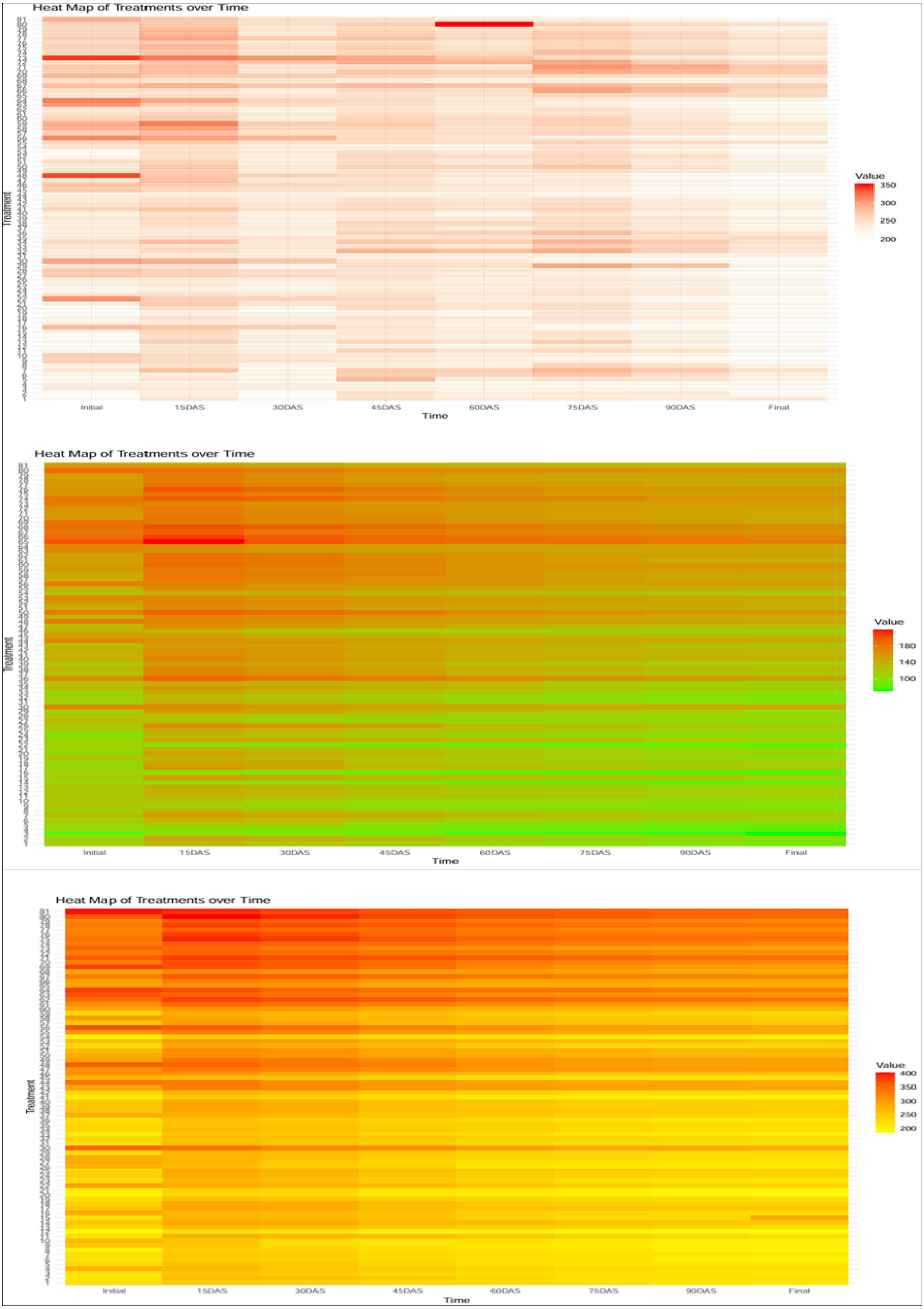

Fig. 3. The heat map of soil available nitrogen (A), phosphorus (B) and potassium (C) during the growth stages of maize.

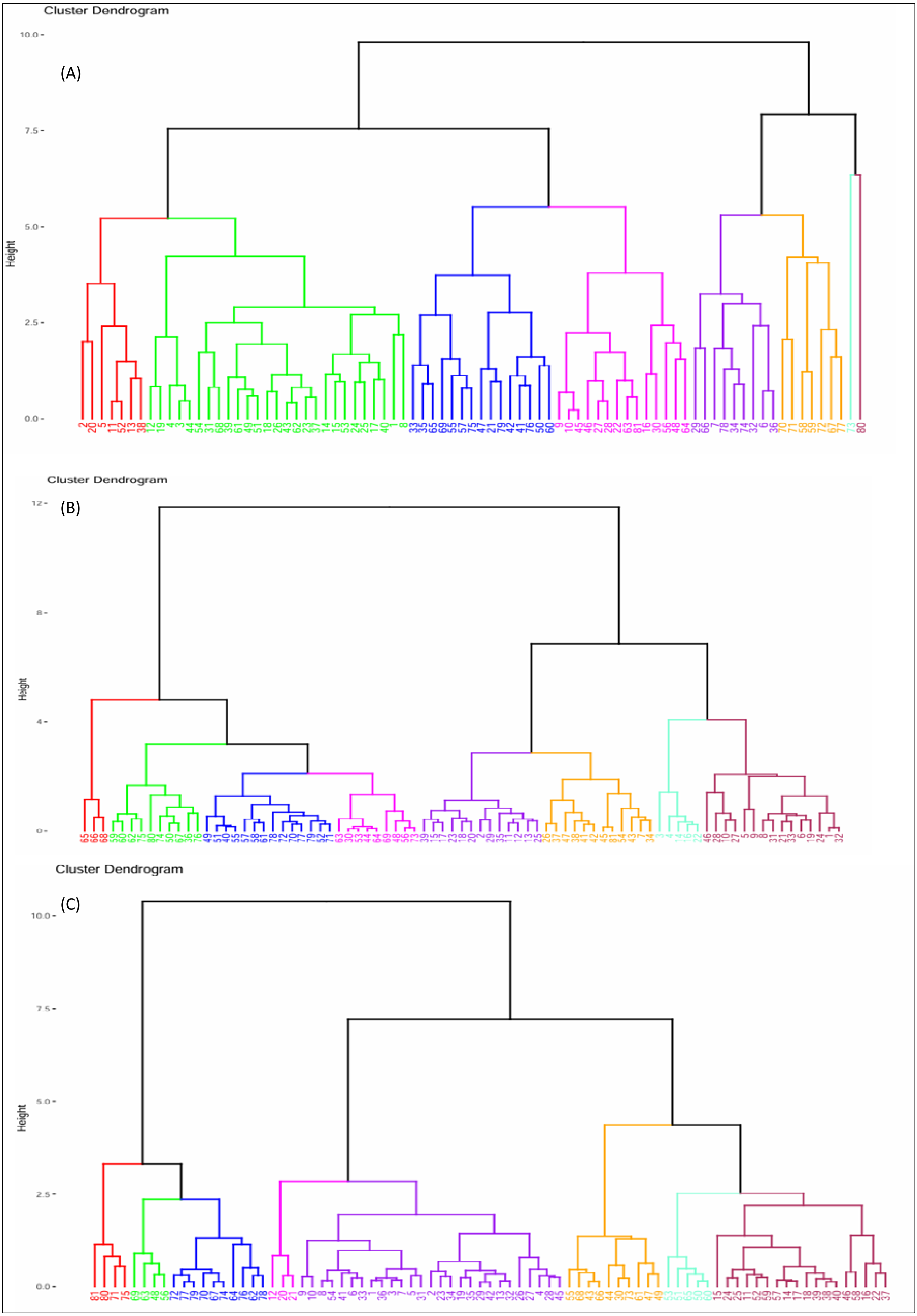

Fig. 4. Hierarchical clustering of treatments based on their Soil available nitrogen (A), Phosphorus (B) and potassium (C) characteristics.

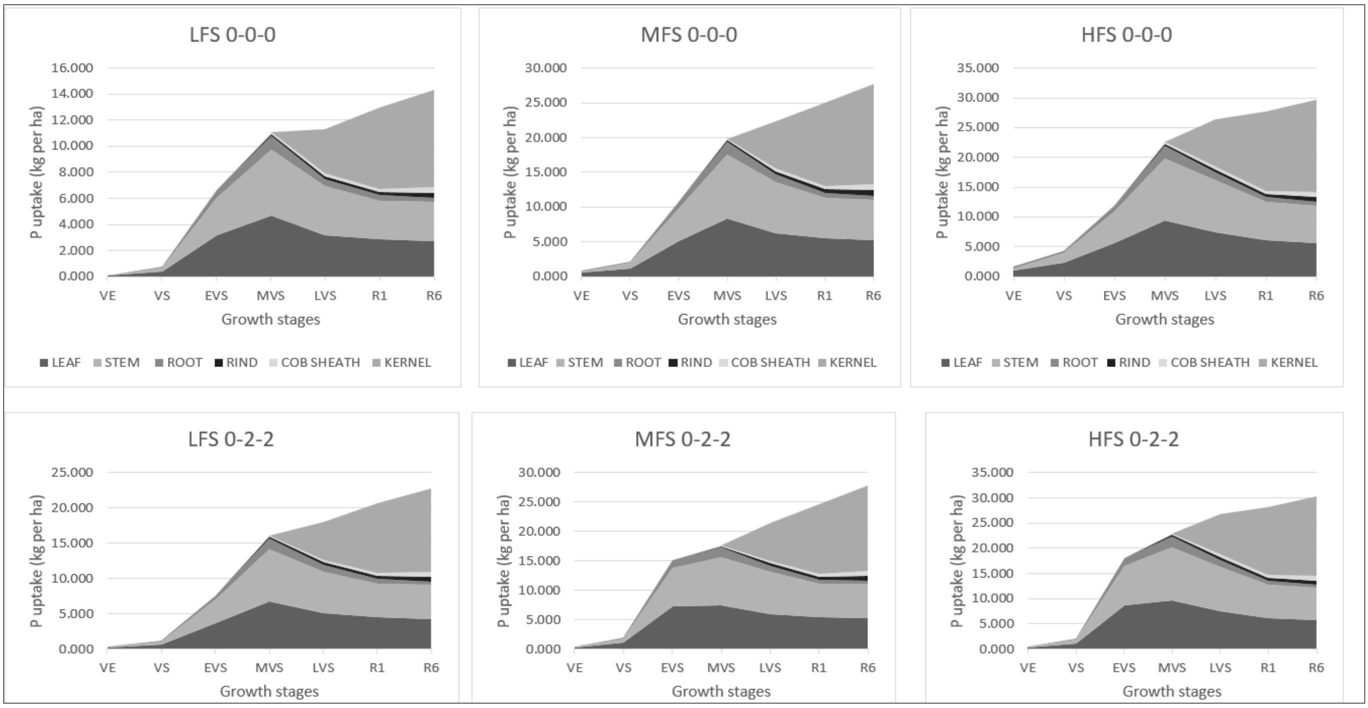

Fig. 5. Nitrogen partitioning across different maize plant parts during growth stages under control and 100 % PK treatments in low, medium and high fertility strips.

100 % NK (2-0-2)

The nitrogen uptake by different parts of maize during the growth stages varied differently across the 100 % NK (2-0-2) and 100 % NP (2-2-0) treatments in the LFS, MFS and HFS, represented in Fig. 6.

The nutrient uptake in maize varied significantly across growth stages and fertilizer levels with higher fertilizer levels generally resulting in increased nutrient uptake. During the vegetative emergence stage, nutrient uptake by the leaf, stem and root was lowest across all treatments, ranging from 0.163, 0.068 and 0.049 kg ha^{-1} under LFS to 0.234, 0.098 and 0.070 kg ha^{-1} under HFS, respectively. By the vegetative stage, uptake increased significantly, with the leaf showing 2.933, 5.988 and 7.589 kg ha^{-1} uptake under LFS, MFS and HFS, respectively. Stem and root uptakes were highest under HFS, recording 3.863 and 2.484 kg ha^{-1}, respectively. At the early vegetative stage, nutrient uptake continued to rise, particularly in HFS, where the leaf, stem and root recorded 9.345, 6.542 and 2.804 kg ha^{-1}, respectively. Maximum uptake across all vegetative parts occurred during the mid-vegetative stage, with the leaf, stem and root in HFS reaching 39.429, 28.750 and 10.268 kg ha^{-1}, respectively. Uptake by rind and cob sheath also peaked during this stage, showing 2.464 and 1.232 kg ha^{-1} under HFS. In the late vegetative stage, nutrient uptake by vegetative parts

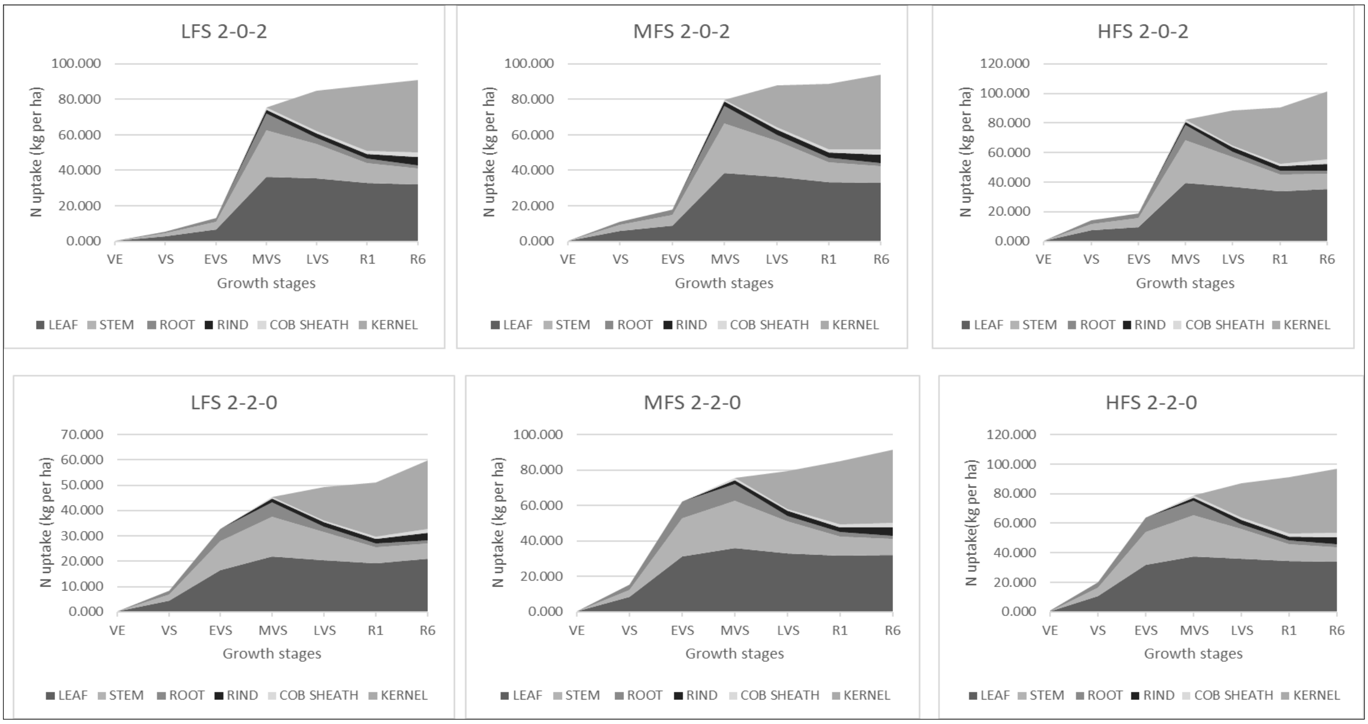

Fig. 6. Nitrogen partitioning across different maize plant parts during growth stages under 100 % NK and 100 % NP treatments in low, medium and high fertility strips.

began to decline, while kernel uptake became substantial. Kernel uptake was 22.729, 23.468 and 23.638 kg ha^{-1} under LFS, MFS and HFS, respectively. By the reproductive stages, kernel uptake dominated, increasing from 36.947 kg ha^{-1} under LFS at R1 to 40.985 kg ha^{-1} at R6. Similarly, kernel uptake increased from 37.344 to 42.268 kg ha^{-1} in MFS and from 37.894 to 45.514 kg ha^{-1} in HFS. Nutrient uptake by vegetative parts such as leaves, stems and roots decreased significantly during these stages, while rind and cob sheath uptake showed moderate increases, particularly at R6.

100 % NP (2-2-0)

During the vegetative emergence stage, nutrient uptake was lowest across all treatments. Under LFS, nutrient uptake by the leaf, stem and root was 0.176, 0.073 and 0.053 kg ha^{-1}, respectively, compared to 0.244, 0.102 and 0.073 kg ha^{-1}under MFS and 0.413, 0.172 and 0.124 kg ha^{-1}under HFS. By the vegetative stage, nutrient uptake increased substantially, with leaf uptake reaching 4.576, 8.289 and 10.786 kg ha^{-1} under LFS, MFS and HFS, respectively. Stem and root uptakes followed a similar trend, peaking at 5.491 and 3.530 kg ha^{-1} respectively, under HFS. During the early vegetative stage, nutrient uptake increased sharply, with the leaf, stem and root under HFS reaching 31.945, 22.361 and 9.583 kg ha^{-1}, respectively, compared to 31.124, 21.787 and 9.337 kg ha^{-1}under MFS and 16.361, 11.453 and 4.908 kg ha^{-1}under LFS. Maximum nutrient uptake occurred during the mid-vegetative stage, where uptake by the leaf, stem and root under HFS peaked at 37.766, 27.538 and 9.835 kg ha^{-1}, respectively. Uptake by rind and cob sheath was also highest under HFS, recording 2.360 and 1.180 kg ha^{-1}, respectively. In the late vegetative stage, nutrient uptake in vegetative parts declined, while kernel uptake became prominent. Kernel uptake increased to 13.146, 21.186 and 23.255 kg ha^{-1}under LFS, MFS and HFS, respectively. By the reproductive stage, kernel uptake further increased, reaching 21.470 kg ha^{-1} under LFS, 35.606 kg ha^{-1} under MFS and 38.327 kg ha^{-1} under HFS. By the reproductive maturity stage, kernel uptake was highest, recording 26.897, 41.097 and 43.652 kg ha^{-1} under LFS, MFS and HFS, respectively. Nutrient uptake by vegetative parts decreased during reproductive stages, while rind and cob sheath uptakes showed moderate increases, peaking at 4.850 and 2.910 kg ha^{-1}, respectively, under HFS at R6.

100 % NPK (2-2-2)

The nitrogen uptake by different parts of maize during the growth stages varied differently across 100 % NPK (2-2-2) treatments in the LFS, MFS and HFS, represented in Fig. 7.

The nutrient uptake in maize varied significantly across growth stages and fertilizer levels. During the vegetative emergence stage, the uptake of nutrients was minimal across all treatments. Under LFS, nutrient uptake by the leaf, stem and root was 0.183, 0.076 and 0.055 kg ha^{-1}, respectively, compared to 0.239, 0.099 and 0.072 kg ha^{-1}under MFS and 0.320, 0.133 and 0.096 kg ha^{-1} under HFS. In the vegetative stage, nutrient uptake increased sharply, with the leaf, stem and root uptake reaching 4.622, 2.353 and 1.513 kg ha^{-1}under LFS, compared to 7.509, 3.823 and 2.457 kg ha^{-1}under MFS and 8.622, 4.390 and 2.822 kg ha^{-1}under HFS. During the early vegetative stage, nutrient uptake rose substantially, particularly under HFS, where leaf, stem and root uptake reached 20.799, 14.559 and 6.240 kg ha^{-1}, respectively. Mid-vegetative stage saw peak nutrient uptake in vegetative parts. Under HFS, uptake by the leaf, stem and root reached 36.685, 26.749 and 9.553 kg ha^{-1}, respectively, while rind and cob sheath uptake were 2.293 and 1.146 kg ha^{-1}During the late vegetative stage, nutrient uptake in vegetative parts declined slightly, while kernel uptake began to increase. Kernel uptake reached 12.481, 20.841 and 21.513 kg ha^{-1}under LFS, MFS and HFS, respectively. At the reproductive stage, kernel uptake further increased, reaching 22.483, 33.964 and 37.105 kg ha^{-1} under LFS, MFS and HFS, respectively. By the reproductive maturity stage, kernel uptake peaked, recording 26.936, 38.925 and 41.995 kg ha^{-1} under LFS, MFS and HFS, respectively. During this stage, uptake by the rind and cob sheath also increased, with the rind reaching 4.666 kg ha^{-1} and cob sheath reaching 2.800 kg ha^{-1}under HFS.

Phosphorus partitioning of maize in selected treatments

The phosphorus uptake by different parts of maize during the growth stages varied differently across the control (0-0-0) and 100 % PK (0-2-2) treatments in the LFS, MFS and HFS, represented in Fig. 8.

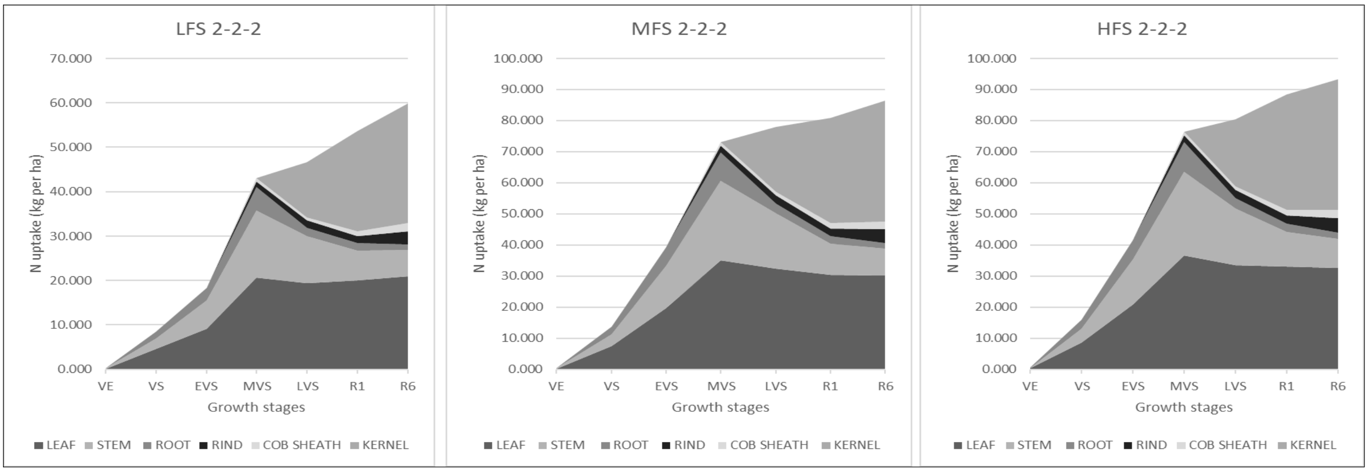

Fig. 7. Nitrogen partitioning across different maize plant parts during growth stages under 100 % NPK treatment in low, medium and high fertility strips.

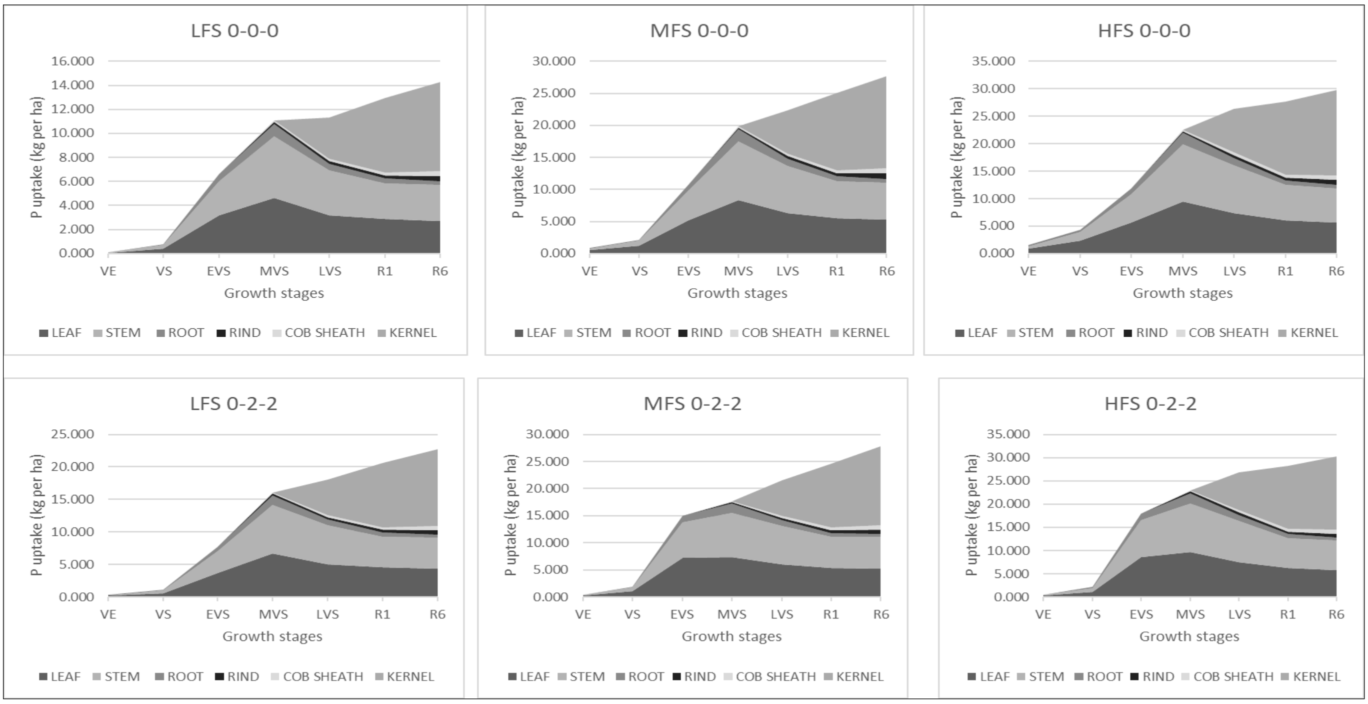

Fig. 8. Phosphorus partitioning across different maize plant parts during growth stages under control and 100 % PK treatments in low, medium and high fertility strips.

Control (0-0-0)

Phosphorus uptake in maize increased with fertilizer application. During the vegetative emergence stage, uptake was low under LFS, MFS and HFS, with values ranging from 0.055 to 0.952 kg ha^{-1} for leaf uptake. At the vegetative stage, uptake increased, reaching 0.423, 1.198 and 2.402 kg ha^{-1} under LFS, MFS and HFS, respectively. In the early vegetative stage, P uptake continued to rise, with values of 3.171, 5.156 and 5.692 kg ha^{-1} under LFS, MFS and HFS, respectively. At the mid-vegetative stage, P uptake peaked, particularly under MFS and HFS, with leaf and stem uptake reaching 9.466 and 10.368 kg ha^{-1}, respectively. Kernel uptake increased at the late vegetative stage, reaching 3.396, 6.702 and 7.918 kg ha^{-1} under LFS, MFS and HFS, respectively. At the reproductive stage, kernel uptake continued to rise, reaching 6.235 and 7.437 kg ha^{-1} under LFS and 13.313 and 15.468 kg ha^{-1} under HFS.

100 % PK (0-2-2)

Phosphorus uptake in maize showed a clear increase with higher fertilizer treatments. At the vegetative emergence stage, P uptake was low across all fertilizer treatments, with values ranging from 0.213 to 0.349 kg ha^{-1} for leaf. At the vegetative stage, uptake increased significantly, with LFS, MFS and HFS showing values of 0.632, 1.055 and 1.180 kg ha^{-1}, respectively. In the early vegetative stage, the uptake further increased, with LFS, MFS and HFS reaching 3.676, 7.219 and 8.648 kg ha^{-1}, respectively. At the mid-vegetative stage, P uptake peaked, particularly in MFS and HFS, where leaf and stem uptake reached 9.632 and 10.550 kg ha^{-1}, respectively. At the late vegetative stage, uptake remained high, with HFS showing the highest values of 8.037 kg ha^{-1}for the kernel. At the reproductive stage, there was a further increase in kernel uptake, with values reaching 9.926 and 11.840 kg ha^{-1} for LFS, 11.837 and 14.420 kg ha^{-1}for MFS and 13.547 and 15.768 kg ha^{-1} for HFS.

100 % NK (2-0-2)

The phosphorus uptake by different parts of maize during the growth stages varied differently across the 100 % NK (2-0-2) and 100 % NP (2-2-0) treatments in the LFS, MFS and HFS, represented in Fig. 9.

In the low fertilizer system, phosphorus uptake was the lowest. At the VE stage, the uptake in the leaf, stem and root was 0.219, 0.091 and 0.055 kg ha^{-1}, respectively. Uptake increased at later stages, with the R6 stage showing the highest kernel uptake at 8.376 kg ha^{-1}. The cob sheath and rind recorded 0.483 kg ha^{-1} each, while the leaf and stem absorbed 3.060 and 3.382 kg ha^{-1}, respectively. In the medium fertilizer system, phosphorus uptake was higher than in the LFS. At the VE stage, the leaf, stem and root absorbed 0.211, 0.088 and 0.053 kg ha^{-1}, respectively. By the R6 stage, the kernel recorded the highest phosphorus uptake at 14.279 kg ha^{-1}, followed by the cob sheath and rind with 0.824 kg ha^{-1}each. Uptake in the leaf and stem reached 5.217 and 5.767 kg ha^{-1}, respectively. In the high fertilizer system, phosphorus uptake was maximized. At the VE stage, the leaf, stem and root absorbed 0.676, 0.282 and 0.169 kg ha^{-1}, respectively. By the R6 stage, the kernel showed the highest phosphorus uptake at 22.921 kg ha^{-1}, with the cob sheath and rind each absorbing 1.322 kg ha^{-1}. The leaf and stem absorbed 8.375 and 9.257 kg ha^{-1}, respectively, while the root absorbed 0.882 kg ha^{-1}.

100 % NP (2-2-0)

Phosphorus uptake in the LFS was the lowest across all stages. At the VE stage, uptake in the leaf, stem and root was 0.363, 0.151 and 0.091 kg ha^{-1}, respectively. Uptake increased gradually, with the kernel having the highest uptake at the R6 stage (11.038 kg ha^{-1}). Cob sheath and rind absorbed 0.637 kg ha^{-1}each, while the leaf and stem absorbed 4.033 and 4.458 kg ha^{-1}, respectively. In the MFS, phosphorus uptake

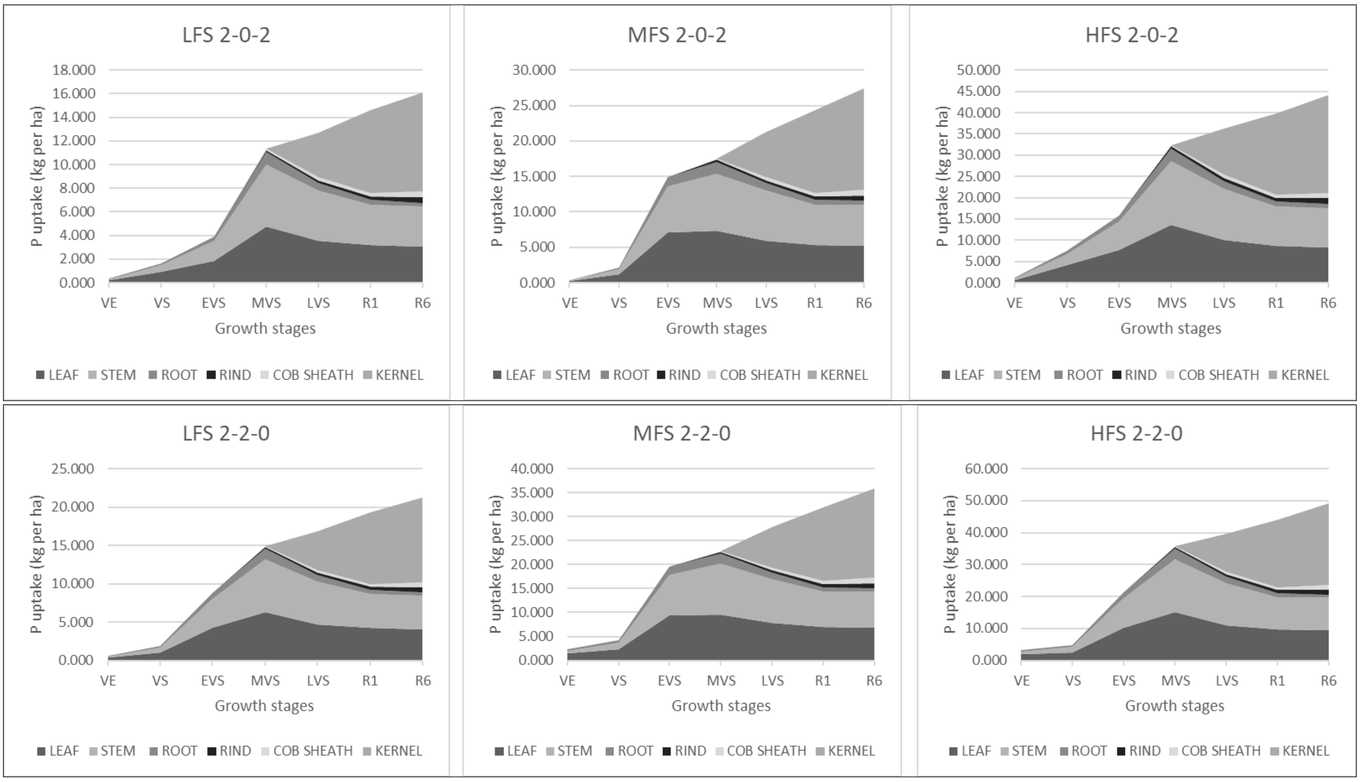

Fig. 9. Phosphorus partitioning across different maize plant parts during growth stages under 100 % NK and 100 % NP treatments in low, medium and high fertility strips.

improved substantially compared to the LFS. At the VE stage, the leaf, stem and root absorbed 1.412, 0.588 and 0.353 kg ha^{-1}, respectively. Uptake peaked at the R6 stage, with the kernel showing the highest uptake of 18.667 kg ha^{-1}. Cob sheath and rind absorbed 1.077 kg ha^{-1} each, while the leaf and stem absorbed 6.821 and 7.539 kg ha^{-1}, respectively. Phosphorus uptake was maximized under the HFS. At the VE stage, uptake in the leaf, stem and root was 1.950, 0.813 and 0.488 kg ha^{-1}, respectively. The highest uptake occurred at the R6 stage, with the kernel absorbing 25.544 kg ha^{-1}, followed by the cob sheath and rind with 1.474 kg ha^{-1} each. Leaf and stem uptake reached 9.333 and 10.316 kg ha^{-1}, respectively, while root uptake was 0.982 kg ha^{-1}.

100 % NPK (2-2-2)

The phosphorus uptake by different parts of maize during the growth stages varied differently across the 100 % NPK (2-2-2) treatments in the LFS, MFS and HFS, represented in Fig. 10.

At the VE stage, phosphorus uptake was lowest across all plant parts, with 0.356 kg ha^{-1} in the leaf, 0.148 kg ha^{-1} in the stem and 0.089 kg ha^{-1} in the root. Uptake increased substantially by the R6 stage, where the kernel absorbed the highest amount (17.602 kg ha^{-1}). Phosphorus uptake in the leaf and stem at R6 was 6.432 and 7.109 kg ha^{-1}, respectively, while uptake in the cob sheath and rind reached 1.016 kg ha^{-1}each. Phosphorus uptake was higher in the MFS compared to the LFS. At the VE stage, uptake was 0.528 kg ha^{-1}in the leaf, 0.220 kg ha^{-1} in the stem and 0.132 kg ha^{-1}in the root. By the R6 stage, the kernel absorbed 27.410 kg ha^{-1}, the highest among all plant parts. Uptake in the leaf and stem reached 10.015 and 11.069 kg ha^{-1}, respectively, while the cob sheath and rind absorbed 1.581 kg ha^{-1} each. Under the HFS, phosphorus uptake reached its maximum values. At the VE stage, the leaf, stem and root absorbed 0.812, 0.338 and 0.203 kg ha^{-1}, respectively. Uptake increased significantly by the R6 stage, with the kernel absorbing 27.508 kg ha^{-1}. Phosphorus uptake in the leaf and stem was 10.051 and 11.109 kg ha^{-1}, respectively. while the cob sheath and rind absorbed 1.587 kg

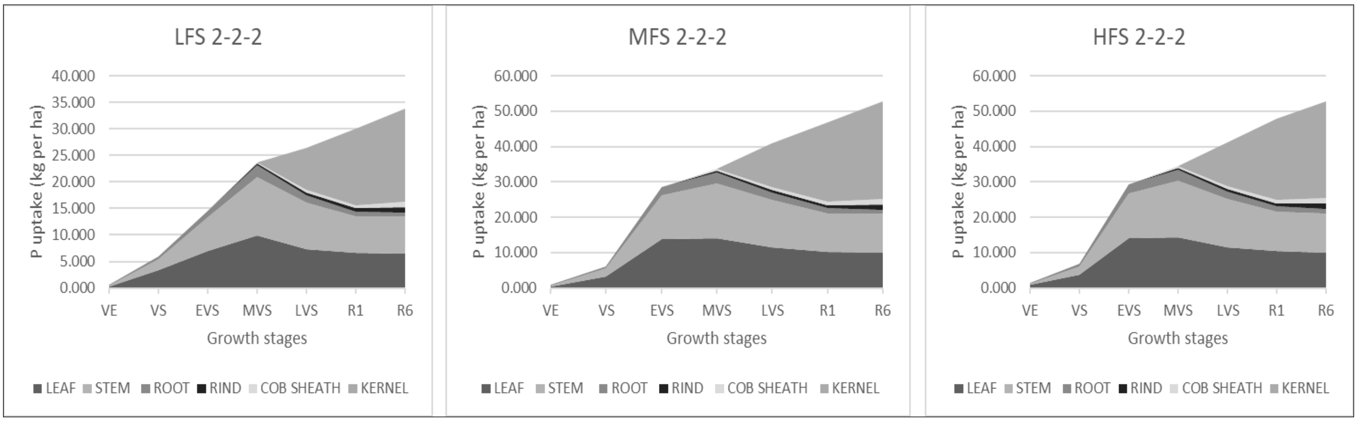

Fig. 10. Phosphorus partitioning across different maize plant parts during growth stages under 100 % NPK treatment in low, medium and high fertility strips.

ha^{-1} each.

Potassium partitioning of maize in selected treatments

The potassium uptake by different parts of maize during the growth stages varied differently across the control (0-0-0) and 100 % PK (0-2-2) treatments in the LFS, MFS and HFS, represented in Fig. 11.

Control (0-0-0)

Under the LFS, potassium uptake was lowest at the VE stage, with the leaf, stem and root absorbing 0.587, 0.188 and 0.169 kg ha^{-1}, respectively. Uptake increased significantly as growth advanced, with the R6 stage showing the highest values. At this stage, the kernel absorbed the highest amount of potassium (40.325 kg ha^{-1}), followed by the leaf (34.948 kg ha^{-1}) and stem (32.260 kg ha^{-1}). The cob sheath and rind absorbed 9.409 and 6.721 kg ha^{-1}, respectively, while the root absorbed 10.753 kg ha^{-1}. Potassium uptake under the MFS was higher than that in the LFS. At the VE stage, the leaf, stem and root absorbed 2.082, 0.666 and 0.599 kg ha^{-1}, respectively. By the R6 stage, the kernel had the highest uptake (41.976 kg ha^{-1}), followed by the leaf (36.379 kg ha^{-1}) and stem (33.581 kg ha^{-1}). The cob sheath and rind absorbed 9.794 and 6.996 kg ha^{-1}, respectively, while the root absorbed 11.194 kg ha^{-1}. The HFS showed the highest potassium uptake across all growth stages and plant parts. At the VE stage, the leaf, stem and root absorbed 3.120, 0.998 and 0.899 kg ha^{-1}, respectively. At the R6 stage, the kernel absorbed the highest amount of potassium (53.900 kg ha^{-1}), followed by the leaf (46.713 kg ha^{-1}) and stem (43.120 kg ha^{-1}). The cob sheath and rind absorbed 12.577 and 8.983 kg ha^{-1}, respectively, while the root absorbed 14.373 kg ha^{-1}.

100 % PK (0-2-2)

Under the low fertility strip, potassium uptake was lowest at the VE stage, with the leaf, stem and root absorbing 1.845, 0.590 and 0.531 kg ha^{-1}, respectively. Potassium uptake increased significantly with plant growth, reaching its peak at the R6 stage. At R6, the kernel absorbed the highest amount of potassium (42.101 kg ha^{-1}), followed by the leaf (36.487 kg ha^{-1}), stem (33.681 kg ha^{-1}) and root (11.227 kg ha^{-1}). The cob sheath and rind absorbed 9.823 kg ha^{-1} and 7.017 kg ha^{-1}, respectively. In the medium fertility strip, potassium uptake was greater than in the LFS. At the VE stage, potassium uptake by the leaf, stem and root was 3.997, 1.279 and 1.151 kg ha^{-1}, respectively. By the R6 stage, the kernel showed the highest uptake (43.798 kg ha^{-1}), followed by the leaf (37.958 kg ha^{-1}), stem (35.038 kg ha^{-1}) and root (11.679 kg ha^{-1}). The cob sheath and rind absorbed 10.220 and 7.300 kg ha^{-1}, respectively. The high fertility strip exhibited the highest potassium uptake across all growth stages and plant parts. At the VE stage, the leaf, stem and root absorbed 4.167, 1.333 and 1.200 kg ha^{-1}, respectively. Potassium uptake peaked at the R6 stage, where the kernel absorbed the highest amount (56.067 kg ha^{-1}), followed by the leaf (48.592 kg ha^{-1}), stem (44.854 kg ha^{-1}) and root (14.951 kg ha^{-1}). The cob sheath and rind absorbed 13.082 and 9.345 kg ha^{-1}, respectively.

100 % NK (2-0-2)

The potassium uptake by different parts of maize during the growth stages varied differently across the 100 % NK (2-0-2) and 100 % NP (2-2-0) treatments in the LFS, MFS and HFS, represented in Fig. 12.

In the low fertility strip, potassium uptake was lowest at the VE stage, where the leaf, stem and root absorbed 2.340, 0.749 and 0.674 kg ha^{-1}, respectively. Potassium uptake progressively increased as the plants developed, peaking at the R6 stage. At R6, the kernel absorbed the highest amount of potassium (44.433 kg ha^{-1}), followed by the leaf (38.509 kg

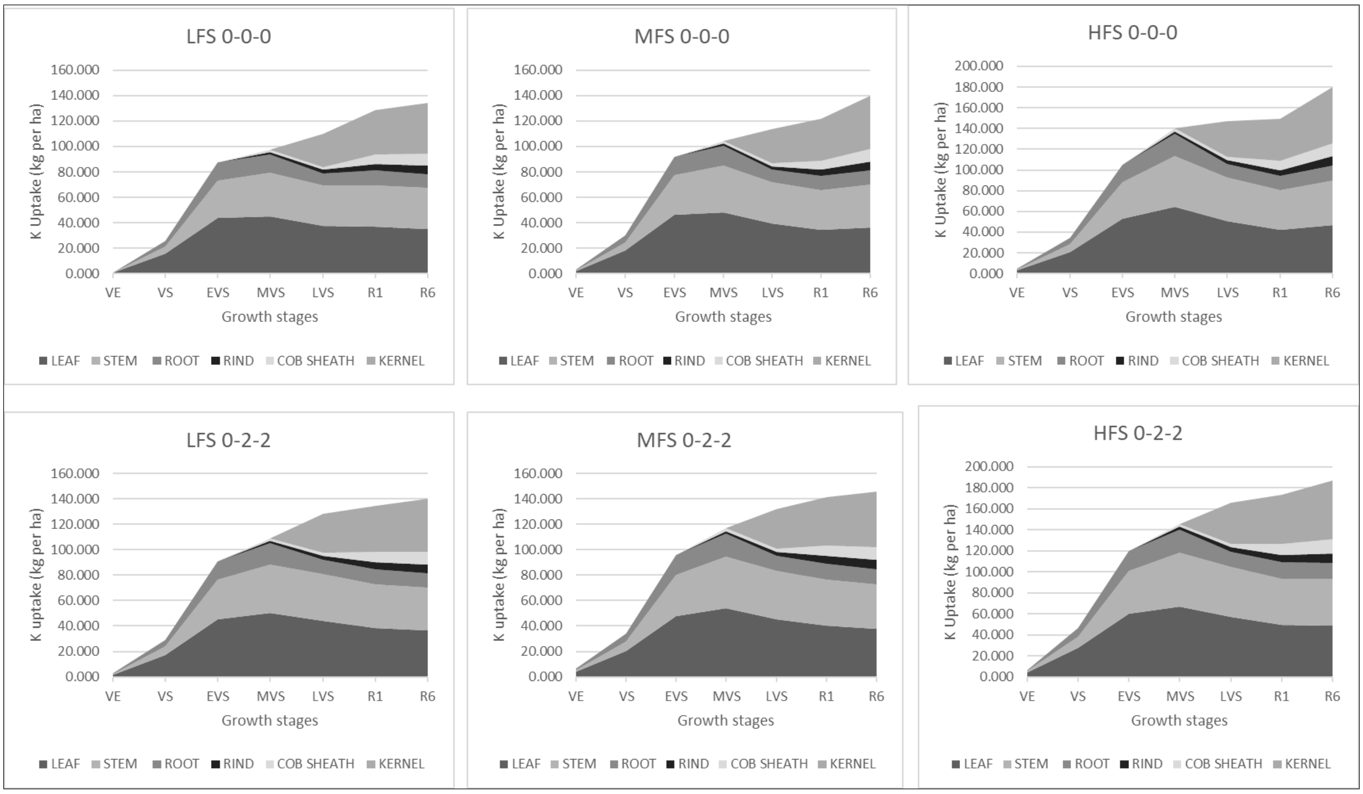

Fig. 11. Potassium partitioning across different maize plant parts during growth stages under control and 100 % PK treatments in low, medium and high fertility strips.

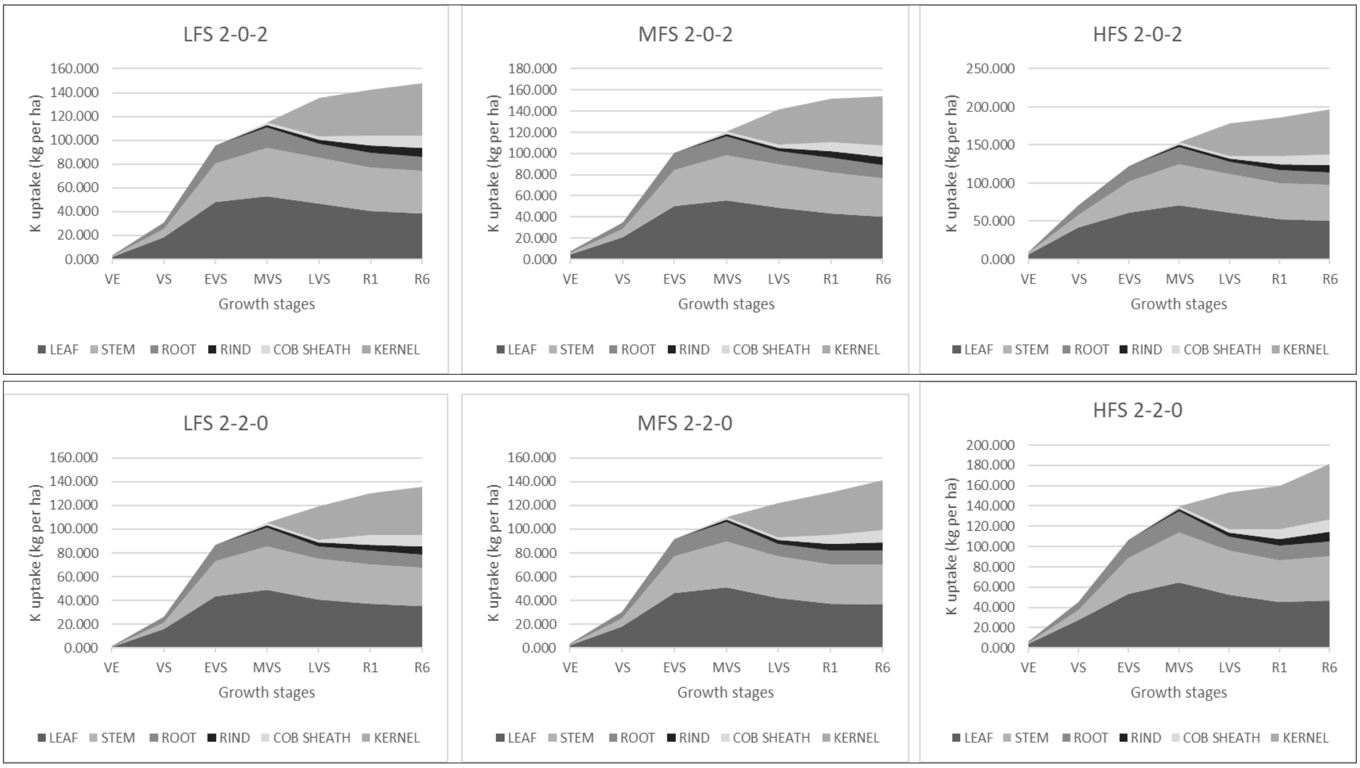

Fig. 12. Potassium partitioning across different maize plant parts during growth stages under 100 % NK and 100 % NP treatments in low, medium and high fertility strips.

ha^{-1}), stem (35.546 kg ha^{-1}) and root (11.849 kg ha^{-1}). The cob sheath and rind absorbed 10.368 and 7.405 kg ha^{-1}, respectively. In the medium fertility strip, potassium uptake was higher than in the LFS. At the VE stage, the leaf, stem and root absorbed 4.752, 1.521 and 1.368 kg ha^{-1}, respectively. By the R6 stage, the kernel absorbed the highest potassium (46.190 kg ha^{-1}), followed by the leaf (40.032 kg ha^{-1}), stem (36.952 kg ha^{-1}) and root (12.317 kg ha^{-1}). Potassium uptake by the cob sheath and rind was 10.778 and 7.698 kg ha^{-1}, respectively. The high fertility strip showed the highest potassium uptake across all growth stages and plant parts. At the VE stage, the leaf, stem and root absorbed 6.321, 2.023 and 1.820 kg ha^{-1}, respectively. Potassium uptake peaked at the R6 stage, where the kernel absorbed 58.914 kg ha^{-1}, followed by the leaf (51.059 kg ha^{-1}), stem (47.131 kg ha^{-1}) and root (15.710 kg ha^{-1}). The cob sheath and rind absorbed 13.747 and 9.819 kg ha^{-1}, respectively.

100 % NP (2-2-0)

Under the LFS, potassium uptake was minimal at the VE stage (leaf: 0.764, stem: 0.244, root: 0.220 kg ha^{-1}) and increased significantly by VS (leaf: 15.733, stem: 5.769, root: 4.720 kg ha^{-1}). Peak uptake occurred at MVS (leaf: 48.666, stem: 37.029, root: 15.869 kg ha^{-1}), with additional uptake in the rind (2.116 kg ha^{-1}) and cob sheath (2.010 kg ha^{-1}). By R6, the kernel absorbed the most (40.739 kg ha^{-1})followed by the leaf (35.307 kg ha^{-1}), stem (32.591 kg ha^{-1}), root (10.864 kg ha^{-1}), cob sheath (9.506 kg ha^{-1}) and rind (6.790 kg ha^{-1}). Under the MFS, potassium uptake was higher than in LFS, starting at VE (leaf: 2.351, stem: 0.752, root: 0.677 kg ha^{-1}) and peaking at MVS (leaf: 50.908, stem: 38.735, root: 16.601 kg ha^{-1}, rind: 2.213 kg ha^{-1}, cob sheath: 2.103 kg ha^{-1}). At R6, the kernel absorbed the most (42.401 kg ha^{-1}), followed by the leaf (36.748 kg ha^{-1}), stem (33.921 kg ha^{-1}), root (11.307 kg ha^{-1}), cob sheath (9.894 kg ha^{-1}) and rind (7.067 kg ha^{-1}). Under the HFS, potassium uptake was highest across all stages. At VE, the leaf, stem and root absorbed 4.068, 1.302 and 1.172 kg ha^{-1}, respectively, with peak uptake at MVS (leaf: 64.416, stem: 49.012, root: 21.005 kg ha^{-1}, rind: 2.801 kg ha^{-1}, cob sheath: 2.661 kg ha^{-1}). By R6, the kernel absorbed the most (54.405 kg ha^{-1}), followed by the leaf (47.151 kg ha^{-1}), stem (43.524 kg ha^{-1}), root (14.508 kg ha^{-1}), cob sheath (12.695 kg ha^{-1}) and rind (9.068 kg ha^{-1}).

100 % NPK (2-2-2)

The potassium uptake by different parts of maize during the growth stages varied differently across the 100 % NPK (2-2-2) treatments in the LFS, MFS and HFS, represented in Fig. 13.

Under the LFS, potassium uptake at the VE stage was minimal (leaf: 2.531, stem: 0.810, root: 0.729 kg ha^{-1}) but increased significantly by the VS stage (21.629, 7.931 and 6.489 kg ha^{-1}, respectively). Peak uptake occurred at the MVS stage (leaf: 53.541, stem: 40.738, root: 17.459 kg ha^{-1}, rind: 2.328, cob sheath: 2.211 kg ha^{-1}). By the R6 stage, the kernel absorbed the most potassium (44.880 kg ha^{-1}), followed by the leaf (38.896 kg ha^{-1}), stem (35.904 kg ha^{-1}) and root (11.968 kg ha^{-1}). Under the MFS, potassium uptake exceeded LFS levels. At the VE stage, uptake was 5.042, 1.613 and 1.452 kg ha^{-1} in the leaf, stem and root, respectively, peaking at the MVS stage (leaf: 56.243, stem: 42.794, root: 18.340 kg ha^{-1}, rind: 2.445, cob sheath: 2.323 kg ha^{-1}). By the R6 stage, the kernel absorbed 46.648 kg ha^{-1}, followed by the leaf (40.429 kg ha^{-1}), stem (37.319 kg ha^{-1}) and root (12.440 kg ha^{-1}). Under the HFS, potassium uptake was highest. At the VE stage, the leaf, stem and root absorbed 6.044, 1.934 and 1.741 kg ha^{-1}, respectively, with peak uptake at the MVS stage (leaf: 71.311, stem: 54.258, root: 23.254 kg ha^{-1}, rind: 3.100, cob sheath: 2.945 kg ha^{-1}). By the R6 stage, the kernel absorbed the most potassium (59.459 kg ha^{-1}), followed by the leaf (51.531 kg ha^{-1}), stem (47.567 kg ha^{-1}) and root (15.856 kg ha^{-1}).

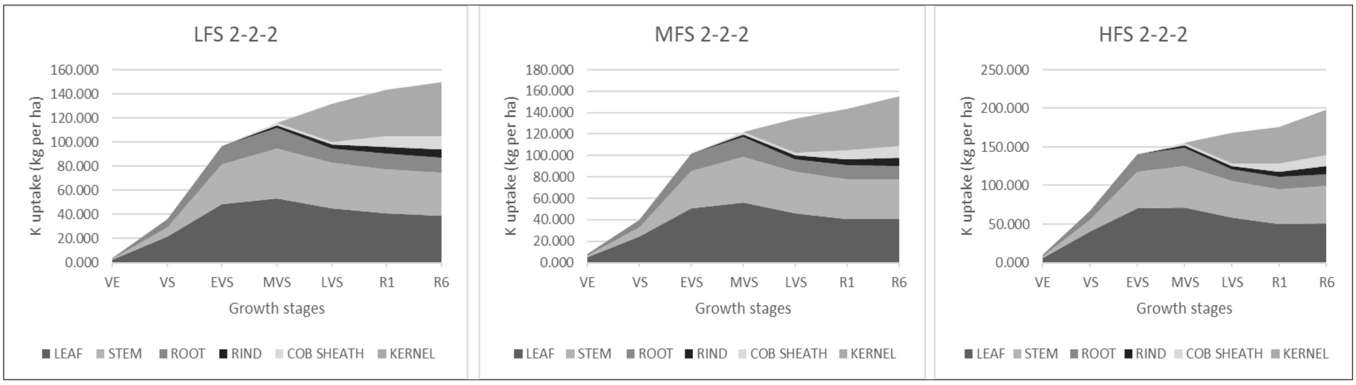

Fig. 13. Potassium partitioning across different maize plant parts during growth stages under 100 % NPK treatment in low, medium and high fertility strips.

Quality parameters of maize kernel

The crude protein, moisture content and ash content of maize kernel was shown in Table 1. The crude protein content of maize kernels ranged from 7.69 % in the control to 9.15 % in the 100 % NPK treatment. Nitrogen-containing treatments, such as 100 % NK (8.00 %) and 100 % NP (8.03 %), exhibited higher protein content compared to the control. Moisture content was highest in the control (13.1 %) and lowest in the 100 % NPK treatment (11.02 %). Treatments 100 % PK (12.8 %) and 100 % NK (12.9 %) showed intermediate moisture levels. Ash content varied between 1.40 % in the 100 % PK treatment and 1.53 % in the 100 % NPK treatment, indicating a slight increase in mineral accumulation with balanced fertilization.

Table 1. Effect of fertilization on crude protein, moisture and ash content of maize kernel

Treatments	Crude protein (%)	Moisture (%)	Ash (%)
Control (0-0-0)	7.69	13.1	1.47
100 % PK (0-2-2)	7.98	12.8	1.40
100 % NK (2-0-2)	8.00	12.9	1.45
100 % NP (2-2-0)	8.03	13.0	1.42
100 % NPK (2-2-2)	9.15	11.02	1.53
SEM±	**0.25**	**0.39**	**0.02**
CD at 5 %	**0.99**	**1.53**	**0.08**

The crude fat, crude fibre and carbohydrate content of maize kernel was shown in Table 2. Crude fat content ranged from 4.15 % in the control to 4.44 % in the 100 % NPK treatment. Treatments 100 % NK (4.35 %) and 100 % NP (4.33 %) also showed higher fat content than the control. Crude fibre content was highest in the 100 % NPK treatment (1.77 %) and lowest in the control (1.62 %). Other treatments, such as 100 % PK (1.64 %) and 100 % NP (1.67 %), showed intermediate values. Carbohydrate content ranged from 71.01 % in the 100 % PK treatment to 72.08 % in the 100 % NPK treatment. The control exhibited 71.82 %, while other treatments showed intermediate values.

Table 2. Effect of fertilization on crude fat, crude fibre and carbohydrate content of maize kernel

Treatments	Crude fat (%)	Crude fiber (%)	Carbohydrate (%)
Control (0-0-0)	4.15	1.62	71.82
100 % PK (0-2-2)	4.30	1.64	71.01
100 % NK (2-0-2)	4.35	1.69	71.35
100 % NP (2-2-0)	4.33	1.67	71.59
100 % NPK (2-2-2)	4.44	1.77	72.08
SEM±	**0.047**	**0.027**	**0.185**
CD at 5 %	**0.13**	**0.07**	**0.51**

Quality parameters of maize fodder

The crude protein, moisture content and ash content of maize fodder was shown in Table 3. Crude protein content in maize fodder ranged from 7.45 % in the control to 7.99 % in the 100 % NPK treatment. Treatments 100 % PK (7.60 %), 100 % NK (7.62 %) and 100 % NP (7.66 %) showed slight increases compared to the control. Moisture content was highest in the control (12.33 %) and lowest in the 100 % NPK treatment (10.81 %). Treatments 100 % PK (12.19 %), 100 % NK (12.24 %) and 100 % NP (12.30 %) exhibited similar moisture levels. Ash content ranged from 7.93 % in the 100 % PK treatment to 8.90 % in the 100 % NPK treatment. The control recorded 8.20 %, while 100 % NK (7.98 %) and 100 % NP (8.01 %) showed intermediate values.

Table 3. Effect of fertilization on crude protein, moisture and ash content of maize fodder

Treatments	Crude protein (%)	Moisture (%)	Ash (%)
Control (0-0-0)	7.45	12.33	8.20
100 % PK (0-2-2)	7.60	12.19	7.93
100 % NK (2-0-2)	7.62	12.24	7.98
100 % NP (2-2-0)	7.66	12.30	8.01
100 % NPK (2-2-2)	7.99	10.81	8.90
SEM±	**0.08**	**0.29**	**0.18**
CD at 5 %	**0.35**	**1.15**	**0.71**

The crude fat, crude fibre and carbohydrate content of maize kernel was shown in Table 4. Crude fat content varied from 2.48 % in the control to 2.69 % in the 100 % NPK treatment. Other treatments, including 100 % PK (2.51 %), 100 % NK (2.56 %) and 100 % NP (2.59 %), showed incremental increases compared to the control. Crude fibre content was highest in the 100 % NPK treatment (31.09 %) and lowest in the control (28.89 %). Treatments 100 % PK (29.12 %), 100 % NK (29.21 %) and 100 % NP (29.24 %) showed moderate increases. Carbohydrate content ranged from 80.48 % in the

Table 4. Effect of fertilization on crude fat, crude fibre and carbohydrate content of maize fodder

Treatments	Crude fat (%)	Crude fiber (%)	Carbohydrate (%)
Control (0-0-0)	2.48	28.89	81.92
100 % PK (0-2-2)	2.51	29.12	81.68
100 % NK (2-0-2)	2.56	29.21	81.72
100 % NP (2-2-0)	2.59	29.24	81.79
100 % NPK (2-2-2)	2.69	31.09	80.48
SEM±	**0.04**	**0.40**	**0.26**
CD at 5 %	**0.14**	**1.11**	**0.73**

100 % NPK treatment to 81.92 % in the control. Treatments 100 % PK (81.68 %), 100 % NK (81.72 %) and 100 % NP (81.79 %) showed slight decreases compared to the control.

Discussion

The observed trends in soil available nitrogen can be attributed to fertilizer application, plant uptake and soil mineralization dynamics (Fig. 3A). The increase in nitrogen availability at 60 DAS aligns with the application of fertilizers and reduced early uptake, indicating a temporary build-up in the soil (24). This stage might coincide with a period of rapid mineralization or slow uptake. The subsequent decline in nitrogen levels reflects increased plant demand during later growth stages, especially during the reproductive phase (25). The differences among treatments highlight the effectiveness of different fertilizer rates, with higher doses maintaining elevated nitrogen levels for a longer duration.

The observed patterns in soil available phosphorus align with the expected dynamics of phosphorus in agricultural systems (Fig. 3B). The peak at 15 DAS corresponds to the initial fertilizer application, which temporarily elevates phosphorus availability in the soil (26). This stage likely represents the period when phosphorus is most readily accessible to plants. The gradual decline in phosphorus levels over time reflects its uptake by the crop during key growth stages, particularly during vegetative and early reproductive phases. Additionally, phosphorus fixation in the soil, especially in calcareous or acidic conditions, could contribute to the observed decrease (27).

The observed decline in soil available potassium over time reflects the natural dynamics of nutrient uptake by crops during critical growth stages, particularly during the vegetative and reproductive phases when potassium demand peaks (Fig. 3C). Treatments that maintained higher potassium levels suggest effective soil management practices, such as balanced fertilization, efficient nutrient release, or improved organic matter integration (28). Conversely, treatments with rapid declines in potassium levels highlight the need for enhanced potassium supplementation or adjustments in soil amendment strategies to sustain nutrient availability (29). The convergence of potassium levels at the final stage suggests the exhaustion of available K in most treatments, emphasizing the importance of targeted and timely fertilizer applications to meet crop requirements. Future efforts should focus on identifying slow-release potassium sources or improving soil properties to enhance nutrient retention (30). Additionally, exploring the role of soil microbial activity, irrigation practices and soil texture could further optimize potassium management strategies and improve crop productivity (31).

The cluster dendrogram effectively illustrates the variation in soil available nitrogen across treatments (Fig. 4A), offering insights into their relative similarities and differences. Major clusters represent treatments with comparable nitrogen management or soil properties, while subclusters highlight more specific groupings based on subtle differences (32). Treatments grouped together likely share similar soil characteristics, nutrient management strategies, or crop uptake patterns. The cluster dendrogram provides valuable insights into the variability and similarities of soil available phosphorus among treatments. Major clusters represent broad groupings of treatments with similar phosphorus dynamics, potentially influenced by shared fertilization regimes, soil types or management practices (Fig. 4B). Subclusters, on the other hand, indicate finer distinctions that could be linked to specific treatment factors such as phosphorus sources, microbial activity or crop uptake rates. The hierarchical structure suggests that phosphorus availability in the soil is influenced by complex interactions between soil properties, amendments and crop nutrient demand (33). This clustering can guide phosphorus management strategies by identifying treatments with similar responses, enabling more targeted and efficient fertilizer applications (34).

The hierarchical clustering analysis provides insights into the variability of soil available potassium levels across the studied samples (Fig. 4C). The distinct clusters observed suggest significant variation in K availability, which could be attributed to factors such as soil type and management practices. The grouping of soil samples into clusters facilitates the identification of regions or areas requiring tailored nutrient management practices (35). For instance, clusters with lower K availability might benefit from potassium fertilization to enhance soil fertility and crop productivity. Conversely, regions with higher K levels may need adjustments to avoid over-fertilization, which can lead to environmental concerns.

The results highlight that fertilizer levels significantly influence nutrient uptake and redistribution in maize (Fig. 5). The increased nutrient uptake across vegetative stages under HFS indicates that a higher nutrient supply enhances plant growth, particularly during critical stages such as EVS and MVS (36). Peak uptake in vegetative parts during MVS under all treatments emphasizes the importance of ensuring optimal nutrient availability during this period for maximum biomass accumulation. Kernel uptake became prominent during LVS and dominated in the reproductive stages, especially R1 and R6, reflecting the translocation of nutrients from vegetative organs to the kernel (37). This was most pronounced in HFS, where kernel nutrient uptake reached 25.33 kg ha^{-1} at R6, surpassing both MFS and LFS. The efficient nutrient redistribution in HFS suggests the potential for enhanced kernel yield and quality when sufficient fertilizer is applied. The decline in nutrient uptake by leaves, stems and roots during reproductive stages reflects the plant's strategy to allocate nutrients to grain filling (38). These findings underline the importance of stage -specific nutrient management. For example, maximizing nutrient availability during vegetative growth ensures sufficient accumulation in biomass, while maintaining nutrient availability during the transition to reproductive stages supports kernel development. The results suggest that higher fertilizer levels can improve nutrient-use efficiency and enhance crop productivity, provided that the application aligns with the crop's nutrient demand (39).

The data highlight the importance of stage-specific nutrient management (Fig. 6 and 7). Adequate nutrient availability during vegetative stages ensures robust plant growth, while sustained nutrient supply during reproductive stages supports kernel development and grain filling (40). Higher fertilizer levels, as observed in HFS, enhance nutrient uptake efficiency and productivity.

Phosphorus uptake increased with higher fertilizer application, especially under MFS and HFS (Fig. 8-10). Early stages showed minimal uptake, but increased significantly in the later stages. At MVS, uptake was highest under MFS and HFS, reflecting better growth due to increased phosphorus availability. The late stages saw a shift in phosphorus allocation to the kernels, with HFS leading to the highest kernel uptake, particularly at R1 and R6. This indicates that higher phosphorus availability enhances kernel development and overall yield. Appropriate phosphorus management is crucial for optimizing maize growth and maximizing yield (41). These findings emphasize the need for a balanced fertilization approach. The medium fertility strip strikes a balance between maximizing phosphorus uptake (especially in the kernel) and minimizing input costs and environmental risks. Stage-specific phosphorus application, particularly during the reproductive stage, can enhance nutrient use efficiency and yield potential.

The results demonstrate a clear relationship between fertility strip treatments and potassium uptake in maize (Fig. 11-13). Potassium uptake increased progressively with plant growth, peaking at the R6 stage, where the kernel became the dominant sink across all fertility strips. This trend emphasizes the role of potassium in grain development and its importance during the reproductive stage of maize growth. The fertility strips significantly influenced potassium uptake. The HFS consistently resulted in the highest uptake across all growth stages and plant parts, underscoring the importance of optimal potassium availability for maximum productivity. The distribution of potassium among plant parts revealed that the leaf, stem and kernel acted as primary sinks, especially during the later stages of growth. While the kernel absorbed the most potassium at the R6 stage, significant uptake in the cob sheath, rind and root at this stage highlights their supporting role in nutrient translocation and grain filling. Potassium uptake in maize is closely linked to both growth stage and fertility strip treatment (42). The HFS enhanced potassium absorption, particularly in key plant parts such as the kernel, leaf and stem, thereby maximizing productivity.

The significant increase in crude protein content (Table 1) with the 100 % NPK treatment highlights the critical role of nitrogen in protein synthesis. Nitrogen is essential for amino acid formation and its balanced application with phosphorus and potassium maximized protein accumulation in maize kernels (43). The reduced moisture content in the 100 % NPK treatment suggests improved kernel maturity and storage potential. Balanced fertilization likely enhanced the physiological processes that optimize moisture regulation during kernel development (44). Higher ash content in the 100 % NPK treatment indicates improved mineral uptake and accumulation due to balanced fertilization. This result reflects the importance of phosphorus and potassium in supporting metabolic processes that enhance mineral content (45).

The increase in crude fat content (Table 2) with nitrogen-containing treatments, especially 100 % NPK, may be attributed to improved enzymatic activity involved in lipid biosynthesis. This enhancement in fat content contributes to better energy value and quality of the maize kernel (46). The higher crude fibre content in the 100 % NPK treatment suggests enhanced structural development of the kernel. Balanced fertilization likely improved the synthesis of cell wall components, which contribute to fibre content (47). The higher carbohydrate content observed in the 100 % NPK treatment indicates efficient photosynthesis and carbohydrate accumulation due to the synergistic effects of nitrogen, phosphorus and potassium (48). This result underscores the importance of balanced fertilization in maximizing energy reserves in the kernel. Balanced fertilization with 100 % NPK consistently improved all quality parameters, including crude protein, fat, fibre and carbohydrate content, while reducing moisture content, making it the most effective treatment for enhancing maize kernel quality.

The increase in crude protein content with fertilization (Table 3), particularly in the 100 % NPK treatment, highlights the role of nitrogen in promoting protein synthesis in maize fodder. The balanced application of nitrogen, phosphorus and potassium enhanced amino acid production, contributing to improved protein content (49). The reduced moisture content in the 100 % NPK treatment indicates improved physiological maturity of the fodder. Lower moisture levels enhance the storage quality of the fodder and reduce the risk of spoilage (50). Higher ash content in the 100 % NPK treatment reflects improved mineral uptake and accumulation in maize fodder. This result underscores the role of balanced fertilization in supporting metabolic processes and enhancing the mineral content of fodder (45).

The increase in crude fat content with fertilization (Table 4), especially in the 100 % NPK treatment, suggests improved enzymatic activity involved in lipid synthesis. Enhanced fat content contributes to better energy value and nutritional quality of the fodder (46). The significant increase in crude fibre content in the 100 % NPK treatment indicates enhanced structural development of the plant. Balanced fertilization supports the synthesis of cell wall components, which contribute to fibre content and improve the digestibility of fodder (47). The slight reduction in carbohydrate content with balanced fertilization (100 % NPK) may be due to the allocation of assimilates toward protein and fibre synthesis. Despite this, the carbohydrate levels remain high, ensuring the energy value of the fodder is maintained (48). The 100 % NPK treatment consistently improved the quality parameters of maize fodder, including crude protein, fat and fibre, while maintaining optimal carbohydrate levels and reducing moisture content. This highlights the importance of balanced fertilization in producing high-quality maize fodder.

Conclusion

This research emphasizes the importance of balanced NPK fertilization in enhancing maize yield, quality and soil fertility. Results indicated that balanced NPK fertilization (100 % NPK) significantly enhanced maize kernel quality, with increases of 19 %, 7 % and 0.36 % in crude protein, fat and carbohydrate contents, respectively, compared to the control. The 100 % NPK treatment effectively increased crude protein, fat and carbohydrate content, improving kernel and fodder quality. Nutrient uptake analyses showed that high-fertility conditions supported optimal growth and nutrient translocation to kernels, enhancing grain quality. Soil analysis showed sustained nutrient availability with 100 % NPK, though excessive levels risked depletion and environmental losses. Soil nitrogen showed an initial uniformity, peaking at 60 DAS in high-fertilizer treatments before declining due to plant uptake. Phosphorus levels peaked at 15 DAS in high-dose plots and declined steadily, likely from uptake and immobilization. Potassium started high but declined gradually, with variation among treatments; most converged to similar levels by harvest. Potassium played a crucial role in grain filling and nutrient movement, particularly in high-fertility conditions. The study advocates for stage-specific nutrient management to optimize maize productivity while maintaining soil health.

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Authors' contributions

ANN Conceptualized and designed the study, conducted the experiments, analyzed the data, interpreted the results and wrote the manuscript. Served as the corresponding author and coordinated the research activities. KMR Provided critical guidance on experimental design, contributed to the data interpretation and reviewed the manuscript. Supervised the implementation of balanced NPK fertilization techniques. SJ Offered technical expertise in soil science and agricultural chemistry, contributed to refining the research methodology and assisted in the critical review and improvement of the manuscript. TMN Provided inputs on agrometeorological aspects influencing nutrient uptake and soil sustainability. Assisted in data analysis and the interpretation of results related to environmental sustainability. VP Contributed to field-level implementation and data collection. Provided technical assistance in soil and plant sample analysis and collaborated on manuscript review. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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References

1. Shiferaw B, Prasanna BM, Hellin J, Bänziger M. Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. Food Security. 2011;3:307–27. https://doi.org/10.1007/s12571-011-0140-5
2. Maitra S, Singh V. Emerging trends of maize biorefineries in the 21st century: Scientific and technological advancements in biofuel and bio-sustainable market. J Cereal Sci. 2021;101:103272. https://doi.org/10.1016/j.jcs.2021.103272
3. Khare N, Khare P, Singh S. Molecular and physiological concepts: Macronutrients in crop plant growth and development. In: Agricultural crop improvement. CRC Press; 2025. p. 148–64. https://doi.org/10.1201/9781032630366-11
4. Shah F, Wu W. Soil and crop management strategies to ensure higher crop productivity within sustainable environments. Sustainability. 2019;11(5):1485. https://doi.org/10.3390/su11051485
5. Mustafa G, Hayat N, Alotaibi BA. How and why to prevent over fertilization to get sustainable crop production. In: Sustainable plant nutrition. Academic Press; 2023. p. 339-54. https://doi.org/10.1016/B978-0-443-18675-2.00019-5
6. El Gayar A. A study on: Nutrients in sustainable cropping systems. AAHE-144; 2021.
7. Rashmi I, Shirale A, Kartikha KS, Shinogi KC, Meena BP, Kala S. Leaching of plant nutrients from agricultural lands. In: Essential plant nutrients: Uptake, use efficiency and management. 2017. p. 465-89. https://doi.org/10.1007/978-3-319-58841-4_19
8. Aryal B, Gurung R, Camargo AF, Fongaro G, Treichel H, Mainali B, et al. Nitrous oxide emission in altered nitrogen cycle and implications for climate change. Environ Pollut. 2022;314:120272. https://doi.org/10.1016/j.envpol.2022.120272
9. Yimer T, Abera G, Beyene S, Ravensbergen APP, Ukato A, Rasche F. Optimizing fertilization schemes to narrow the maize yield gap in smallholder farming systems in southern Ethiopia. Heliyon. 2024;10(13):e33926. https://doi.org/10.1016/j.heliyon.2024.e33926
10. Zulfiqar F, Navarro M, Ashraf M, Akram NA, Munné-Bosch S. Nanofertilizer use for sustainable agriculture: Advantages and limitations. Plant Sci. 2019;289:110270. https://doi.org/10.1016/j.plantsci.2019.110270
11. Raza I, Zubair M, Zaib M, Khalil MH, Haidar A, Sikandar A, et al. Precision nutrient application techniques to improve soil fertility and crop yield: A review with future prospect. Int Res J Educ Technol. 2023;5(8).

12. Yadav MR, Kumar R, Parihar CM, Yadav RK, Jat SL, Ram H, et al. Strategies for improving nitrogen use efficiency: A review. Agric Rev. 2017;38(1):29-40. https://doi.org/10.18805/ag.v0iOF.7306
13. Ramamoorthy B, Narasimham RL, Dinesh RS. Fertilizer application for specific yield targets on Sonora 64 (wheat). Indian Farming. 1967;17:43-5.
14. Subbiah BV, Asija GL. A rapid procedure for estimation of available nitrogen in soils. Curr Sci. 1956;25:259-60.
15. Bray RH, Kurtz LT. Determination of total, organic and available phosphorus in soil. Soil Sci. 1945;9:39-46. https://doi.org/10.1097/00010694-194501000-00006
16. Page AL, Miller RH, Kenay R. Methods of Soil Analysis Part-2. Soil Sci Soc Am. Madison, Wisconsin, USA; 1982.
17. Rangaiah KM, Nagaraju B, Kasturappa G, Nagendrachari AN, Kadappa BP, Narayanaswamy UKS, et al. Inductive cum targeted yield model-based integrated fertilizer prescription for sweet corn (*Zea mays* L. *Saccharata*) on Alfisols of Southern India. PLoS One. 2024;19(8):e0307168. https://doi.org/10.1371/journal.pone.0307168
18. Piper CS. Soil and plant analysis. Bombay: Hands Publishers; 1966. p. 137-53.
19. Jackson ML. Soil Chemical analysis. New Delhi: Prentice Hall of India Pvt. Ltd.; 1973. 498 p.
20. AOAC. Official Methods of Analysis of the Association of Official Agricultural Chemists. 10th ed. Washington DC; 1965. p. 744-5.
21. ISI. Method of Tests for Animal Feeds and Feeding Stuffs: 7874 Part 1. Minerals and Trace Element. New Delhi: Indian Standards Institution, Manak Bhawan, Bahadur Shah Jafar Marg; 1975.
22. Mahadevan SA. Laboratory Manual for Nutrition Research. New Delhi: Vikash Publishing House Pvt. Ltd.; 1965. p. 56-8.
23. Igbabul B, Shember J, Amove J. Physicochemical, microbiological and sensory evaluation of yoghurt sold in Marurdi metropolis. Afr J Food Sci Technol. 2014;5:129–35.
24. Kumawat GL. Impact of irrigation methods and nitrogen application on yield and nitrogen use efficiency of winter maize [Doctoral dissertation]. RPCAU, Pusa; 2023.
25. Gastal F, Lemaire G, Durand JL, Louarn G. Quantifying crop responses to nitrogen and avenues to improve nitrogen-use efficiency. In: Crop physiology. Academic Press; 2015. p. 161-206. https://doi.org/10.1016/B978-0-12-417104-6.00008-X
26. Henningsen JN, Görlach BM, Fernández V, Dölger JL, Buhk A, Mühling KH. Foliar P application cannot fully restore photosynthetic capacity, P nutrient status and growth of P deficient maize (*Zea mays* L.). Plants. 2022;11(21):2986. https://doi.org/10.3390/plants11212986
27. Hopkins BG, Hansen NC. Phosphorus management in high‐yield systems. J Environ Qual. 2019;48(5):1265-80. https://doi.org/10.2134/jeq2019.03.0130
28. Brouder SM, Volenec JJ, Murrell TS. The potassium cycle and its relationship to recommendation development. In: Improving potassium recommendations for agricultural crops. Springer International Publishing; 2021. p. 1–46. https://doi.org/10.1007/978-3-030-59197-7_1
29. DAS D, Sahoo J, Raza MB, Barman M, DAS R. Ongoing soil potassium depletion under intensive cropping in India and probable mitigation strategies: A review. Agron Sustain Dev. 2022;42(1):4. https://doi.org/10.1007/s13593-021-00728-6
30. Priya E, Sarkar S, Maji PK. A review on slow-release fertilizer: Nutrient release mechanism and agricultural sustainability. J Environ Chem Eng. 2024;12(4):113211. https://doi.org/10.1016/j.jece.2024.113211
31. Sattar A, Naveed M, Ali M, Zahir ZA, Nadeem SM, Yaseen M, et al. Perspectives of potassium solubilizing microbes in sustainable food production system: A review. Appl Soil Ecol. 2019;133:146-59. https://doi.org/10.1016/j.apsoil.2018.09.012
32. Miyagi A, Takahashi H, Takahara K, Hirabayashi T, Nishimura Y, Tezuka T, et al. Principal component and hierarchical clustering analysis of metabolites in destructive weeds; polygonaceous plants. Metabolomics. 2010;6:146-55. https://doi.org/10.1007/s11306-009-0186-y
33. Zhang X, Zhan Y, Zhang H, Wang R, Tao X, Zhang L, et al. Inoculation of phosphate-solubilizing bacteria (*Bacillus*) regulates microbial interaction to improve phosphorus fractions mobilization during kitchen waste composting. Bioresour Technol. 2021;340:125714. https://doi.org/10.1016/j.biortech.2021.125714
34. Vadde KK, Wang J, Cao L, Yuan T, McCarthy AJ, Sekar R. Assessment of water quality and identification of pollution risk locations in Tiaoxi River (Taihu Watershed), China. Water. 2018;10(2):183. https://doi.org/10.3390/w10020183
35. Khaledian Y, Kiani F, Ebrahimi S, Brevik EC, Aitkenhead‐Peterson J. Assessment and monitoring of soil degradation during land use change using multivariate analysis. Land Degrad Dev. 2017;28(1):128-41. https://doi.org/10.1002/ldr.2541
36. Ray K, Banerjee H, Dutta S, Sarkar S, Murrell TS, Singh VK, et al. Macronutrient management effects on nutrient accumulation, partitioning, remobilization and yield of hybrid maize cultivars. Front Plant Sci. 2020;11:1307. https://doi.org/10.3389/fpls.2020.01307
37. Zhiipao RR, Pooniya V, Biswakarma N, Kumar D, Shivay YS, DASs A, et al. Timely sown maize hybrids improve the post-anthesis dry matter accumulation, nutrient acquisition and crop productivity. Sci Rep. 2023;13(1):1688. https://doi.org/10.1038/s41598-023-28224-9
38. Kirkby EA, Nikolic M, White PJ, Xu G. Mineral nutrition, yield and source–sink relationships. In: Marschner's mineral nutrition of plants. Academic Press; 2023. p. 131-200. https://doi.org/10.1016/B978-0-12-819773-8.00015-0
39. Ampong K, Penn CJ, Camberato JJ. The timing of phosphorus availability to corn: What growth stages are most critical for maximizing yield. Agronomy. 2024;14(11):2731. https://doi.org/10.3390/agronomy14112731
40. Hammad HM, Abbas F, Ahmad A, Bakhat HF, Farhad W, Wilkerson CJ, et al. Predicting kernel growth of maize under controlled water and nitrogen applications. Int J Plant Prod. 2020;14:609-20. https://doi.org/10.1007/s42106-020-00110-8
41. Blandino M, Battisti M, Vanara F, Reyneri A. The synergistic effect of nitrogen and phosphorus starter fertilization sub-surface banded at sowing on the early vigor, grain yield and quality of maize. Eur J Agron. 2022;137:126509. https://doi.org/10.1016/j.eja.2022.126509
42. Karthika KS, Rashmi I, Parvathi MS. Biological functions, uptake and transport of essential nutrients in relation to plant growth. In: Plant nutrients and abiotic stress tolerance. Singapore: Springer; 2018. p. 1-49. https://doi.org/10.1007/978-981-10-9044-8_1
43. Ochieng' IO, Gitari HI, Mochoge B, Rezaei-Chiyaneh E, Gweyi-Onyango JP. Optimizing maize yield, nitrogen efficacy and grain protein content under different N forms and rates. J Soil Sci Plant Nutr. 2021;21(3):1867-80. https://doi.org/10.1007/s42729-021-00486-0
44. Yang F, He B, Zhang G. Enhanced maize yield and water-use efficiency via film mulched ridge–furrow tillage with straw incorporation in semiarid regions. Arch Agron Soil Sci. 2022;68(13):1796-809. https://doi.org/10.1080/03650340.2021.1928647
45. Thakur A, Sharma RP, Sankhyan NK, Kumar R. Maize grain quality as influenced by 46 years' continuous application of fertilizers, farmyard manure (FYM) and lime in an Alfisol of North-western Himalayas. Commun Soil Sci Plant Anal. 2021;52(2):149-60. https://doi.org/10.1080/00103624.2020.1854289

46. Liu J, Liang B, Liu S, Zhang G, Yuan M. Effects of long-term fertilization on grain quality of summer maize. Adv J Food Sci Technol. 2016;11(1):33-9. https://doi.org/10.19026/ajfst.11.2350

47. Fadlalla HA, Abukhlaif HAA, Mohamed SS. Effects of chemical and bio-fertilizers on yield, yield components and grain quality of maize (*Zea mays* L.). Afr J Agric Res. 2016;11(45):4654-60. https://doi.org/10.5897/AJAR2016.11619

48. Verma G, Sharma RP, Sharma SP, Subehia SK, Shambhavi S. Changes in soil fertility status of maize-wheat system due to long-term use of chemical fertilizers and amendments in an Alfisol. Plant Soil Environ. 2012;58:529-33. https://doi.org/10.17221/133/2012-PSE

49. Baghdadi A, Halim RA, Ghasemzadeh A, Ramlan MF, Sakimin SZ. Impact of organic and inorganic fertilizers on the yield and quality of silage corn intercropped with soybean. Peer J. 2018;6:e5280. https://doi.org/10.7717/peerj.5280

50. Singh K, Joshi YP, Chandra H, Singh DK, Singh R, Kumar M. Effect of integrated nutrient management on growth, productivity and quality of sweet sorghum (*Sorghum bicolor*). Indian J Agron. 2015;60(2):291-6. https://doi.org/10.59797/ija.v60i2.4452

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