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Standardization of NPK Nutrients for improving nutrient uptake and nutrient-use efficiency in sweet corn (*Zea mays* var. *Saccharata*) in the Northern Dry Zone of Karnataka

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Abstract
A field experiment was conducted to evaluate the effect of different NPK fertility levels and split application schedules of nitrogen and potassium on nutrient uptake and nutrient-use efficiency in sweet corn (*Zea mays* var. *saccharata*). Three NPK fertility levels, *viz.,* 50, 75 and 100% of the recommended dose, were evaluated in combination with three nutrient application schedules. Among the fertility levels, application of 100% recommended NPK (150:65:65 kg $NP_2O_5K_2O$ ha^{-1}) recorded the highest uptake of nitrogen (130.59 kg ha^{-1}), phosphorus (27.45 kg ha^{-1}), potassium (127.90 kg ha^{-1}) and sulphur (14.20 kg ha^{-1}). Similarly, four-stage application of nitrogen and potassium at basal, 15, 30 and 45 days after sowing (DAS) resulted in the highest uptake of nitrogen (118.69 kg ha^{-1}), phosphorus (22.98 kg ha^{-1}), potassium (122.00 kg ha^{-1}) and sulphur (11.94 kg ha^{-1}). The highest nitrogen (50.39%) and phosphorus (32.99%) recovery efficiencies among fertility levels were recorded under 100% NPK, whereas potassium recovery efficiency was highest (161.73%) under 50% NPK. Among the application schedules, four-stage splitting recorded the highest recovery efficiencies of nitrogen (56.69%), phosphorus (34.23%) and potassium (164.18%). In contrast, 50% NPK recorded the highest agronomic efficiencies of nitrogen (33.36 kg kg^{-1}) and phosphorus (76.99 kg kg^{-1}), as well as the highest physiological efficiencies of nitrogen (69.52 kg kg^{-1}) and phosphorus (310.87 kg kg^{-1}). The interaction between fertility levels and application schedules significantly influenced agronomic efficiency, with L_1S_2 recording the highest values for nitrogen and phosphorus. Overall, higher NPK fertility enhanced nutrient uptake, while appropriately timed split application improved nutrient recovery and agronomic efficiency in sweet corn.

Keywords: Sweet corn, NPK fertility levels, nutrient uptake, nutrient-use efficiency, recovery efficiency, split application

Introduction

Sweet corn (*Zea mays* var. *saccharata*) is an economically important specialty maize crop valued for its tender, sweet kernels and nutritional quality. Its productivity is largely governed by nutrient availability and the efficiency with which applied nutrients are absorbed and utilized by the crop. Nitrogen (N), phosphorus (P) and potassium (K) are the major macronutrients required for optimum plant growth, biomass accumulation and yield formation. Nitrogen plays a vital role in chlorophyll synthesis, protein formation and photosynthetic activity, while phosphorus supports energy transfer, root development and metabolic processes. Potassium regulates enzymatic activity, water relations and assimilate translocation. Therefore, an adequate and balanced supply of NPK is essential for achieving higher productivity and maintaining soil fertility. However, excessive or poorly synchronized fertilizer application may reduce nutrient recovery and increase the potential for nutrient losses. Nutrient uptake represents the quantity of nutrients accumulated by the crop and is determined by nutrient availability, root absorption and biomass production. Although higher fertilizer application may increase nutrient uptake, the resulting improvement in crop productivity may not be proportional to the quantity of nutrients applied. Hence, nutrient-use efficiency indices provide a more comprehensive assessment of fertilizer performance. Recovery efficiency indicates the proportion of applied nutrients recovered in the crop, agronomic efficiency expresses the increase in crop yield per unit of nutrient applied, and physiological efficiency represents the increase in yield per unit of additional nutrient uptake. Evaluating these indices along with nutrient uptake helps identify fertilizer levels that improve nutrient acquisition while ensuring efficient utilization of applied nutrients.

Apart from the quantity of nutrients applied, the timing of fertilizer application plays a significant role in determining nutrient availability and uptake. Crop nutrient requirements vary with growth stages, and a substantial proportion of nutrient demand occurs during periods of rapid vegetative growth and reproductive development. Applying the entire nitrogen and potassium requirement at planting may not adequately synchronize nutrient availability with crop demand throughout the growing season. Split application at appropriate growth stages can improve nutrient supply during critical periods, potentially enhancing nutrient uptake, fertilizer recovery and crop productivity. Despite the importance of both fertilizer rate and application timing, their combined influence on nutrient uptake and the recovery, agronomic and physiological efficiencies of N, P and K require evaluation under specific crop-growing conditions. In particular, identifying an appropriate NPK fertility level together with a suitable schedule of nitrogen and potassium application could help improve nutrient-use efficiency without compromising crop productivity. Therefore, the present investigation was undertaken to evaluate the effects of different NPK fertility levels and split

application schedules of nitrogen and potassium on N, P, K and sulphur uptake, and the recovery, agronomic and physiological efficiencies of N, P and K in sweet corn (*Zea mays* var. *saccharata*).

Materials and methods

The field experiment was conducted during the *kharif* 2025 season at the Agricultural Research Station, Siruguppa, University of Agricultural Sciences, Raichur, Karnataka, India. The research station is located in Agro-climatic Zone III (Northern Dry Zone) of Karnataka, at an altitude of 358 m above mean sea level. The experimental site represented the typical agro-climatic conditions of the Northern Dry Zone, under which the performance of sweet corn was evaluated.

The experiment was conducted using sweet corn hybrid Sugar-75 in a split-plot design with three replications. The main-plot treatments consisted of three NPK fertility levels, *viz.*, 50% (75:32.5:32.5 kg $NP_2O_5K_2O$ ha^{-1}), 75% (112:48.8:48.8 kg $NP_2O_5K_2O$ ha^{-1}) and 100% (150:65:65 kg $NP_2O_5K_2O$ ha^{-1}) of the recommended dose. The sub-plot treatments comprised three nutrient application schedules: (i) Nand K_2O applied at basal, 15 and 30 days after sowing (DAS); (ii) N and K_2O applied at basal, 15, 30 and 45 DAS; and (iii) P_2O_5 and K_2O applied basally, with nitrogen applied at basal, 15, 30 and 45 DAS. Phosphorus was applied basally in all fertilizer treatments. Thus, nine treatment combinations were evaluated, along with an absolute control maintained outside the factorial experimental layout. The recommended agronomic practices were followed uniformly throughout the crop growth period.

Before the establishment of the experiment, representative soil samples were collected from the 0–15 cm soil depth to determine the initial soil properties. The experimental soil had a bulk density of 1.44 Mg m^{-3}, pH of 8.45, electrical conductivity of 0.38 dS m^{-1} and organic carbon content of 5.90 g kg^{-1}. The initial available nitrogen, phosphorus (P_2O_5) and potassium (K_2O) contents were 248.70, 39.42 and 346.21 kg ha^{-1}, respectively.

At harvest, representative plant samples were collected, oven-dried and ground for nutrient analysis. Total nitrogen was estimated using the Kjeldahl method, phosphorus by the vanadomolybdate phosphoric yellow colour method and potassium by flame photometry (Jackson, 1973) [9]. Nutrient uptake was calculated by multiplying the nutrient concentration by the corresponding dry matter yield and expressing the result on a per-hectare basis. Recovery efficiency (RE), agronomic efficiency (AE) and physiological efficiency (PE) were calculated using the following formulae:

Recovery efficiency (%) = $[(U - U_0)/F] \times 100$

Agronomic efficiency (kg yield kg^{-1} nutrient applied) = $(Y - Y_0)/F$

Physiological efficiency (kg yield kg^{-1} additional nutrient uptake) = $(Y - Y_0)/(U - U_0)$

where, Y and Y_0 represent the crop yield in the fertilized treatment and absolute control, respectively; U and U_0 represent the corresponding total nutrient uptake; and F denotes the quantity of the respective nutrient applied (kg ha^{-1}). The experimental data were subjected to statistical analysis appropriate for a split-plot design, following the procedures described by Gomez and Gomez (1984) [6]. Treatment effects were tested using analysis of variance, and critical differences (CD) were calculated at the 5% probability level wherever the treatment effects were significant.

Results and discussion

Nutrient uptake

Nitrogen uptake

Total nitrogen uptake increased significantly with increasing NPK fertility levels, recording the highest value under L_3 (100% NPK; 130.59 kg ha^{-1}), followed by L_2 (75% NPK; 107.93 kg ha^{-1}) and L_1 (50% NPK; 90.88 kg ha^{-1}), with significant differences among all three levels. The higher N uptake under L_3 may be attributed to improved nutrient availability, balanced NPK nutrition and greater biomass production, collectively favouring N absorption and accumulation. Similar increases in N uptake with increasing fertilizer levels were reported by Jat *et al.* (2021) [10] and Shahin *et al.* (2022) [17]. Among the split application schedules, S_2 (N and K applied at basal, 15, 30 and 45 DAS) recorded the highest N uptake (118.69 kg ha^{-1}), which was significantly higher than S_3 (102.37 kg ha^{-1}) but statistically at par with S_1 (108.34 kg ha^{-1}). The improved uptake under S_2 may be associated with better synchronization of N availability with crop demand during successive growth stages, thereby supporting sustained nutrient absorption. Similar benefits of timely split nutrient application were reported by Anita *et al.* (2007) [2] and Suraj *et al.* (2020) [19].

The interaction between NPK fertility levels and split application schedules was non-significant. Nevertheless, L_3S_2 recorded the highest numerical N uptake (141.73 kg ha^{-1}), whereas L_1S_3 recorded the lowest (82.75 kg ha^{-1}). This numerical trend suggests that higher NPK supply combined with more frequent N application may favour N accumulation; however, the interaction effect was not statistically significant.

Phosphorus uptake

Total phosphorus uptake increased significantly with increasing NPK fertility levels, reaching a maximum of 27.45 kg ha^{-1} under L_3, followed by 19.58 kg ha^{-1} under L_2 and 14.14 kg ha^{-1} under L_1, with significant differences among all three levels. The enhanced P uptake under L_3 may be attributed to improved nutrient availability, greater root development and increased dry matter production under balanced NPK nutrition. Similar increases in P uptake under improved fertility management were reported by Sahoo and Mahapatra (2007) [15] and Shahin *et al.* (2022) [17]. With respect to split application schedules, S_2 recorded the highest P uptake (22.98 kg ha^{-1}), followed by S_1 (19.97 kg ha^{-1}) and S_3 (18.21 kg ha^{-1}), with significant differences among all three schedules. Since P_2O_5 was applied basally across all treatments, the higher P uptake under S_2 may be an indirect response to improved N and K availability, which could have promoted root growth, crop development and P acquisition. Similar improvements in nutrient uptake under favourable nutrient management were reported by Jat *et al.* (2021) [10] and Shahin *et al.* (2022) [17].

The interaction between NPK fertility levels and split application schedules was non-significant. However, L_3S_2 recorded the highest numerical P uptake (30.48 kg ha^{-1}), whereas L_1S_3 recorded the lowest (11.70 kg ha^{-1}). This trend indicates a numerical advantage of higher NPK fertility combined with an appropriate N and K application schedule in promoting P acquisition, although the interaction was not statistically significant. Comparable benefits of balanced

nutrient management on crop nutrient uptake were reported by Ray *et al.* (2020) [14] and Shahin *et al.* (2022) [17].

Potassium uptake

Total potassium uptake increased significantly with increasing NPK fertility levels, recording 97.56, 112.29 and 127.90 kg ha^{-1} under L_1, L_2 and L_3, respectively, with significant differences among all three levels. The higher K uptake under L_3 may be attributed to improved K availability, enhanced nutrient absorption and greater biomass production under balanced NPK nutrition. Similar increases in K uptake with improved nutrient supply were reported by Sahoo and Mahapatra (2007) [15] and Ray *et al.* (2020) [14]. Among the split application schedules, S_2 recorded the highest K uptake (122.00 kg ha^{-1}), followed by S_1 (111.10 kg ha^{-1}) and S_3 (104.67 kg ha^{-1}), with significant differences among all three schedules. The greater uptake under S_2 may be associated with more frequent K application, which could have sustained K availability in the root zone during crop growth and facilitated its absorption and translocation. Similar benefits of split application of N and K on nutrient acquisition and nutrient-use efficiency were reported by Suraj *et al.* (2020) [19].

The interaction between NPK fertility levels and split application schedules was non-significant. Numerically, L_3S_2 recorded the highest K uptake (137.93 kg ha^{-1}), whereas L_1S_3 recorded the lowest (86.55 kg ha^{-1}). This numerical trend suggests that higher NPK fertility combined with more frequent K application may favour K accumulation in the crop; nevertheless, the interaction effect was not statistically significant. Similar improvements in nutrient uptake under balanced nutrient management were reported by Ray *et al.* (2020) and Shahin *et al.* (2022) [17].

Sulphur uptake

Total sulphur uptake increased significantly with increasing NPK fertility levels, with the highest uptake under L_3 (14.20 kg ha^{-1}), followed by L_2 (10.24 kg ha^{-1}) and L_1 (6.97 kg ha^{-1}), with significant differences among all three levels. Although sulphur was not an experimental fertilizer factor, the greater S uptake under L_3 may be attributed to improved crop growth, greater root activity and increased biomass production, which could have enhanced the acquisition of native soil sulphur. Adequate NPK nutrition may also support sulphur assimilation and the synthesis of sulphur-containing compounds. Similar improvements in nutrient accumulation under balanced fertility management were reported by Mehta *et al.* (2005) [11] and Shahin *et al.* (2022) [17]. Among the split application schedules, S_2 recorded the highest S uptake (11.94 kg ha^{-1}), which was significantly higher than S_1 (10.38 kg ha^{-1}) and S_3 (9.09 kg ha^{-1}). The greater uptake under S_2 may be associated with improved N and K availability during crop growth, supporting biomass production and subsequent sulphur accumulation. This response highlights the potential importance of synchronizing nutrient supply with crop demand in improving overall nutrient acquisition, as also discussed by Mehta *et al.* (2005) [11] and Suraj *et al.* (2020) [19].

The interaction between NPK fertility levels and split application schedules was non-significant for S uptake. However, L_3S_2 recorded the highest numerical uptake (15.89 kg ha^{-1}), whereas L_1S_3 recorded the lowest (5.43 kg ha^{-1}). These numerical differences may reflect variations in crop growth and overall nutrient acquisition among treatment combinations, but do not establish a significant interaction. The importance of balanced nutrient availability in promoting crop growth and nutrient accumulation was also emphasized by Havlin *et al.* (2014) [8] and Mehta *et al.* (2005) [11].

Efficiencies of NPK nutrients

Recovery efficiency (RE) of nitrogen

Nitrogen recovery efficiency was significantly influenced by NPK fertility levels, with the highest RE recorded under L_3 (100% NPK; 50.39%), followed by L_1 (50% NPK; 47.84%) and L_2 (75% NPK; 47.05%). L_3 recorded significantly higher RE than L_1 and L_2, whereas the latter two were statistically at par. The higher RE under L_3 may be attributed to improved nutrient availability and greater crop growth, resulting in enhanced recovery of applied N. Among the split application schedules, S_2 (N and K applied at basal, 15, 30 and 45 DAS) recorded the highest RE (56.69%), followed by S_1 (47.32%) and S_3 (41.27%), with significant differences among all three schedules. The superior performance of S_2 may be associated with better synchronization of N supply with crop demand, thereby enhancing N absorption and potentially reducing nutrient losses. The importance of balanced nutrient supply and appropriately timed fertilizer application in improving nutrient recovery has been emphasized by Fageria and Baligar (2005) [5] and Anita *et al.* (2007) [2]. Similar findings were reported by Gulshan *et al.* (2025) [7] and Sangeen *et al.* (2025) [16].

The interaction between NPK fertility levels and split application schedules was non-significant. Nevertheless, L_1S_2 recorded the highest numerical RE (58.56%), followed by L_3S_2 (57.82%), whereas L_1S_3 recorded the lowest value (37.00%). The numerical advantage of L_1S_2 may be associated with a lower N application rate combined with frequent nutrient application, resulting in a greater proportion of applied N being recovered by the crop. However, this trend does not establish a statistically significant interaction.

Agronomic efficiency (AE) of nitrogen

Agronomic efficiency of N was significantly influenced by NPK fertility levels, with the highest value recorded under L_1 (50% NPK; 33.36 kg kg^{-1}), followed by L_2 (75% NPK; 27.31 kg kg^{-1}) and L_3 (100% NPK; 25.96 kg kg^{-1}). L_1 recorded significantly higher AE than L_2 and L_3, whereas the latter two were statistically at par. The higher AE under L_1 indicates a greater yield response per unit of N applied, while the decline at higher fertility levels suggests a diminishing marginal yield response to additional N. Among the split application schedules, S_2 recorded the highest AE (33.52 kg kg^{-1}), significantly exceeding S_1 (28.58 kg kg^{-1}) and S_3 (24.53 kg kg^{-1}); S_1 was also significantly superior to S_3. The higher AE under S_2 may be attributed to improved synchronization of N availability with crop demand during active growth stages, resulting in a greater yield response per unit of applied N. These findings are consistent with the observations of Tilahun *et al.* (2013) [20] and Pandey *et al.* (2025) [13], who highlighted the influence of nutrient application strategies and crop response on agronomic efficiency.

The interaction between NPK fertility levels and split application schedules significantly influenced N agronomic efficiency. L_1S_2 recorded the highest AE (41.17 kg kg^{-1}),

which was significantly superior to all other treatment combinations, whereas L_3S_3 recorded the lowest value (24.04 kg kg^{-1}). The superior performance of L_1S_2 may be attributed to the combined advantage of a lower N application rate and more frequent nutrient application, resulting in a greater yield response per unit of N applied. This emphasizes the importance of optimizing fertilizer rates and application schedules to improve agronomic efficiency, as also discussed by Dobermann (2007).

Physiological efficiency (PE) of nitrogen

Nitrogen physiological efficiency was significantly influenced by NPK fertility levels, with the highest PE recorded under L_1 (69.52 kg kg^{-1}), followed by L_2 (58.16 kg kg^{-1}) and L_3 (51.66 kg kg^{-1}). L_1 recorded significantly higher PE than L_2 and L_3, whereas the latter two were statistically at par. The higher PE under L_1 indicates more efficient conversion of additional N uptake into yield, whereas the lower values at higher fertility levels suggest that increased N uptake was not accompanied by a proportional increase in yield. This decline may reflect differences in the efficiency of utilizing absorbed N for yield formation under varying fertility levels. Split application schedules did not significantly influence N physiological efficiency. Numerically, S_1 recorded the highest PE (60.45 kg kg^{-1}), followed by S_3 (59.88 kg kg^{-1}) and S_2 (59.01 kg kg^{-1}). Although S_2 recorded higher N uptake and recovery efficiency, this was not accompanied by a corresponding increase in physiological efficiency, indicating that greater nutrient recovery does not necessarily result in more efficient conversion of absorbed N into yield.

The interaction between NPK fertility levels and split application schedules was non-significant. Numerically, L_1S_1 recorded the highest PE (70.78 kg kg^{-1}), followed by L_1S_2 (70.30 kg kg^{-1}), whereas L_3S_1 recorded the lowest value (50.44 kg kg^{-1}). The higher numerical PE under L_1S_1 may indicate more efficient conversion of additional N uptake into yield at the lower fertility level. Conversely, the lower PE under L_3S_1 suggests that greater N uptake was not matched by a proportional yield response. These findings highlight the distinction between nutrient recovery and the subsequent utilization of absorbed nutrients for yield formation, as explained by Fageria and Baligar (2005) [5] and Dobermann (2007) [3].

Phosphorus-use efficiency

Recovery efficiency (RE) of phosphorus

Phosphorus recovery efficiency (RE) was significantly influenced by fertility levels and split application schedules. Among the fertility levels, L_3 recorded the highest RE (32.99%), followed by L_2 (27.83%) and L_1 (25.92%). L_3 was significantly superior to L_1 and L_2, whereas the latter two were statistically at par. The improved recovery under L_3 may be attributed to balanced nutrient availability, enhanced root development and greater phosphorus acquisition. Fageria and Baligar (2005) highlighted the importance of balanced nutrition in improving nutrient recovery, which is consistent with the findings of Nagendrachari *et al.* (2026) [12].

Among the split application schedules, S_2 recorded the highest RE (34.23%), followed by S_1 (27.96%) and S_3 (23.67%), with all three schedules differing significantly. The higher recovery under S_2 may be associated with better synchronization of nitrogen and potassium supply with crop demand, thereby supporting root activity and phosphorus uptake. The interaction effect was non-significant; however, L_3S_2 recorded the highest numerical RE (37.66%), followed by L_2S_2 (32.75%) and L_1S_2 (32.28%), while L_1S_3 recorded the lowest value (17.54%). These numerical differences suggest a possible advantage of combining adequate fertility with an appropriate nutrient application schedule, although the interaction was not statistically significant.

Agronomic efficiency (AE) of phosphorus

Phosphorus agronomic efficiency (AE) was significantly higher under L_1 (76.99 kg kg^{-1}), followed by L_2 (62.95 kg kg^{-1}) and L_3 (59.92 kg kg^{-1}), with L_2 and L_3 being statistically at par. The greater AE under L_1 indicates a higher yield response per unit of phosphorus applied, whereas the lower values at higher fertility levels may reflect a diminishing marginal yield response to additional nutrient input. This relationship between nutrient application and yield response has been discussed by Dobermann (2007) [3], while similar trends were reported by Dutta *et al.* (2025) [4]. Among the split application schedules, S_2 recorded the highest AE (77.33 kg kg^{-1}), followed by S_1 (65.93 kg kg^{-1}) and S_3 (56.60 kg kg^{-1}), with significant differences among all three schedules. The improved AE under S_2 may be attributed to better synchronization of nutrient availability with crop demand, resulting in a greater yield response. Similar benefits of appropriately timed nutrient application were reported by Anita *et al.* (2007) [2] and Tilahun *et al.* (2013) [20].

The interaction between fertility levels and split application schedules significantly influenced phosphorus AE. The L_1S_2 combination recorded the highest value (95.00 kg kg^{-1}), which was significantly superior to all other combinations, whereas L_3S_3 recorded the lowest AE (55.48 kg kg^{-1}). The higher efficiency under L_1S_2 indicates that a relatively lower phosphorus input, combined with an appropriate nutrient application schedule, resulted in a greater yield response per unit of phosphorus applied.

Physiological efficiency (PE) of phosphorus

Phosphorus physiological efficiency (PE) differed significantly among fertility levels, with L_1 recording the highest value (310.87 kg kg^{-1}), followed by L_2 (227.82 kg kg^{-1}) and L_3 (181.82 kg kg^{-1}); all three levels differed significantly. The higher PE under L_1 indicates more efficient conversion of additionally absorbed phosphorus into economic yield. In contrast, the greater phosphorus uptake under higher fertility levels was not accompanied by a proportional increase in yield, resulting in lower PE. This inverse relationship between nutrient uptake and physiological efficiency under increasing nutrient supply was also discussed by Fageria and Baligar (2005) [5]. Among the split application schedules, S_3 recorded the highest PE (251.61 kg kg^{-1}), which was statistically at par with S_1 (240.30 kg kg^{-1}), but significantly higher than S_2 (228.60 kg kg^{-1}). The comparatively higher PE under S_3 suggests more efficient conversion of absorbed phosphorus into economic yield, whereas the greater phosphorus uptake under S_2 did not result in a proportionate yield advantage. Similar variations in nutrient-use efficiency in response to nutrient management practices were reported by Dutta *et al.* (2025) [4].

The interaction effect on phosphorus PE was non-significant. Nevertheless, L_1S_3 recorded the highest

numerical PE (328.56 kg kg^{-1}), whereas L_3S_2 recorded the lowest (179.05 kg kg^{-1}). The higher numerical value under L_1S_3 indicates greater yield production per unit of additional phosphorus uptake, while the lower value under L_3S_2 suggests that increased phosphorus acquisition was not matched by a proportional yield increase. As emphasized by Dobermann (2007) [3], greater nutrient uptake does not necessarily translate into higher physiological efficiency.

Potassium-use efficiency

Recovery efficiency (RE) of potassium

Potassium recovery efficiency (RE) was significantly influenced by NPK fertility levels and split application schedules. Among the fertility levels, L_1 recorded the highest RE (161.73%), followed by L_2 (137.90%) and L_3 (127.54%). L_1 was significantly superior to the other two levels, whereas L_2 and L_3 were statistically at par. The higher recovery under L_1 indicates a greater proportion of applied potassium was recovered by the crop at the lower fertility level, while increased K input at higher fertility levels did not result in a proportional increase in recovery. Fageria and Baligar (2005) [5] explained that nutrient recovery efficiency is governed by the relationship between nutrient application and crop uptake, and similar trends were reported by Ajmal *et al.* (2024) [1]. Among the split application schedules, S_2 recorded the highest RE (164.18%), followed by S_1 (139.41%) and S_3 (123.59%), with all three schedules differing significantly. The improved recovery under S_2 may be associated with better synchronization of potassium availability with crop demand, thereby supporting K absorption during active crop growth. The interaction effect was non-significant; however, L_1S_2 recorded the highest numerical RE (199.57%), followed by L_1S_1 (157.78%), whereas L_3S_3 recorded the lowest (116.65%). These numerical trends suggest that a lower K input combined with an appropriate application schedule may improve the proportion of applied K recovered by the crop, although the interaction was not statistically significant.

Agronomic efficiency (AE) of potassium

Potassium agronomic efficiency (AE) was significantly higher under L_1 (76.99 kg kg^{-1}), followed by L_2 (62.95 kg kg^{-1}) and L_3 (59.92 kg kg^{-1}), with L_2 and L_3 being statistically at par. The higher AE under L_1 indicates a greater yield response per unit of potassium applied, whereas the lower values at higher fertility levels may reflect a diminishing marginal response to additional K input. Similar variations in potassium-use efficiency under different nutrient management levels were reported by Sharma and Singh (2021) [18]. Among the split application schedules, S_2 recorded the highest AE (77.33 kg kg^{-1}), followed by S_1 (65.93 kg kg^{-1}) and S_3 (56.60 kg kg^{-1}), with significant differences among all three schedules. The higher AE under S_2 may be attributed to better synchronization of K availability with crop demand, resulting in improved yield response per unit of applied potassium. The benefits of appropriately timed nutrient application in enhancing nutrient-use efficiency have also been reported by Anita *et al.* (2007) [2] and Tilahun *et al.* (2013) [20].

The interaction between fertility levels and split application schedules significantly influenced potassium AE. L_1S_2 recorded the highest AE (95.00 kg kg^{-1}), significantly superior to the other treatment combinations. L_1S_1 (78.33 kg kg^{-1}) and L_2S_2 (69.56 kg kg^{-1}) were statistically at par, while L_3S_2 recorded 67.43 kg kg^{-1} and was at par with several lower-valued combinations. The higher AE under L_1S_2 indicates that the lower K application level, when combined with the S_2 schedule, produced a greater yield response per unit of potassium applied. This is consistent with the findings of Sharma and Singh (2021) [18].

Physiological efficiency (PE) of potassium

Potassium physiological efficiency (PE) was not significantly influenced by NPK fertility levels. Numerically, L_1 recorded the highest PE (47.44 kg kg^{-1}), followed by L_3 (46.98 kg kg^{-1}) and L_2 (45.61 kg kg^{-1}). The marginal numerical variation among fertility levels suggests that increasing nutrient supply did not substantially alter the conversion of additionally absorbed potassium into economic yield. As discussed by Fageria and Baligar (2005) [5] and Dobermann (2007) [3], physiological efficiency is determined by the extent to which absorbed nutrients contribute to yield formation. Similarly, split application schedules had no significant effect on potassium PE. S_1 recorded the highest numerical value (47.14 kg kg^{-1}), followed closely by S_2 (47.05 kg kg^{-1}) and S_3 (45.84 kg kg^{-1}). The small numerical differences indicate that the application schedules did not significantly alter the efficiency of converting absorbed potassium into economic yield, despite their differences in recovery efficiency.

The interaction effect on potassium PE was also non-significant. Numerically, L_1S_1 recorded the highest PE (49.65 kg kg^{-1}), followed by L_3S_3 (47.56 kg kg^{-1}), whereas L_2S_3 recorded the lowest value (44.88 kg kg^{-1}). These numerical variations indicate differences in the conversion of absorbed potassium into yield among treatment combinations; however, they were not statistically significant. The findings reinforce the distinction between nutrient recovery and physiological efficiency, as higher nutrient uptake does not necessarily translate into a proportionate increase in economic yield (Ajmal *et al.*, 2024) [1].

Table 1: Uptake N, P, K and S by sweet corn crop at harvest as influenced by different levels of NPK

Treatments	N uptake (kg ha^{-1})	P uptake (kg ha^{-1})	K uptake (kg ha^{-1})	S uptake (kg ha^{-1})
Factor I (L): (Levels of N, P_2O_5 and K_2O kg ha^{-1})				
L_1: 50% NPK (75:32.5:32.5 kg NPK ha^{-1})	90.88	14.14	97.56	6.97
L_2: 75% NPK (112:48.8:48.8 kg NPK ha^{-1})	107.93	19.58	112.29	10.24
L_3: 100% NPK (150:65:65 kg NPK ha^{-1})	130.59	27.45	127.90	14.20
S.Em. ±	3.62	0.81	3.97	0.35
C.D. (P=0.05)	14.21	3.17	15.59	1.36
Factor II (S): (Split application of N and K_2O)				
S_1: N and K_2O at basal, 15 and 30 DAS (3 equal splits @ 33%)	108.34	19.97	111.10	10.38

S_2: N and K_2O at basal, 15, 30 and 45 DAS (4 equal splits @ 25%)	118.69	22.98	122.00	11.94
S_3: N at basal, 15, 30 and 45 DAS (4 equal splits @ 25%)	102.37	18.21	104.67	9.09
S.Em. ±	3.64	0.80	3.47	0.20
C.D. (P=0.05)	11.20	2.46	10.71	0.60
Interactions				
L_1S_1	90.97	14.22	96.28	7.06
L_1S_2	98.92	16.49	109.86	8.41
L_1S_3	82.75	11.70	86.55	5.43
L_2S_1	105.81	19.28	112.06	10.21
L_2S_2	115.41	21.98	118.20	11.51
L_2S_3	102.56	17.48	106.63	9.01
L_3S_1	128.24	26.40	124.96	13.87
L_3S_2	141.73	30.48	137.93	15.89
L_3S_3	121.80	25.46	120.82	12.85
S.Em. ±	6.29	1.39	6.32	0.44
C.D. (P=0.05)	NS	NS	NS	NS
Absolute control	55.00	6.00	45.00	3.14

Note: P applied as basal @ 100 % in S_1 and S_2; P & K applied as basal @ 100 % in S_3

Table 2: Recovery efficiency (%), Agronomic efficiency (kg kg^{-1}) and Physiological efficiency (kg kg^{-1}) of Nitrogen, phosphorous and potassium as influenced by different levels of NPK

Treatments	Nitrogen			Phosphorus			Potassium		
	RE (%)	AE (kg kg^{-1})	PE (kg kg^{-1})	RE (%)	AE (kg kg^{-1})	PE (kg kg^{-1})	RE (%)	AE (kg kg^{-1})	PE (kg kg^{-1})
Factor I (L): (Levels of N, P_2O_5 and K_2O kg ha^{-1})									
L_1: 50% NPK (75:32.5:32.5 kg NPK ha^{-1})	47.84	33.36	69.52	25.92	76.99	310.87	161.73	76.99	47.44
L_2: 75% NPK (112:48.8:48.8 kg NPK ha^{-1})	47.05	27.31	58.16	27.83	62.95	227.82	137.90	62.95	45.61
L_3: 100% NPK (150:65:65 kg NPK ha^{-1})	50.39	25.96	51.66	32.99	59.92	181.82	127.54	59.92	46.98
S.Em. ±	0.55	1.15	2.23	1.14	2.67	4.11	3.72	1.92	1.40
C.D. (P=0.05)	2.15	4.50	8.75	4.47	10.47	16.15	14.59	7.54	NS
Factor II (S): (Split application of N and K_2O)									
S_1: N and K_2O at basal, 15 and 30 DAS (3 equal splits @ 33%)	47.32	28.58	60.45	27.96	65.93	240.30	139.41	65.93	47.14
S_2: N and K_2O at basal, 15, 30 and 45 DAS (4 equal splits @ 25%)	56.69	33.52	59.01	34.23	77.33	228.60	164.18	77.33	47.05
S_3: N at basal, 15, 30 and 45 DAS (4 equal splits @ 25%)	41.27	24.53	59.88	23.67	56.60	251.61	123.59	56.60	45.84
S.Em. ±	1.07	0.84	1.15	0.81	2.01	4.00	4.74	1.94	1.52
C.D. (P=0.05)	3.30	2.60	NS	2.49	6.20	12.31	14.59	5.97	NS
Interactions									
L_1S_1	47.96	33.94	70.78	25.29	78.33	309.71	157.78	78.33	49.65
L_1S_2	58.56	41.17	70.30	32.28	95.00	294.33	199.57	95.00	47.60
L_1S_3	37.00	24.97	67.49	17.54	57.62	328.56	127.85	57.62	45.07
L_2S_1	45.16	27.16	60.14	27.21	62.61	230.08	137.42	62.61	45.56
L_2S_2	53.70	30.17	56.19	32.75	69.56	212.41	150.00	69.56	46.37
L_2S_3	42.28	24.59	58.16	23.52	56.69	240.96	126.29	56.69	44.88
L_3S_1	48.83	24.63	50.44	31.38	56.84	181.09	123.02	56.84	46.20
L_3S_2	57.82	29.22	50.54	37.66	67.43	179.05	142.97	67.43	47.17
L_3S_3	44.53	24.04	53.99	29.94	55.48	185.32	116.65	55.48	47.56
S.Em. ±	1.61	1.65	2.76	1.61	3.90	6.99	7.66	3.34	2.57
C.D. (P=0.05)	NS	5.10	NS	NS	12.01	NS	NS	10.30	NS

Note: P applied as basal @ 100 % in S_1 and S_2; P & K applied as basal @ 100 % in S_3

Conclusion

The study demonstrated that application of 100% recommended NPK (150:65:65 kg $NP_2O_5K_2O$ ha^{-1}) maximized the uptake of nitrogen (130.59 kg ha^{-1}), phosphorus (27.45 kg ha^{-1}), potassium (127.90 kg ha^{-1}) and sulphur (14.20 kg ha^{-1}) in sweet corn. Among the nutrient application schedules, applying nitrogen and potassium at basal, 15, 30 and 45 days after sowing (S_2) resulted in the highest uptake of all four nutrients, along with the highest recovery efficiencies of N (56.69%), P (34.23%) and K (164.18%) and the highest agronomic efficiencies of these nutrients. In contrast, the 50% recommended NPK level (L_1) recorded the highest agronomic efficiencies of N and P and physiological efficiencies of both nutrients, indicating that increased fertilizer application did not necessarily improve nutrient-use efficiency. The L_1S_2 combination recorded the highest agronomic efficiencies of N and P, whereas interaction effects on nutrient uptake and most other

nutrient-use efficiency indices were non-significant. Overall, the findings indicate that 100% recommended NPK is effective in maximizing nutrient uptake, while four-stage split application of N and K improves nutrient recovery and agronomic efficiency. Thus, integrating an appropriate fertilizer dose with suitable application scheduling is important for enhancing nutrient utilization and productivity of sweet corn.

Disclaimer (Artificial Intelligence)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript. Acknowledgements

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Competing Interests

The authors declare that they have no competing interests.

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