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Research article

Unlocking growth potential: Synergistic potassium fertilization for enhanced yield, nutrient uptake, and energy fractions in Chinese cabbage

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ABSTRACT

The implementation of integrated potassium management presents a viable approach for augmenting plant growth, yield, and nutrient uptake while enhancing soil nutrient availability. A field experiment was executed during the rabi season of 2020, employing a randomized complete block design encompassing eight treatments involving standard (100%) and reduced (75% and 50%) rates of the recommended dose of potassium (RDK) administered through muriate of potash (MOP). Treatments included variations in the incorporation/exclusion of plant growth-promoting rhizobacteria (PGPR), farmyard manure (FYM) at 25% of potassium recommendation, and foliar application of nano potash. The use of 100% RDK +25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS (T_8) exhibited significant enhancements in green fodder yield (64.0 ± 2.2 t ha^{-1}) over control with no potassium application (47.3 ± 3.7 t ha^{-1}) and found at par with and 75% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS (T_7). These treatments yielded maximum percent increase for plant height (34.9%), leaf count (38.5%), leaf dimensions (28.8–31.5%), stem girth (25.84%), root volume (27.0%), and root length (37.64%), observed at the harvest stage compared to control (T_1-no potassium application). The treatment T_8 was on par with T_7 and recorded highest uptake of macro (N, P, and K) and micro (Zn, Fe, Cu, and Mn) nutrients. While soil parameters

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such as available nitrogen and potassium levels were notably increased through the application of treatment T_7 across various treatment combinations and found significantly superiority over treatment T_8. Multivariate analysis also highlighted treatment T_7 is more efficient in maintaining sustainability. Hence, based on the present findings it can be concluded that application of 75% RDK +25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS (T_7) can be recommended for achieving enhanced productivity and soil fertility improvement within agricultural systems.

1. Introduction

High-quality forage plays a pivotal role in enhancing animal productivity through multifaceted mechanisms [1]. It serves as a primary source of indispensable nutrients, encompassing proteins, carbohydrates, vitamins, and minerals, crucial for the development of musculature, bones, and visceral organs [2–4]. Moreover, superior forage supports reproductive endeavours by ensuring optimal fecundity and reproductive prowess in animals [5–8]. Proficient nourishment from high quality forage is essential for effective copulation, conception, and the birthing of robust progeny [5,9]. Additionally, preeminent forage plays a crucial role in lactogenesis, providing the necessary nutrients for milk biosynthesis, resulting in increased output and enhanced product quality [10–12]. Noteworthy improvements in milk composition, characterized by heightened protein and lipid contents, are also attendant upon the provision of nutrient-rich fodder [10,13,14]. Beyond the purview of growth and procreation, high-caliber forage occupies a pivotal role in the sphere of pathogenic resistance [15,16]. Livestock that partake of a well-calibrated dietary regimen manifest heightened aptitude in warding off pathogenic onslaughts [17]. Specific nutrients such as vitamins A, C, and E, alongside trace minerals like zinc and selenium, conspire to bolster an efficacious immune milieu, thereby curtailing susceptibility to maladies and engendering holistic well-being [18,19]. The utilization of Chinese cabbage (*Brassica rapa* subsp. *pekinensis*) as a livestock forage holds promise in augmenting nutrient assimilation and overall productivity, providing essential vitamins, minerals, and dietary fibers [20]. Chinese cabbage contributes to holistic vitality, supporting growth, immune responsiveness, and reproductive aptitude in livestock [20,21].

Potassium (K), an ineluctable botanical nutrient, exerts a pivotal sway over plant ontogeny and physiological processes of manifold import [22,23]. Noteworthy contributions encompass photosynthesis, nutrient assimilation, and hydraulic homeostasis [24,25]. Insufficiency of K reserves within the edaphic milieu precipitates a constricting milieu wherein these operations become truncated, culminating in diminished phytogenic expansion and concomitant abatement of crop yields [26–28]. The dearth of K precipitates concomitant dysregulation in the uptake of critical nutrients such as nitrogen (N) and phosphorous (P), thus propagating disarray in nutrient equilibrium and deployment, thereby further attenuating the comprehensive fecundity and developmental propensities of forage crops [29,30]. Subpar K levels exact a toll upon root development within forage crops, an exigent facet in nutrient and moisture acquisition, as well as the anchoring of vegetative constituents within the soil matrix [31,32]. Inadequate K endowments yield superficial rhizogenic systems, in turn engendering curtailed access to nutritive substances and aqueous endowments [33]. Potassium insufficiency reverberates onto the nutritional profile of forage crops, modulating the accrual of carbohydrates, proteins, and other indispensable nutrients, precipitating a diminution in nutritional value [34]. Forage evincing depleted K content may exhibit attenuated digestibility and energy content, thereby potentiating a derogatory impact upon the zootechnical exhibition and productiveness of livestock [16]. Counteraction of subpar K state within the soil milieu, together with the amelioration of yield and quality attributes within forage crops, conveys imperativeness predicated upon judicious pedological stewardship [35].

This research gap holds substantial ramifications, evident from documented evidence indicating a declining net K balance, from −3.29 million tonnes (Mt) in 2000–01 to a more pronounced −7.2 Mt by 2015–16 in Indian subcontinent [36]. The persistent depletion of soil K, coupled with consequential shifts in K-bearing mineral composition, exerts adverse effects on soil fertility and crop productivity [36]. The overreliance on chemical fertilizers not only disrupts soil ecology and reduces fertility but also perturbs environmental equilibrium, contaminates groundwater, and negatively affects human well-being [37,38].

In light of these considerations, the adoption of an integrated K management strategy emerges as pivotal, contributing to enhanced soil quality, augmented crop yield, and long-term agricultural sustainability [39,40]. As an integral tactics in nutrients management, using different types of fertilizers contributes in enhancing soil health and crop productivity [41–43]. In this connection, organic fertilizers had the potential to improve soil properties via adjusting soil acidity due to supplying with humic acids which enhance crop growth [44,45]. Also, as a comparing with mineral nutrition, various organic fertilizers dramatically improved crop yield and quality [46]. Furthermore, providing soils with the beneficial products such as humus which release as a result of organic matter decomposition showed enhancements in microorganisms activity and enhanced crop yields [47]. Moreover inoculation of bio inoculants stimulates nutrient uptake for crop growth [48]. One the other side, the use of nutrients in nano form exhibited distinctive improvements in nutrient utilization and plant production [49,50]. Earlier many researches had been conducted in isolation or in combination with RDK with PGPR/FYM/nano potash in field crops but there exists a paucity of comprehensive data pertaining effect of combined use of these sources of potassium on crop growth, yield, energy fractions and soil fertility. Hence, the present study aimed to judiciously utilize the MOP, FYM, PGPR, and foliar spray of nano potash, collectively to fulfil the intricate nutritional demands of Chinese cabbage to improve the growth, yield, and energy fractions without deteriorating the soil fertility.

Within this context, there exists a compelling research gap that warrants an experimental inquiry into the specific impact of K application on Chinese cabbage. This investigation holds the potential to contribute valuable insights toward the cultivation of high-quality fodder with high yield, thereby bolstering animal productivity and fostering advancements in sustainable agricultural practices.

2. Materials and methods

2.1. PGPR formulation

A PGPR formulation “NPK liquid biofertilizer” was obtained from Division of Microbiology, ICAR-Indian Agricultural Research Institute, New Delhi for present study. This formulation is consisting of three different microbial strains namely *Azotobacter chroococcum* (N_2 fixing bacteria), *Pseudomonas straita* (P-solubilizing bacteria), and *Bacillus decolorationis* (K-solubilizing bacteria). Each bacterial strain contains 10^9 or greater CFU/mL in formulation.

2.2. Experimental site

In the winter of 2020, an empirical investigation was undertaken at the research farm within the agronomy section of the ICAR-National Dairy Research Institute, situated in Karnal, Haryana. Geospatial coordinates indicated that the experimental site was positioned at 29°45′ N latitude and 76°58′ E longitude, maintaining an elevation of 245 m above sea level. The prevailing climatic dynamics of the locale are characterized by North-East monsoon precipitation during the winter season and South-West monsoon rainfall during the rainy period. For the period spanning October to December of 2020, meteorological records for this vicinity documented a cumulative precipitation of 43.6 mm. The zenith of relative humidity, reaching 98.3 percent on average, was distinctly marked during the 46th standard week (November 12th to November 18th). The crop development phase in the 40th standard week bore witness to the most elevated rate of evaporation, quantified at 4.8 mm per day, accompanied by a zenithal temperature of 34.5 °C and an insolation duration of 8.6 h daily. A comprehensive analysis of the physical and chemical attributes characterizing the soil within the experimental field. The soil’s textural classification identifies it as clay loam. Notably, the electrical conductivity (EC) registers at 0.286 dSm^{-1}, and soil’s pH measurement is recorded at 7.46. The organic carbon content of the soil stands at 0.66%, a factor that contributes substantively to its overall fertility profile. Pertaining to nutrient availability, noteworthy quantities include 198 kg ha^{-1} of accessible N, 29.1 kg ha^{-1} of accessible P, and 235 kg ha^{-1} of accessible K. Additionally, the soil accommodates trace elements, specifically 0.665 parts per million (ppm) of zinc (Zn), 9.998 ppm of iron (Fe), 6.561 ppm of manganese (Mn), and 0.876 ppm of copper (Cu). Collectively, these enumerated properties furnish valuable insights into the soil’s intricate constitution and its potential capacity to underpin crop cultivation and resultant agricultural productivity.

The sowing was performed in the 8th day of October month during 2020. The experimental trial was executed following a randomized complete block design comprising eight distinct treatments, each of which was replicated three times. The treatments encompassed the following categorizations: T_1 - control (No K); T_2 - recommended dose of potassium fertilizer (RDK) via muriate of potash (MOP); T_3 - 75% RDK (MOP) + nano K fertilizer spray at 25 and 40 days after sowing (DAS); T_4 - 50% RDK + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_5 - 75% RDK + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_6 - 50% RDK+25% K infusion through FYM + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_7 - 75% RDK + 25% K enrichment through FYM + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_8 - 100% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS.

The experimental plot was meticulously prepared, and the preliminary evaluation of soil fertility entailed systematic soil sampling employing a zig-zag approach. During the definitive land preparation phase, thoroughly decomposed FYM was judiciously administered at a rate of 25% of the stipulated K dose (2 t ha^{-1}), meticulously aligned with the designated treatment regimen. In anticipation of sowing, the seeds were subjected to a bio-inoculant treatment involving PGPR and were subsequently subjected to an overnight resting period in subdued lighting. Subsequent to sowing, a basal application strategy was executed, wherein half of the prescribed N dosage was disseminated through urea, along with P administered through diammonium phosphate (DAP) at the rate of 120 kg ha^{-1} N and 60 kg ha^{-1} P. The N and P contents intrinsic to DAP and FYM were judiciously calibrated within the treatment schemes, resulting in compensatory adjustments concerning the quantities of urea and DAP. The residual N component was subsequently delivered in a divided fashion, timed to coincide with the 30 DAS interval. Potassium supplementation was administered via a varied assortment of sources, the specifics of which were in accordance with the treatment stipulations, involving MOP and nano potash. The entire quantum of MOP was implemented as an initial dose, while nano potash was tactically dispensed through foliar application, synchronized to the temporal landmarks of 25 and 40 DAS. The plantation of Chinese cabbage ensued, with row-wise demarcations maintaining a separation of 30 cm, and a spatial configuration of 10 cm between individual plants, utilizing a seeding rate of 4 kg ha^{-1}.

2.3. Plant sampling, chemical analysis and parameter calculation

Throughout the course of the crop growth period, dry matter accumulation, leaf area, and leaf area index were systematically assessed at 15 DAS, 30 DAS, 45 DAS and at harvest (60 DAS), employing a sampling regimen involving five arbitrarily selected plants derived from the designated net plot area. Whereas, growth parameters such as plant height, leaf count, leaf length, leaf width, stem girth, leaf: stem ratio, root length and root volume and yield were recorded at harvest (60 DAS). The evaluation encompassed several pivotal attributes including plant height (cm), leaf length, leaf width, and primary root length, with quantification facilitated by the utilization of a meter scale. Stem girth, a significant indicator of plant development, was meticulously gauged through the utilization of vernier calipers. Root volume, a paramount measure of subterranean expansion, was quantified utilizing the volume displacement method [51], which hinged upon the determination of water volume displaced during submergence of plant tissue within a receptacle of water.

To mitigate potential border effects, the harvest of Chinese cabbage was executed by preserving a 0.5 m stretch along each periphery of the experimental plot. A randomized selection protocol was enacted for the retrieval of plants from each field plot, subsequently segregating the sampled plants into discrete categories of leaf, stem, and root components. Rigorous cleansing procedures were observed for the root segment, entailing sequential washing with tap water followed by a triadic rinsing sequence with deionized water or distilled water. The partitioned plant components were subjected to incremental air drying, succeeded by desiccation within an oven at a consistent temperature of 60 °C until a state of constant weight was achieved. The ensuing dried samples were systematically weighed and subsequently processed using a Wiley mill to attain finely ground specimens, requisite for the determination of nutrient concentration.

The quantification of nutrient uptake entailed the multiplication of the ascertained nutrient concentrations with the corresponding yield of Chinese cabbage stover for each designated treatment scenario. The underlying soil matrix was subjected to comprehensive analysis, encompassing soil pH, electrical conductivity (EC), organic carbon content, as well as the availability of N, P, and K, specifically within the soil stratum extending from 0 to 15 cm depth. The evaluation of organic carbon content was executed via the Wet oxidation-reduction titration method, whereas the determination of available soil N was facilitated through the alkaline permanganate method. For the quantification of P and K, the respective Olsen's and Ammonium acetate extractant methods were implemented. Further scrutiny of micronutrient content was undertaken employing the DTPA extraction procedure, with subsequent quantification being accomplished through the utilization of Atomic Absorption Spectroscopy (AAS).

2.4. *Estimation of energy fractions in maize fodder*

Various equations were employed to estimate distinct energy fractions within the fodder maize crop. The determination of digestible energy (DE) was carried out utilizing equations (1) and (2), as provided by Fonnesbeck et al., 1984 [52]. To evaluate the digestible feed energy (DFE), equation (3), established by Bull, 1981 [53], was applied. The estimation of metabolizable energy (ME) was executed through the utilization of equation (4), as presented by Gonzalez, 1982 [54], while the computation of net energy (NE) content in maize fodder was accomplished using equation (5), outlined by Riviere, 1977 [55].

$$\mathrm{DE}\ \left(\mathrm{Mcal\ kg^{-1}}\right) = 0.27 + [0.0428X\ \mathrm{DMD}\ (\%)] \qquad \text{equation 1}$$

$$\mathrm{DE}\ \left(\mathrm{MJ\ kg^{-1}}\right) = \mathrm{DE}\ \left(\mathrm{Mcal\ kg^{-1}}\right) X\ 4.184 \qquad \text{equation 2}$$

$$\mathrm{DFE}\ \left(\mathrm{MJ\ kg^{-1}}\right) = \left[\frac{4.4\times\ \mathrm{TDN}\ (\%)}{100}\right] X4.184 \qquad \text{equation 3}$$

$$\mathrm{ME}\ \left(\mathrm{MJ\ kg^{-1}}\right) = \mathrm{DE}\left(\mathrm{MJ\ kg^{-1}}\right) x0.821 \qquad \text{equation 4}$$

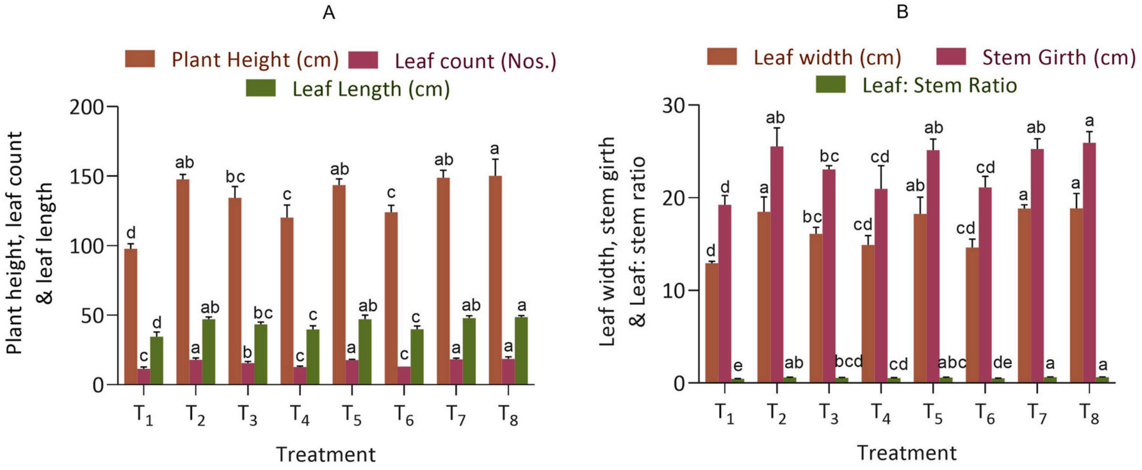

Fig. 1. Effect of potassium fertilization on plant morphology characteristics: A) plant height, leaf length, and stem girth; B) leaf count, leaf width, and leaf:stem ratio. T_1 - control (No K); T_2 - recommended dose of potassium fertilizer (RDK) via muriate of potash (MOP); T_3 - 75% RDK (MOP) + nano K fertilizer spray at 25 and 40 days after sowing (DAS); T_4 - 50% RDK + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_5 - 75% RDK + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_6 - 50% RDK+25% K infusion through FYM + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_7 - 75% RDK + 25% K enrichment through FYM + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_8 - 100% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS; FYM: farmyard manure; PGPR: plant growth promoting rhizobacteria; DAS: days after sowing.

$$\text{NE}\ (\text{MJ kg}^{-1}) = \left[\frac{(\text{TDN}\ (\%)X3.65)\text{-}100}{188.3}\right]X6.9 \quad \text{equation 5}$$

2.5. Statistical analysis

Statistical analysis was carried out at 95% level of confidence, using analysis of variance (ANOVA) and post hoc test as described by Gomez and Gomez, 1984 [56] and represented the data using mean ± standard error of the mean (SEM). Graphpad PRISM 8.0 and Originpro 8.0 software were used for statistical analysis and graph plotting.

3. Results

3.1. Plant growth

3.1.1. Plant morphology

The experimental results have illuminated significant divergences in the morphological attributes of plants across distinct treatment groups, as illustrated in Fig. 1. Remarkably, treatment T_8 has emerged as a pivotal contributor, showcasing the most noteworthy measurements in terms of plant height (150.27 ± 12.0 cm) and leaf count (18.50 ± 1.6) (Fig. 1A). This distinct treatment has not only demonstrated its statistical equivalence with treatments T_7 (148.97 ± 5.3 cm and 18.33 ± 0.7), T_2 (147.67 ± 3.6 cm and 17.97 ± 1.2), and T_5 (143.63 ± 4.5 cm and 17.67 ± 0.5), but has also displayed a substantial advantage over treatment T_1 (97.80 ± 3.6 cm and 11.37 ± 1.3) during the critical harvest stage. Particularly notable is the observed percentage amplification of both plant height (34%) and leaf count (38.54%) within the domain of treatment T_8, a phenomenon that gains prominence when contrasted with the baseline control treatment.

At the harvest stage, the investigation yielded noteworthy insights into leaf morphology, particularly with regard to leaf length and leaf width in Chinese cabbage (Fig. 1A and B). Among the various treatments, it was observed that the T_8 treatment exhibited the most substantial leaf dimensions, with a maximum leaf length of 48.60 ± 1.1 cm and a leaf width of 18.87 ± 1.6 cm (Fig. 1A and B).

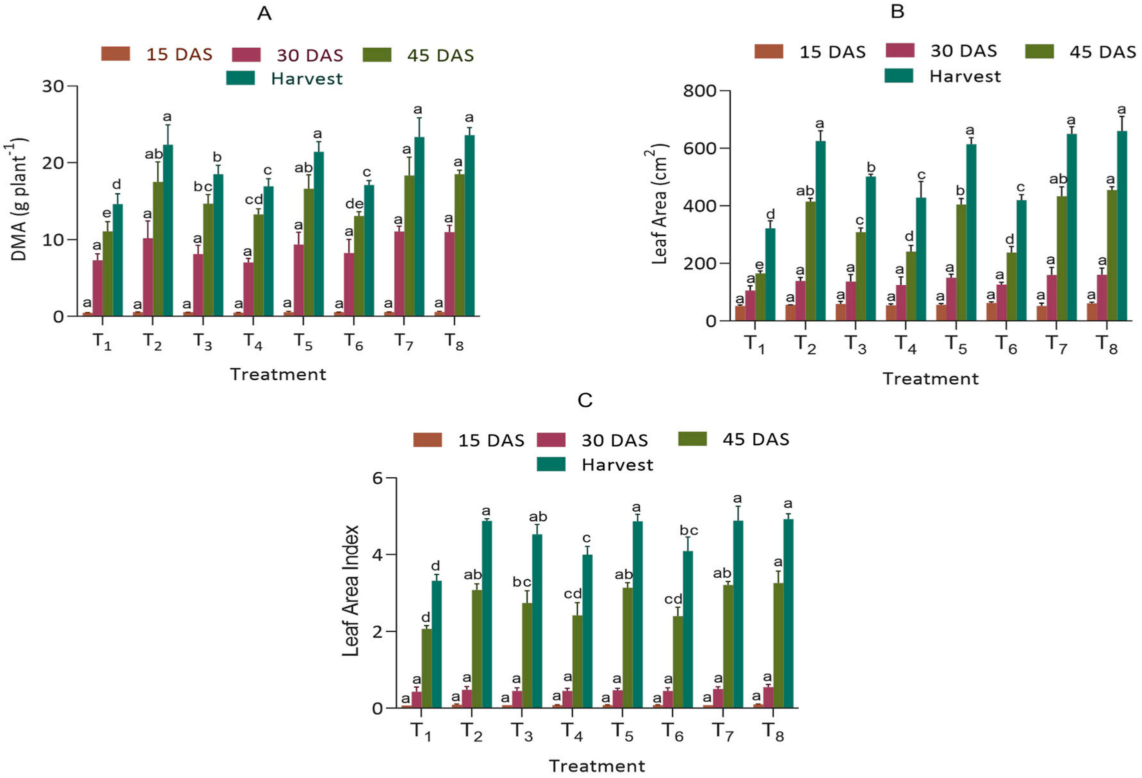

Fig. 2. Effect of potassium fertilization on dry matter accumulation (A), leaf area (B), and leaf area index (C). T_1 - control (No K); T_2 - recommended dose of potassium fertilizer (RDK) via muriate of potash (MOP); T_3 - 75% RDK (MOP) + nano K fertilizer spray at 25 and 40 days after sowing (DAS); T_4 - 50% RDK + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_5 - 75% RDK + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_6 - 50% RDK+25% K infusion through FYM + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_7 - 75% RDK + 25% K enrichment through FYM + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_8 - 100% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS; FYM: farmyard manure; PGPR: plant growth promoting rhizobacteria; DAS: days after sowing.

Significantly, treatment T_8 demonstrated statistical comparability with treatment T_7, T_2, and T_5 in terms of leaf length (47.93 ± 1.6 cm, 47.10 ± 1.6 cm, and 47.00 ± 3.0 cm, respectively) and leaf width (18.83 ± 0.4 cm, 18.48 ± 1.6 cm, and 18.26 ± 1.8 cm, respectively). Furthermore, treatment T_8 exhibited notable superiority over the control treatment (T_1) with respect to leaf length (34.60 ± 3.3 cm) and leaf width (12.93 ± 0.2 cm). Of particular significance is the observation that treatment T_8 demonstrated the most substantial percentage increments in leaf length (28.80%) and leaf width (31.47%) in comparison to the treatment without K application (T_1).

The experimental findings have revealed substantial variations in the morphological attributes of Chinese cabbage across the diverse treatment groups, as illustrated in Fig. 1B. Notably, treatment T_8 exhibited the most elevated measurements for stem girth, registering a value of 25.93 ± 1.2 cm, and for the leaf: stem ratio, with a value of 0.63 ± 0.04. This treatment demonstrated statistical parity with treatment T_7, which yielded stem girth and leaf: stem ratio values of 25.27 ± 1.1 cm and 0.63 ± 0.03, respectively, as well as treatment T_2, which recorded stem girth and leaf: stem ratio values of 25.53 ± 2.0 cm and 0.61 ± 0.03, respectively. Additionally, treatment T_8 shared these attributes with treatment T_5, where stem girth measured 25.13 ± 1.2 cm and leaf: stem ratio stood at 0.60 ± 0.03. In contrast, treatment T_8 displayed significant superiority over the control treatment (T_1), characterized by stem girth of 19.23 ± 1.0 cm and a leaf: stem ratio of 0.47 ± 0.01, both assessed at the harvest stage. Remarkably, treatment T_8 exhibited the most substantial percentage increments in both stem girth (25.83%) and leaf: stem ratio (25.40%) when juxtaposed with the control treatment.

3.1.2. Dry matter accumulation and leaf characteristics

Significant variations in dry matter accumulation were apparent among treatments at 45 DAS, and final harvest as illustrated in Fig. 2A. Notably, at 45 DAS, treatments T_8 and T_7 demonstrated the highest dry matter accumulation, recording values of 18.50 ± 0.54 g plant^{-1} and 18.37 ± 2.37 g plant^{-1}, respectively. Treatments T_8 and T_7 values were found at par with values recorded in treatment T_2 (17.50 ± 2.60 g plant^{-1}) and T_5 (16.64 ± 1.79 g plant^{-1}) and significantly exceeded those of other treatments. Upon final harvest, T_8 and T_7 exhibited prominence, showcasing the highest dry matter accumulations of 23.60 ± 0.99 g plant^{-1} and 23.37 ± 2.49 g plant^{-1}, respectively. Treatments T_8 and T_7 values found at par with values recorded in treatment T_2 (22.35 ± 2.58 g plant^{-1}) and T_5 (21.44 ± 1.32 g plant^{-1}) and significantly superior over remaining treatments. Treatment T_1 recorded the lowest values 11.08 ± 1.26 g plant^{-1} and 14.64 ± 1.32 g plant^{-1} of dry matter accumulation at 45 DAS and final harvest, respectively. Remarkably, treatment T_8 exhibited the most substantial percentage increments in dry matter accumulation at 45 DAS (36.21%) and at final harvest (37.97%) when juxtaposed with the control treatment.

Significant variations in leaf area were apparent among treatments at 45 DAS, and final harvest (Fig. 2B). Notably, at 45 DAS, treatments T_7 and T_8 demonstrated the leaf area, recording values of 455.00 ± 11.3 (cm^2) and 433.10 ± 32.4 (cm^2), respectively. Treatments T_7 and T_8 values were found at par with values recorded in treatment T_2 (414.91 ± 10.9 cm^2) and T_5 (404.06 ± 20.8 cm^2) and significantly exceeded those of other treatments. Upon final harvest, T_8 and T_7 exhibited prominence, showcasing the highest leaf area of 659.56 ± 50.7 cm^2 and 649.93 ± 24.4 cm^2, respectively. Treatments T_8 and T_7 values found at par with values recorded in treatment T_2 (22.35 ± 2.58 cm^2) and T_5 (21.44 ± 1.32 cm^2) and significantly superior over remaining treatments. Treatment T_1 recorded the lowest values 164.90 ± 8.5 cm^2 and 321.74 ± 26.1 cm^2 of leaf area at 45 DAS and final harvest, respectively. Treatment T_8 exhibited the most substantial percentage increments in leaf area at 45 DAS (63.75%) and at final harvest (51.21%) when juxtaposed with the control treatment.

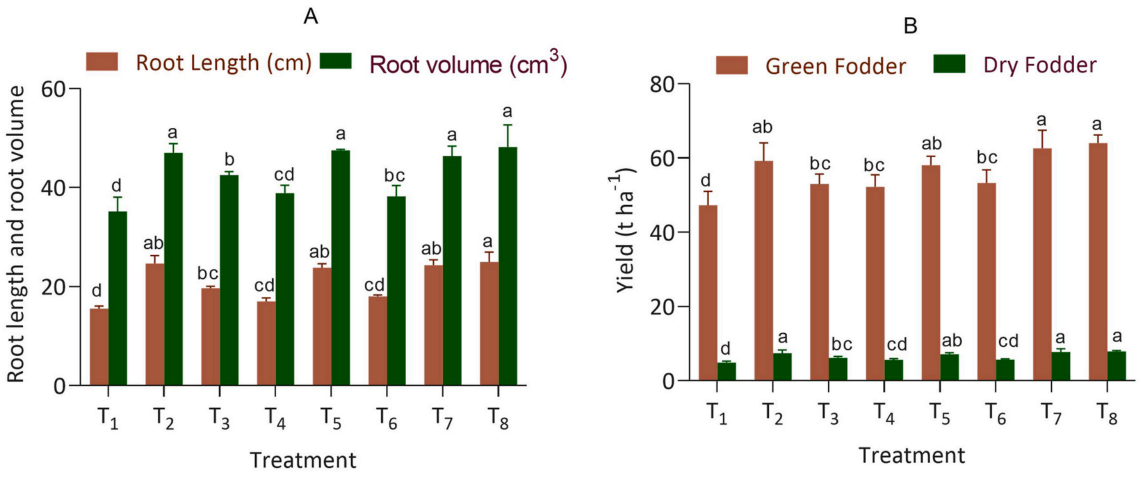

Fig. 3. Effect of potassium fertilization on root characteristics (A) and yield of Chinese cabbage (B). T_1 - control (No K); T_2 - recommended dose of potassium fertilizer (RDK) via muriate of potash (MOP); T_3 - 75% RDK (MOP) + nano K fertilizer spray at 25 and 40 days after sowing (DAS); T_4 - 50% RDK + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_5 - 75% RDK + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_6 - 50% RDK+25% K infusion through FYM + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_7 - 75% RDK + 25% K enrichment through FYM + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_8 - 100% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS; FYM: farmyard manure; PGPR: plant growth promoting rhizobacteria; DAS: days after sowing.

Significant variations in leaf area index were apparent among treatments at 45 DAS, and final harvest (Fig. 2C). Notably, at 45 DAS, treatments T_8 demonstrated the highest leaf area, recording values of 3.26 ± 0.31. Treatments T_8 values were found at par with values recorded in treatment T_7, (3.21 ± 0.09), T_2 (3.08 ± 0.16), and T_5 (3.14 ± 0.13) and significantly exceeded those of other treatments. Upon final harvest, T_8 recorded the highest leaf area index of 4.93 ± 0.14. Treatments T_8 values found at par with values recorded in treatment T_7 (4.89 ± 0.37), T_2 (4.88 ± 0.06), and T_5 (4.87 ± 0.18) and significantly superior over remaining treatments. Treatment T_1 recorded the lowest values 2.07 ± 0.08 and 3.32 ± 0.17 of leaf area index at 45 DAS and final harvest, respectively. Treatment T_8 exhibited the most substantial percentage increments in leaf area index at 45 DAS (36.50%) and at final harvest (32.66%) when juxtaposed with the control treatment.

3.1.3. *Root characteristics*

The different treatments exerted significant variations in root volume and root length in Chinese cabbage (Fig. 3A). The treatment T_8 emerged as the treatment with the most remarkable effect on root characteristics. With a root volume of 48.17 ± 4.5 cm^3 and a root length of 24.97 ± 2.0 cm, T_8 showcased the highest values for both parameters. The treatment T_8 was at par with T_7, which yielded a root volume of 46.35 ± 2.0 cm^3 and a root length of 24.30 ± 1.1 cm, T_2 with a root volume of 47.00 ± 1.9 cm^3 and root length of 24.67 ± 1.6 cm and T_5 with a root volume of 47.50 ± 0.2 cm^3 and a root length of 23.83 ± 0.8 cm and found significantly superior over the remaining treatments. The treatment T_1, which yielded a root volume of 35.17 ± 2.9 cm^3 and a corresponding root length of 15.57 ± 0.5 cm, displayed the lowest values for both parameters. Treatment T_8 exhibited the most noteworthy proportional enhancements in root volume, manifesting an increase of 25.39%, along with a rise of 26.99% in root length, as contrasted with the control treatment.

3.2. *Green and dry fodder yield*

Significant variations in green and dry fodder yields were observed due to different nutrient management treatments (Fig. 3B). The

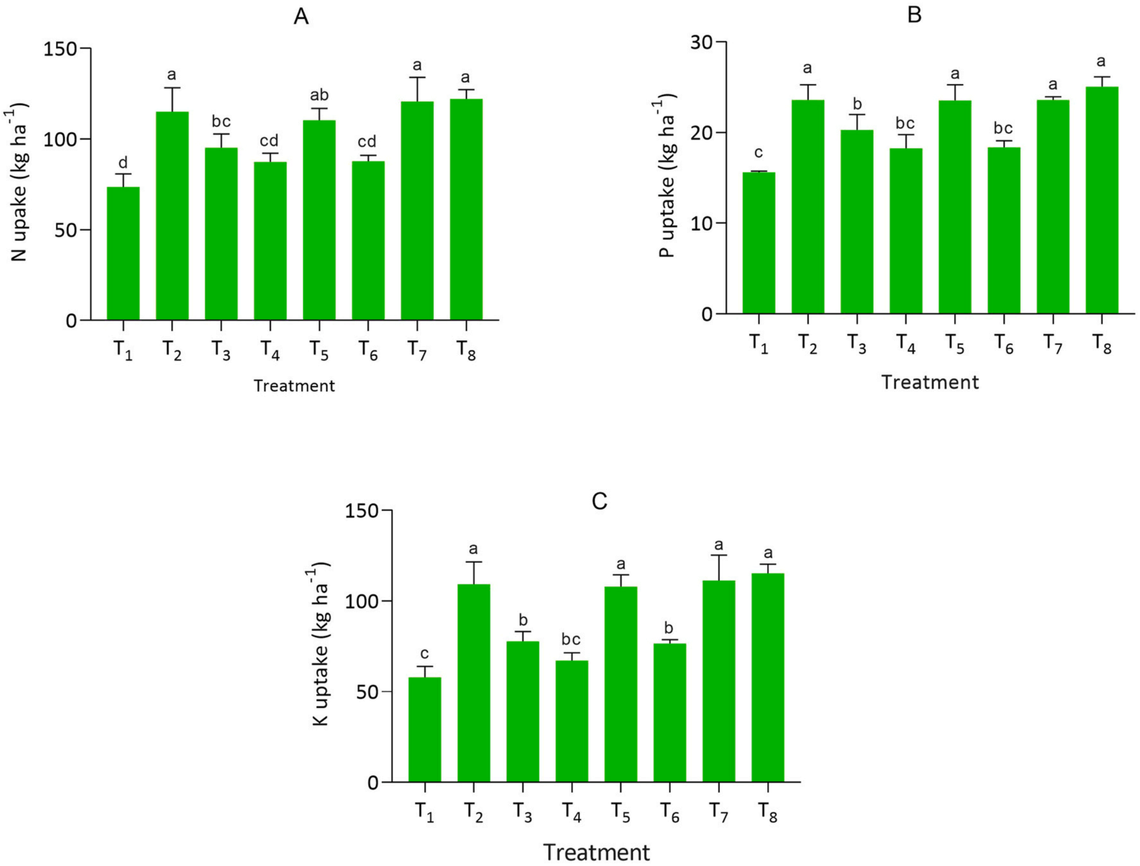

Fig. 4. Effect of potassium fertilization on macronutrient uptake in Chinese cabbage: N uptake (A), P uptake (B), and K uptake (C). T_1 - control (No K); T_2 - recommended dose of potassium fertilizer (RDK) via muriate of potash (MOP); T_3 - 75% RDK (MOP) + nano K fertilizer spray at 25 and 40 days after sowing (DAS); T_4 - 50% RDK + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_5 - 75% RDK + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_6 - 50% RDK+25% K infusion through FYM + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_7 - 75% RDK + 25% K enrichment through FYM + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_8 - 100% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS; FYM: farmyard manure; PGPR: plant growth promoting rhizobacteria; DAS: days after sowing.

treatment T_8 emerged as the treatment with the most remarkable effect on fodder production. With a green fodder yield of 64.0 ± 2.2 t ha^{-1} and a dry fodder yield of 7.87 ± 0.33 t ha^{-1}, T_8 showcased the highest values for both parameters. The treatment T_8 was found at par for green and dry fodder yield with treatment T_7, which yielded 62.6 ± 4.9 t ha^{-1} of green fodder and 7.79 ± 0.83 t ha^{-1} of dry fodder, T_5 with values of green fodder yield 58.1 ± 2.4 t ha^{-1} and dry fodder yield of 7.15 ± 0.44 t ha^{-1}, and T_2 with green fodder yield of 59.2 ± 4.9 t ha^{-1} and a dry fodder yield of 7.45 ± 0.86 t ha^{-1} and also found significantly superior over all the remaining treatments. The treatment T_1, exhibited the lowest values for both green and dry fodder yields, with values of 47.3 ± 3.7 t ha^{-1} and 4.88 ± 0.44 t ha^{-1}, respectively. Treatment T_8 exhibited the most noteworthy proportional enhancements in green fodder yield, manifesting an increase of 26.09%, along with a rise of 38.0% in dry fodder yield, as contrasted with the control treatment.

3.3. Nutrient uptake

3.3.1. Macronutrient uptake

The statistical analysis underscores pronounced disparities in macronutrient uptake among the various treatments, as illustrated in Fig. 4A to C. Treatment T_7 (120.81 ± 13.2 kg ha^{-1}) and treatment T_8 (122.23 ± 5.1 kg ha^{-1}) exhibited the highest mean N uptakes, revealing statistically significant distinctions when compared to the remaining treatments (Fig. 4A). Notably, treatment T_2 (115.13 ± 13.2 kg ha^{-1}) also showcased substantial N uptake, placing it on par with T_7 and T_8 in terms of its influence on N uptake. It is worth highlighting that treatment T_2's N uptake is significantly superior to that of Treatment T_1 (73.66 ± 7.1 kg ha^{-1}), which displayed the lowest mean N uptake within the treatments.

Regarding P uptake, the data illustrated as Fig. 4B revealed that treatment T_8 (25.06 ± 1.07 kg ha^{-1}) displays notably enhanced P uptake, indicative of its efficacy in promoting elevated P uptake. This observation is consistent with treatments T_7 (23.59 ± 0.34 kg ha^{-1}), T_5 (23.53 ± 1.73 kg ha^{-1}), and T_2 (23.58 ± 1.68 kg ha^{-1}), all of which exhibited substantial and statistically significant improvements in P uptake compared to the baseline control treatment T_1 (15.62 ± 0.12 kg ha^{-1}), which records the lowest P uptake value among the treatments.

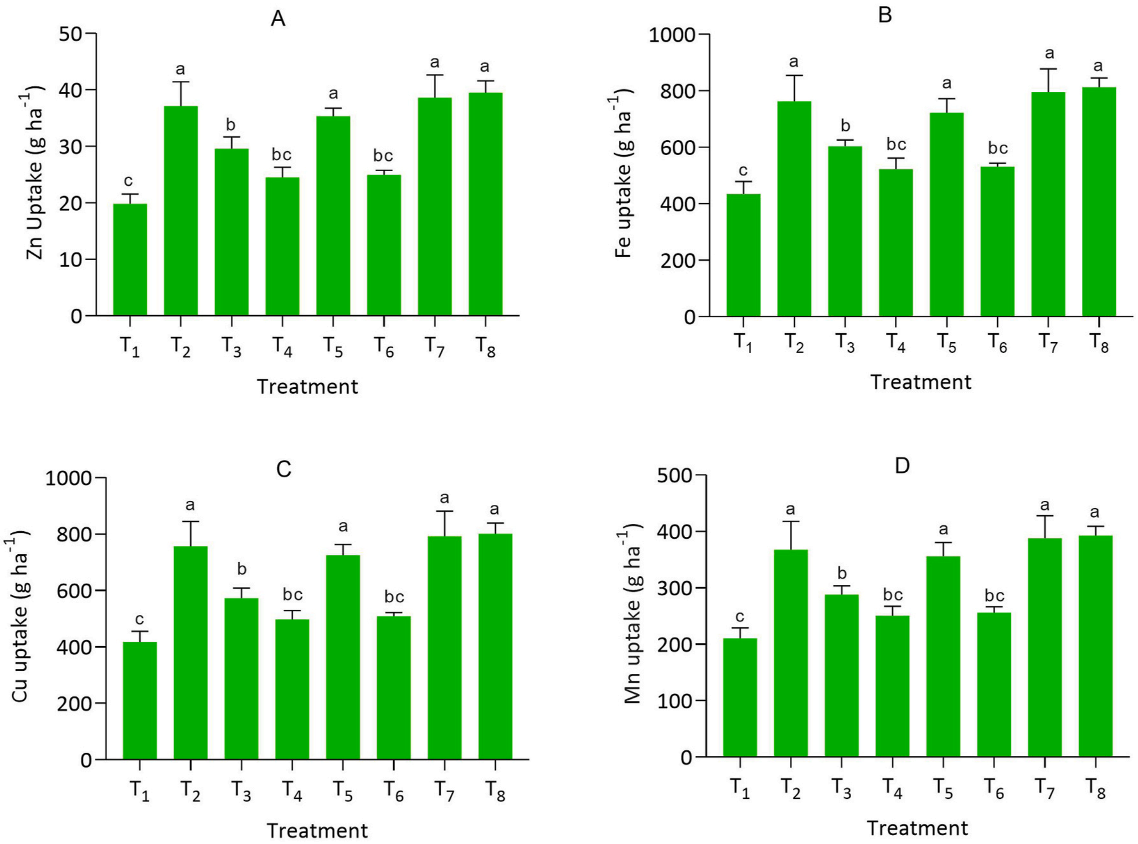

Fig. 5. Effect of potassium fertilization on micronutrient uptake in Chinese cabbage: Zn uptake (A); Fe uptake (B), Cu uptake (C), and Mn uptake (D). T_1 - control (No K); T_2 - recommended dose of potassium fertilizer (RDK) via muriate of potash (MOP); T_3 - 75% RDK (MOP) + nano K fertilizer spray at 25 and 40 days after sowing (DAS); T_4 - 50% RDK + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_5 - 75% RDK + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_6 - 50% RDK+25% K infusion through FYM + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_7 - 75% RDK + 25% K enrichment through FYM + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_8 - 100% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS; FYM: farmyard manure; PGPR: plant growth promoting rhizobacteria; DAS: days after sowing.

Furthermore, the K uptake data depicted as Fig. 4C demonstrated treatment T_8 (115.31 ± 5.0 kg ha^{-1}) as an effective facilitator of heightened K uptake, aligning with the increased K uptake observed. This is mirrored by treatments T_7 (111.36 ± 14.0 kg ha^{-1}), T_2 (109.35 ± 12.2 kg ha^{-1}), and T_5 (107.88 ± 6.6 kg ha^{-1}), all of which manifest considerable and statistically significant enhancements in K uptake in contrast to the control treatment T_1 (57.89 ± 6.0 kg ha^{-1}), characterized by the lowest K uptake value among the treatments.

3.3.2. Micronutrient uptake

The investigation into micronutrient uptake within Chinese cabbage under diverse nutrient treatments, as depicted from Fig. 5A to D, has brought to light compelling variations. Noteworthy is Treatment T_8's conspicuous amplification in the mean uptake values for zinc (Zn) (39.51 ± 2.1 ppm), iron (Fe) (812.57 ± 32.5 ppm), copper (Cu) (801.05 ± 37.3 ppm), and manganese (Mn) (392.83 ± 16.2 ppm). This augmentation finds parallel in treatment T_7, characterized by Zn (38.65 ± 4.0 ppm), Fe (795.82 ± 82.0 ppm), Cu (791.74 ± 89.7 ppm), and Mn (387.52 ± 40.1 ppm), as well as in treatment T_5 with Zn (35.35 ± 1.4 ppm), Fe (722.50 ± 49.8 ppm), Cu (725.09 ± 38.1 ppm), and Mn (356.13 ± 24.0 ppm). These treatments collectively establish a statistically significant superiority over the remaining interventions. Moreover, treatment T_3 has exhibited significantly heightened levels of Zn (29.59 ± 2.1 ppm), Fe (603.68 ± 22.2 ppm), Cu (572.96 ± 35.4 ppm), and Mn (288.32 ± 15.3 ppm), akin to the Zn (24.50 ± 1.8 ppm), Fe (522.54 ± 39.3 ppm), Cu (498.08 ± 30.6 ppm), and Mn (250.43 ± 16.8 ppm) levels seen in treatment T_4, and the Zn (24.99 ± 0.8 ppm), Fe (531.03 ± 12.9 ppm), Cu (508.86 ± 13.2 ppm), and Mn (255.86 ± 10.5 ppm) levels found in treatment T_6. Notably, treatments T_3, T_4, and T_6 have all demonstrated significant superiority over treatment T_1, characterized by lower levels of Zn (19.87 ± 1.7 ppm), Fe (434.67 ± 44.1 ppm), Cu (418.20 ± 37.0 ppm), and Mn (210.48 ± 18.6 ppm). The profound variations in micronutrient uptake underscore the intricate interplay between nutrient treatments and plant nutrient uptake mechanisms, underscoring the potential to optimize micronutrient availability for enhanced plant growth and development.

3.4. Energy fractions

The investigation into DE reveals pronounced variations among the treatments, as highlighted in Table 1. Specifically, treatment T_2 exhibits the highest DE value (11.65 ± 0.12 MJ kg^{-1}) and shares statistical parity with Treatments T_7 (11.59 ± 0.10 MJ kg^{-1}) and T_8 (11.64 ± 0.11 MJ kg^{-1}), which also display elevated DE values. These findings signify a substantial increase in energy content in comparison to the control treatment, T_1 (11.13 ± 0.04 MJ kg^{-1}). Conversely, treatments T_4 and T_6 exhibit relatively lower DE values (11.27 ± 0.07 MJ kg^{-1} and 11.25 ± 0.02 MJ kg^{-1}, respectively), implying a reduction in energy content. These values align statistically with the energy content of control treatment T_1 (11.13 ± 0.04 MJ kg^{-1}).

Similarly, in the context of DFE, treatment T_2 recorded the highest DFE value (11.20 ± 0.20 MJ kg^{-1}), paralleled by treatments T_7 (11.09 ± 0.17 MJ kg^{-1}) and T_8 (11.17 ± 0.19 MJ kg^{-1}). Notably, these treatments demonstrate significantly higher DFE values than the control treatment T_1 (10.30 ± 0.07 MJ kg^{-1}). Conversely, treatments T_4 (10.54 ± 0.13 MJ kg^{-1}) and T_6 (10.51 ± 0.04 MJ kg^{-1}) exhibit comparatively reduced DFE values, indicating a diminished digestible feed energy content, statistically similar to that of control treatment T_1 (10.30 ± 0.07 MJ kg^{-1}).

Similarly, in the context of ME, treatment T_2 recorded the highest ME value (9.57 ± 0.10 MJ kg^{-1}), paralleled by treatments T_8 (9.56 ± 0.09 MJ kg^{-1}), T_7 (9.52 ± 0.08 MJ kg^{-1}), and T_5 (9.50 ± 0.02 MJ kg^{-1}), all of which exhibit significantly higher ME values compared to the control treatment T_1 (9.14 ± 0.03 MJ kg^{-1}). Conversely, treatments T_4 (9.25 ± 0.06 MJ kg^{-1}) and T_6 (9.24 ± 0.02 MJ kg^{-1}) exhibited comparatively higher values but statistically similar to that of control treatment T_1 (9.14 ± 0.03 MJ kg^{-1}).

Furthermore, regarding NE, treatments T_2 recorded the highest NE value (8.13 ± 0.15 MJ kg^{-1}), at par with treatments T_8 (8.12 ± 0.14 MJ kg^{-1}), T_7 (8.06 ± 0.12 MJ kg^{-1}), and T_5 (8.03 ± 0.02 MJ kg^{-1}), all of which exhibit significantly higher NE values compared to the control treatment T_1 (7.49 ± 0.05 MJ kg^{-1}). Conversely, treatments T_4 (7.66 ± 0.09 MJ kg^{-1}) and T_6 (7.64 ± 0.03 MJ kg^{-1})

Table 1

Effect of potassium fertilization on energy fractions of Chinese cabbage.

Treatments	DE (MJ kg^{-1})	DFE (MJ kg^{-1})	ME (MJ kg^{-1})	NE (MJ kg^{-1})
T_1	11.13 ± 0.04^{d}	10.30 ± 0.07^{b}	9.14 ± 0.03^{d}	7.49 ± 0.05^{d}
T_2	11.65 ± 0.12^{a}	11.20 ± 0.20^{a}	9.57 ± 0.10^{a}	8.13 ± 0.15^{a}
T_3	11.40 ± 0.01^{bc}	10.77 ± 0.01^{b}	9.36 ± 0.00^{bc}	7.82 ± 0.01^{bc}
T_4	11.27 ± 0.07^{cd}	10.54 ± 0.13^{b}	9.25 ± 0.06^{cd}	7.66 ± 0.09^{cd}
T_5	11.57 ± 0.02^{ab}	11.06 ± 0.03^{a}	9.50 ± 0.02^{ab}	8.03 ± 0.02^{ab}
T_6	11.25 ± 0.02^{cd}	10.51 ± 0.04^{b}	9.24 ± 0.02^{cd}	7.64 ± 0.03^{cd}
T_7	11.59 ± 0.10^{a}	11.09 ± 0.17^{a}	9.52 ± 0.08^{a}	8.06 ± 0.12^{a}
T_8	11.64 ± 0.11^{a}	11.17 ± 0.19^{a}	9.56 ± 0.09^{a}	8.12 ± 0.14^{a}
LSD (P = 0.05)	0.17	0.28	0.14	0.21

T_1 - control (No K); T_2 - recommended dose of potassium fertilizer (RDK) via muriate of potash (MOP); T_3 - 75% RDK (MOP) + nano K fertilizer spray at 25 and 40 days after sowing (DAS); T_4 - 50% RDK + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_5 - 75% RDK + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_6 - 50% RDK+25% K infusion through FYM + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_7 - 75% RDK + 25% K enrichment through FYM + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_8 - 100% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS; DE:digestible energy; DFE: digestible feed energy; ME: metabolizable energy, NE: net energy; FYM: farmyard manure; PGPR: plant growth promoting rhizobacteria; DAS: days after sowing.

exhibited comparatively higher values but statistically similar to that of control treatment T_1 (7.49 ± 0.05 MJ kg^{-1}).

3.5. Soil nutrient availability

The measurements of available N reveal discernible variations across the treatment groups, as evident from the data presented in Table 2. Among the treatments, Treatment T_7 exhibited the highest level of available N (195.5 ± 1.6), which is statistically at par with treatment T_6 (192.9 ± 1.5) and significantly superiority over remaining treatments. Treatment T_5 (188.5 ± 2.5) found at par with treatment T_6 and significantly superior over control treatment T_1 (183.9 ± 4.8). In contrast, treatments T_2 to T_4 (180.4 ± 1.6, 180.3 ± 3.8, and 182.0 ± 1.2) displayed lower levels of available N and found at par with control treatment T_1(183.9 ± 4.8). In case of P availability, no significant difference was observed due to treatment variations. The highest P availability was observed in treatment T_7 (27.0 ± 0.2) whereas lowest P was observed in treatment T_1 (24.4 ± 0.7). Further in case of available K, treatment T_7 exhibited the highest level of available K (233.0 ± 18.45), which is statistically at par with treatment T_8 (230.1 ± 1.86), T_5 (221.8 ± 10.52), and T_2 (218.0 ± 10.18) and T_3 (215.2 ± 1.18) and significantly superiority over remaining treatments. Treatment T_1 recorded the lowest values 191.1 ± 6.92 of available K after harvest of the Chinese cabbage.

3.6. Overall impact of integrated potassium fertilization on growth, yield, soil health and energy fractions of Chinese cabbage

The data analysis yielded significant principal components, PC1 and PC2, in the experimentation, explaining 99.62% and 0.35% variance, respectively (Fig. 6). Treatments grouped into two clusters: cluster I includes treatments T_1, T_3, T_4, T_6, and cluster II includes treatments T_2, T_5, T_7, T_8. Cluster I correlated positively with PC1 but negatively with PC2, while cluster II correlated positively with PC1 and PC2. Parameters grouped into four clusters: cluster I (plant height, iron uptake, available N and available K), cluster II (leaf area, manganese uptake, copper uptake), cluster III (leaf width, leaf count, root length, dry matter accumulation, stem girth, leaf area index, dry fodder yield, P uptake, K uptake, zinc uptake, digestible energy, digestible feed energy, metabolic energy, and net energy), and cluster IV (root volume, green fodder yield, N uptake, and leaf length and available P).

Additionally, treatment T_8 also contributed significantly in improving plant height, leaf length, leaf area, root volume, GFY, iron uptake, available N, available P, available K, N uptake, manganese uptake, and copper uptake. The statistical analyzed data shown in scatter plot matrix (Fig. 7) showed that the treatments applied with higher doses of K through organic and inorganic sources of K (T_2 to T_8) showed a strict regression coefficient (r^2) > 0.97. Based on the response of various parameters, the regression coefficient between treatments applied for K through MOP alone and integrated K management through MOP, FYM, PGPR and foliar spray of nano-potash were >0.98 (T_2 to T_8), >0.98 (T_3 to T_8), >0.98 (T_4 to T_8), >0.98 (T_5 to T_8), >0.98 (T_6 and T_8), >0.99 (T_7 and T_8), while the regression coefficient (r^2) among the treatments applied recommended dose of fertilizer alone varied from 0.98 to 0.99. Treatment T_8 showed significant improvement among various parameters. The scatter plot matrix revealed that integrated application using treatment T_8 have high potential for improving the plant growth, green fodder yield, soil fertility, and energy fractions.

4. Discussion

The experimental results unveil noteworthy variations in plant height and leaf count across distinct treatment groups, as illustrated in Fig. 1A. Notably, treatment T_8 emerges as a standout, manifesting remarkable plant height and leaf count. Remarkably, T_8 not only parallels the metrics of T_7, T_2, and T_5 but also notably surpasses T_1 in both 45 DAS and harvesting stages. The discernible augmentation in plant height and leaf count is potentially attributed to enhanced K availability, facilitated by the combined effects of diverse K sources in treatments T_8, T_7, and T_5, while T_2 exclusively received K from MOP, albeit at a higher dosage compared to T_3, T_4, and T_6. Intriguingly, the absence of K application in T_1 and the application of low K doses in T_3, T_4, and T_6 correspond to diminished plant

Table 2
Effect of potassium fertilization on available Nitrogen (kg ha^{-1}), Phosphorus (kg ha^{-1}) and Potassium (kg ha^{-1}) in soil.

Treatments	Available N	Available P	Available K
T_1	183.9 ± 4.8^{cd}	24.4 ± 0.7	191.1 ± 6.92^{c}
T_2	180.4 ± 1.6^{d}	25.5 ± 0.8	218.0 ± 10.18^{ab}
T_3	180.3 ± 3.8^{d}	25.3 ± 0.8	215.2 ± 1.18^{ab}
T_4	182.0 ± 1.2^{d}	25.8 ± 0.8	205.0 ± 2.88^{bc}
T_5	188.5 ± 2.5^{bc}	25.6 ± 0.5	221.8 ± 10.52^{ab}
T_6	192.9 ± 1.5^{ab}	25.5 ± 0.8	208.0 ± 1.73^{bc}
T_7	195.5 ± 1.6^{a}	27.0 ± 0.2	233.0 ± 18.45^{a}
T_8	186.2 ± 3.2^{cd}	26.4 ± 0.8	230.1 ± 1.86^{a}
LSD (P = 0.05)	6.18	NS	18.90

T_1 - control (No K); T_2 - recommended dose of potassium fertilizer (RDK) via muriate of potash (MOP); T_3 - 75% RDK (MOP) + nano K fertilizer spray at 25 and 40 days after sowing (DAS); T_4 - 50% RDK + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_5 - 75% RDK + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_6 - 50% RDK+25% K infusion through FYM + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_7 - 75% RDK + 25% K enrichment through FYM + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_8 - 100% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS; Av N: available nitrogen in soil; Av P: available phosphorus in soil; Av K: available potassium in soil; FYM: farmyard manure; PGPR: plant growth promoting rhizobacteria; DAS: days after sowing.

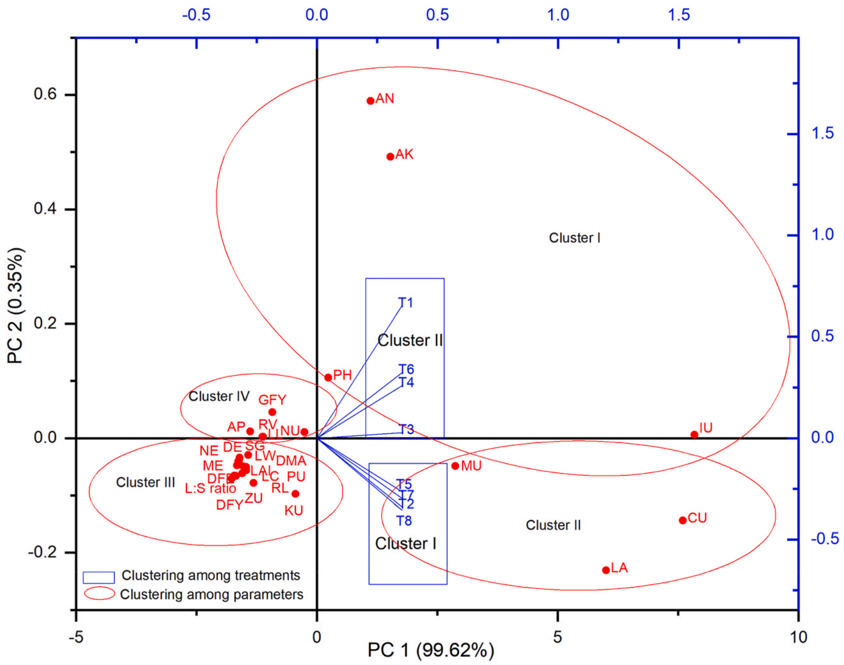

Fig. 6. Principal component analysis among treatments and various parameters of growth, yield, soil health, and energy fractions of Chinese cabbage. T_1 - control (No K); T_2 - recommended dose of potassium fertilizer (RDK) via muriate of potash (MOP); T_3 - 75% RDK (MOP) + nano K fertilizer spray at 25 and 40 days after sowing (DAS); T_4 - 50% RDK + PGPR (plant growth promoting rhizobacteria) + nano K fertilizer spray at 25 and 40 DAS; T_5 - 75% RDK + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_6 - 50% RDK+25% K infusion through FYM + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_7 - 75% RDK + 25% K enrichment through FYM + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_8 - 100% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS; DMA:dry matter accumulation; LA:leaf area; LAI: leaf area index; PH; plant height; LL; leaf length; SG; stem girth; NL; number of leaves; LW:leaf width; L:S: leaf to stem ratio; RV:root volume, RL: root length; GFY:green fodder yield, DFY: dry fodder yield, N up; Nitrogen uptake, P up: Phosphorus uptake; K up: potassium uptake; S up: sulphur uptake; Zn up: zinc uptake; Fe up: Iron uptake; Cu up: copper uptake; Mn up: Manganese uptake; DE: digestible energy; DFE: digestible feed energy; ME: Metabolizable energy; NE: net energy; Av N: available nitrogen in soil; Av P: available phosphorus in soil; Av K: available potassium in soil; FYM: farmyard manure; PGPR: plant growth promoting rhizobacteria; DAS: days after sowing. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

height and leaf count. Hasanuzzaman et al. (2018) reported that K stands as an essential element indispensable for the growth and physiological processes of plants. Beyond its role as a structural component in plant composition, potassium assumes a regulatory function in diverse biochemical pathways, including but not limited to protein synthesis, carbohydrate metabolism, and enzyme activation [22]. Further, various pivotal physiological processes crucial for plant development, such as stomatal regulation [57,58] and photosynthesis [59,60], are contingent upon the presence and proper functioning of potassium. Consequently, these mechanisms synergistically enhance nutrient availability, thereby fostering robust leaf development. The involvement of K in facilitating cell elongation is rooted in its facilitation of auxin synthesis, as substantiated by previous studies [58,61], thereby accentuating its function in promoting growth. These findings resonate harmoniously with analogous observations advanced in prior investigations [31,62,63], thus further corroborating the enduring impact of K on plant growth and morphological attributes.

The investigation at the harvest stage provided significant insights into Chinese cabbage leaf morphology, particularly leaf length and width (Fig. 1A and B). Notably, treatment T_8 exhibited the most substantial dimensions, with a leaf length and leaf width. Remarkably, T_8 demonstrated statistical parity with treatments T_7, T_2, and T_5 in terms of both leaf length and width. Furthermore, T_8 exhibited pronounced superiority over the control treatment (T_1) in relation to leaf length and leaf width. The augmentation in leaf length and width is closely associated with heightened K availability, as indicated by the effects of K sources in treatments T_8, T_7, T_5, and T_2, while limited K availability in treatments T_3, T_4, T_6, and T_1 resulted in reduced leaf dimensions. The substantial augmentation in leaf dimensions can be attributed to potassium's central role in pivotal processes encompassing cell division, elongation, and the enhancement of diverse physiological activities, a notion well-supported by previous study [25]. Potassium supplementation interventions have been recognized for their role in enhancing cellular turgor, reducing osmotic potential, and promoting heightened cell wall extensibility throughout the expansive stage of leaf maturation [64] in maize and [65] in *Phaseolus vulgaris*. These findings find resonance in the previous studies [66,67], thereby reinforcing the consistency of these observed effects.

The experimental findings highlight substantial and distinct variations in the morphological attributes, specifically stem girth and leaf: stem ratio, within the context of Chinese cabbage under the influence of various treatment regimens (Fig. 1C). Noteworthy is the emergence of treatment T_8 as a notable contender, demonstrating the highest stem girth and leaf: stem ratio, which aligns comparably with T_7 and T_2. Likewise, treatment T_5 yielded commensurate measurements in this regard. In contrast, T_8 exhibits a pronounced

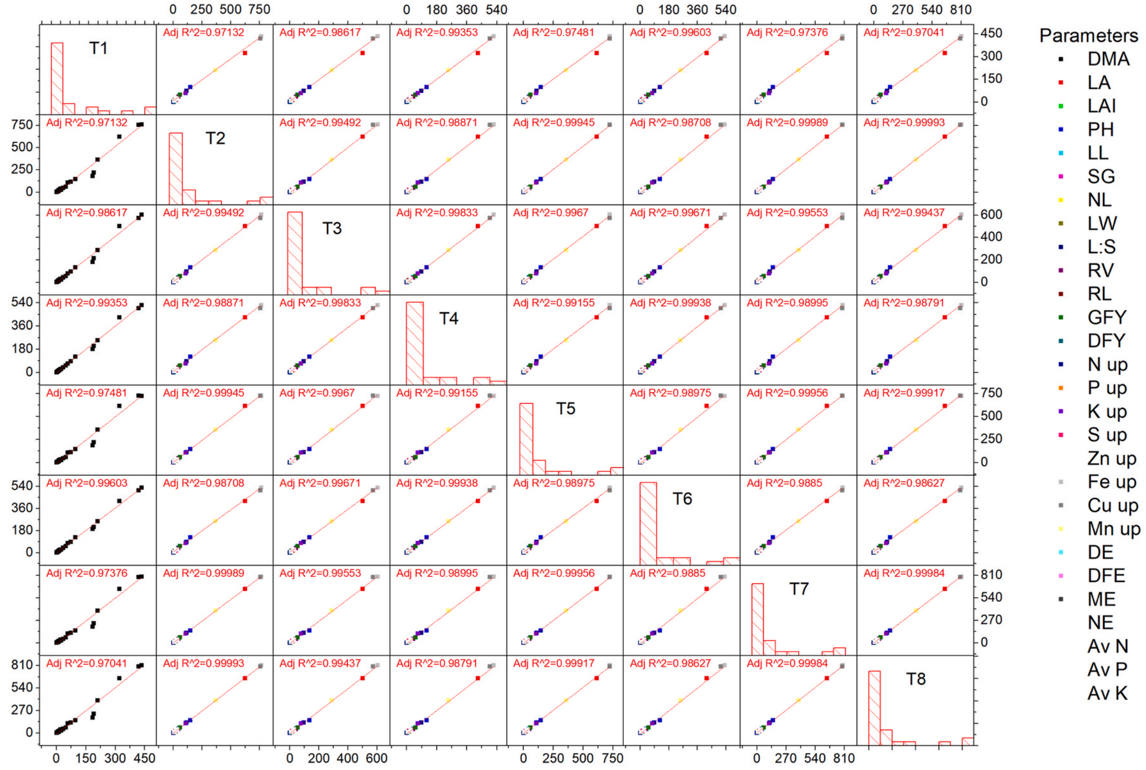

Fig. 7. Scatter plot matrix analysis among treatments and various parameters of growth, yield, soil health, and energy fractions of Chinese cabbage. T_1 - control (No K); T_2 - recommended dose of potassium fertilizer (RDK) via muriate of potash (MOP); T_3 - 75% RDK (MOP) + nano K fertilizer spray at 25 and 40 days after sowing (DAS); T_4 - 50% RDK + PGPR (plant growth promoting rhizobacteria) + nano K fertilizer spray at 25 and 40 DAS; T_5 - 75% RDK + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_6 - 50% RDK+25% K infusion through FYM + PGPR + nano K fertilizer spray @ 25 and 40 DAS; T_7 - 75% RDK + 25% K enrichment through FYM + PGPR + nano K fertilizer spray at 25 and 40 DAS; T_8 - 100% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS; DMA:dry matter accumulation; LA:leaf area; LAI: leaf area index; PH; plant height; LL; leaf length; SG; stem girth; NL; number of leaves; LW:leaf width; L:S: leaf to stem ratio; RV:root volume, RL: root length; GFY:green fodder yield, DFY: dry fodder yield, N up; Nitrogen uptake, P up: Phosphorus uptake; K up: potassium uptake; S up: sulphur uptake; Zn up: zinc uptake; Fe up: Iron uptake; Cu up: copper uptake; Mn up: Manganese uptake; DE: digestible energy; DFE: digestible feed energy; ME: Metabolizable energy; NE: net energy; Av N: available nitrogen in soil; Av P: available phosphorus in soil; Av K: available potassium in soil; FYM: farmyard manure; PGPR: plant growth promoting rhizobacteria; DAS: days after sowing. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

advantage over the control treatment (T_1) by manifesting superior stem girth and leaf: stem ratio at the time of harvest. This intriguing pattern may stem from the pivotal engagement of potassium ions ($K+$), profoundly impacting cellular turgidity and fostering the development of xylem vascular cells and lower epidermal sclerenchyma tissues in maize crop [68]. This synergy aligns conceptually with earlier findings in tomato crop [69]. Nonetheless, a discerning examination of intricate physiological factors beyond K is imperative for a holistic comprehension of the multifaceted mechanisms shaping morphological variations in Chinese cabbage under diverse treatment contexts. Enhanced understanding could emerge from subsequent investigations, shedding light on nuanced pathways at play.

Distinct dry matter variations emerged among treatments at 45 DAS and final harvest (Fig. 2A). Notably, T_8 and T_7 showcased the highest accumulation at 45 DAS, paralleling T_2 and T_5, surpassing other treatments significantly. At the final harvest, T_8 and T_7 continued to excel, recording higher dry matter accumulations comparable to T_2 and T_5, outperforming the remaining treatments. Conversely, T_1 displayed the lowest values at 45 DAS and final harvest. The enhanced dry matter accumulation is attributed to potassium's active role ($K+$) in elevating photosynthesis and facilitating efficient nutrient and photosynthate translocation. Potassium's role aligns with optimizing nutrient distribution and availability within plant tissues [22]. Furthermore, Ju et al. (2021) reported that the augmentation of leaf area expansion mediated by K plays a pivotal role in optimizing solar radiation interception, thereby bolstering the accrual of dry matter in cotton plants [70]. Cheema et al. (2012) consistently corroborate potassium's influential role in dry matter accumulation, affirming its significance in plant growth and physiological processes in canola [71].

Significant leaf area disparities were conspicuous across treatments at 45 days after sowing (DAS) and final harvest (Fig. 2B). Notably, T_8 and T_7 exhibited substantial leaf areas, analogous to T_2 and T_5, surpassing other treatments. Correspondingly, T_8 and T_7 showcased maximal leaf areas at final harvest, mirroring T_2 and T_5, evincing superior performance. In contrast, T_1 demonstrated the lowest values at both stages. Comparable trends were discernible in the leaf area index (Fig. 2C), with T_8 maintaining prominence and significant percentage increments across both stages compared to the control. The observed enhancements in leaf area and leaf area index may stem from proficient carbohydrate allocation for protoplasmic synthesis, leading to enlarged cells with attenuated walls as postulated in previous study [72]. Current findings also align with the previous findings in maize, where a synergistic blend of organic and inorganic K sources, coupled with escalating fertilizer doses, amplified leaf area and index, likely attributed to increased cellular components, enlargement, proliferation, and differentiation, buoyed by augmented photosynthetic activities [67].

Within the spectrum of treatments employed, the evaluation of Chinese cabbage's root volume and root length revealed substantial discrepancies, substantiated through observations in Fig. 3A. Most notably, among these interventions, T_8 emerged as an instrumental agent in eliciting variations in root attributes, as evident in the conspicuous attainment of peak benchmarks for root volume and length. Noteworthy is the congruence of effectiveness demonstrated by T_8, in parallel with T_7, T_2, and T_5, as manifested by their analogous root volumes and synchronous root lengths. This collective emergent trend robustly positions these treatments as markedly superior entities within this analytical framework, thereby emphatically accentuating their salience and impact. In stark juxtaposition, treatment T_1 exhibited the most subdued performance, registering the lowest values for both root volume and length. This discernible escalation in root attributes could ostensibly be ascribed to elevated levels of potassium ions ($K+$), acknowledged stimulants of indole-3-acetic acid (IAA) synthesis – a pivotal contributor to root development. Simultaneously, $K+$ also effectively mitigates ethylene accumulation within the root structure, as elucidated in prior research in *Arabidopsis thaliana* [73]. Studies conducted by Afify et al. (2019) and Kalita et al. (2019) parallelly bolster the observed augmentation in root length and volume within analogous experimental conditions. This comprehensive body of empirical support underscores the intricate role of potassium and its multi-dimensional influence upon root morphology and the dynamics of growth [74,75].

Investigating varied treatments revealed significant disparities in green and dry fodder yields. Particularly noteworthy is the outstanding performance of T_8, showcasing remarkable green and dry fodder yields (Fig. 3B). Treatments T_7, T_5, and T_2 yield comparable results, while T_1 exhibits the least productivity with green and dry fodder yields. Kumar et al. (2021) substantiated that diverse sources of integrated K fertilization enhance microbial populations, soil enzymatic activities, and nutrient availability, fostering crop growth and yield in wheat crop [29]. The intricate synergy of K with other nutrients underscores the intricacies of nutrient interactions, further supporting the paradigm of integrated nutrient management for sustainable agriculture [76–78]. In our experiment, the augmentation in green and dry fodder yields, achieved through intensified dosages and integrated K management, can be attributed to the elevation of yield-contributing factors like plant height, leaf count, and dimensions. Moreover, potassium ions ($K+$) distinctly influence auxin concentrations and their movement from roots to shoots, accentuating multifaceted impact of K on various facets of plant growth and development in tobacco [61]. These enhancements align with fundamental role of K in processes such as photosynthesis facilitation, cell division and elongation, and efficient nutrient and water transportation through roots [22].

In the context of nutrient uptake, treatment T_8 exhibited the highest uptake of both macro and micronutrients, a trend paralleled by treatments T_7, T_5, and T_2, while also demonstrating statistical significance when compared to the remaining treatments (Fig. 4A-C and Fig. 5A-D). In our study, the escalation in N concentration is attributed to role of K in the distribution of nitrate (NO_3^-) between root and shoot compartments, possibly mediated through synergistic interactions between N and K elements. Previous studies reported that the synergistic effects on growth attributes and nutrient uptake when nitrogen is applied along with increasing rate of potassium application in cereal crops [79,80]. Akhtar et al. (2022) also substantiated that elevated K supply augments N uptake in cotton cultivars under varied moisture regimes [81]. Furthermore, the enhanced uptake of P, K, and micronutrients in treatments T_8, T_7, and T_5 can be linked to the integrated application of K through MOP, FYM, PGPR, and nano potash, thereby increasing the availability of these nutrients via mechanisms like solubilization, mineralization, and translocation [82–84]. The augmented uptake of both macro and micronutrients in T_2 treatment can be attributed to heightened K availability and its synergistic impact on the availability and uptake of other nutrients [77,85–87]. The low macro and micro nutrient uptake in treatment T_1 may be due to poor macro and micro nutrient supply.

Fodder plays a fundamental role as a primary energy source in livestock husbandry. Nutritional deficiencies significantly impact plant growth, thereby influencing the energy fractions subsequently provided to livestock [88,89]. The investigation of DE, DFE, ME, and NE across treatments, as depicted in Table 1, reveals noteworthy discrepancies. Particularly, treatment T_2 exhibits the highest values for DE, DFE, ME, and NE, on par with T_7 and T_8, suggesting enhanced energy content compared to the control (T_1). The energy composition of fodder is intricately linked to its content of neutral detergent fibre, acid detergent fibre, and crude protein [90–92]. In this study, elevated energy fractions in T_2, T_7, T_8, and T_5 stem from reduced neutral and acid detergent fibre and increased crude protein content due to improved nutrient availability. Notably, Kumar et al. (2021) affirms that integrated K fertilization from diverse sources bolsters microbial populations, soil enzymatic activities, and nutrient availability, fostering crop growth and yield [29]. This increased nutrient availability curtails the formation of fibre fractions. Jahansouz et al. (2014) emphasize heightened energy fractions attributed to elevated crude protein and diminished fibre, a correlation dependent on nutrient accessibility for plant uptake and growth [93]. Corresponding findings are echoed by other researchers [94–97].

The investigation into available nutrient levels within the treatment groups unveils significant variations, underscoring the impact of different approaches on nutrient availability, as presented in Table 2. Particularly noteworthy is treatment T_7's demonstration of the highest available N concentration, bearing statistical parity with T_6 and displaying marked superiority over the remaining treatments. Likewise, Treatment T_5 parallels T_6 while notably surpassing the control (T_1). In contrast, treatments T_2 to T_4 exhibit comparatively diminished available N levels, mirroring the control (T_1). Conversely, the variation in P availability is not statistically significant across treatments. Treatment T_7 emerges with the highest P availability, while T_1 exhibits the lowest. Shifting focus to available K, Treatment T_7 showcases elevated levels, aligning with T_8, T_5, T_2, and T_3, thereby significantly outperforming the other treatments. In contrast, Treatment T_1 yields the lowest available K levels post-harvest. Kumar et al. (2021) affirms the augmentation of nutrient availability in treatments integrating K fertilization from diverse sources, which facilitates microbial populations, soil enzymatic activities, and nutrient accessibility, ultimately fostering robust crop growth and yield [29]. Notably, the absence of K application in T_1 results in a notable scarcity of nutrients. These results are in conformity with [98,99].

The investigation reveals a robust positive correlation between plant morphology, dry matter accumulation, leaf characteristics, root characteristics, and the enhancement of Chinese cabbage yield, as depicted in Fig. 6. Notably, the augmented application of K, administered through integrated sources such as MOP, FYM, PGPR, and nano potash foliar spray, or through exclusive use of MOP, demonstrates heightened efficacy among the treatments, surpassing treatments with lower K inputs or those devoid of K application. This efficacy is evident in the distinct relationships observed among the treatments, discerned through regression analysis of diverse parameters, as illustrated in Fig. 7. The correlation between improved plant growth and development and the heightened uptake of nutrients, facilitated by the augmented application of integrated K at higher doses compared to lower doses or absence of K, further underscores the pivotal role of integrated K application in optimizing nutrient availability and plant productivity.

5. Conclusion

This study has elucidated substantial variations in the morphological and root characteristics of Chinese cabbage under distinct treatment regimens. Treatment 100% RDK +25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS (T_7) and 75% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS (T_7) exhibited significant enhancements in plant morphological characteristics (plant height, leaf count, leaf dimensions, dry matter accumulation, leaf area, leaf area index, stem girth, leaf: stem ratio) and root characteristics (root volume and root length), accentuating its role in promoting growth and But, treatment 75% RDK + 25% K augmentation through FYM + PGPR and nano K fertilizer spray at 25 and 40 DAS (T_7) prominently influenced nutrient uptake, energy fractions, and maintain the soil fertility, showcasing its potential for enhancing plant growth, yield and quality of Chinese cabbage. Multivariate analysis also highlighted treatment T_7's efficacy and potential, reinforcing its strategic significance in advancing sustainable agricultural practices for improved crop productivity and resource utilization.

Data availability statement

The microbial strains used in consortium formulation was deposited in Microbial Type Culture Collection (MTCC), Chandigarh, India. The accession no. Of sotrains is MTCC 25043 (*Pseudomonas straita*), MTCC 25044 (*Bacillus decolorationis*), and MTCC 25045 (*Azotobacter chroococcum*). Further, any data required will be made available by authors, without undue reservation.

CRediT authorship contribution statement

Mahendra Choudhary: Writing – original draft, Investigation, Formal analysis, Data curation. **Kamal Garg:** Resources, Methodology, Data curation. **Marthala Bhuvaneswar Reddy:** Investigation, Formal analysis. **Babu Lal Meena:** Validation, Methodology, Formal analysis. **Biswajit Mondal:** Visualization, Validation. **Mangal Deep Tuti:** Visualization, Data curation. **Sudhir Kumar:** Visualization, Validation, Methodology, Data curation. **Mukesh Kumar Awasthi:** Writing – review & editing. **Balendu Shekher Giri:** Writing – review & editing, Validation. **Sanjeev Kumar:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Mahendra Vikram Singh Rajawat:** Writing – review & editing, Formal analysis, Data curation.

Declaration of competing interest

Authors declare that there is no conflict of interest.

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