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# Performance of Various Genotypes with Different Plant Geometry to Integrated Nutrient Management on Yield, Quality and Nutrient Uptake of Sunflower

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**ABSTRACT**

Two field experiments were conducted during February, 2024 to May, 2024 and June, 2024 to September 2024 at Annamalai University to evaluate the combined effects of genotype, plant spacing and INM on sunflower performance in North Eastern region Tamil Nadu. The experimental frame work was methodically established as Factorial Randomized Block Design comprising 20 treatments and 3 replications. The particulars of the treatments incorporated into the experimental design consisted of Factor-A (Genotypes and Spacing): $A_1$ - COSFH4 with 60×30 cm, $A_2$ - COSFH4 with 60×45 cm, $A_3$ - KBSH 44 with 60×30 cm, $A_4$ - KBSH 44 with 60×45 cm and Factor-B (Integrated Nutrient Management): $B_1$ – Control, $B_2$ - 100 % RDF + 45 kg S $ha^{-1}$, $B_3$ - 75 % RDN+100 % P K +25 % N through vermicompost (VC) + 45 kg S $ha^{-1}$, $B_4$ - 75 % RDN + 100 % P K +25 % N through poultry manure (PM) + 45 kg S $ha^{-1}$ and $B_5$ - 75 % RDN + 100 % P K +12.5 % N through VC +12.5 N through PM + 45 kg S $ha^{-1}$. The findings indicated that yield, quality and nutrient uptake were markedly influenced by the various genotypes, plant geometry and integrated nutrient management practices. Among the diverse genotypes and spacings assessed, the genotype COSFH4 at a spacing of 60×30 cm ($A_1$) distinctly exhibited the highest yield, quality and nutrient uptake of sunflower in both the crops. Concerning the array of integrated nutrient management practices implemented the treatment $B_5$significantly yielded maximum values for yield, quality and nutrient uptake of sunflower in both cropping seasons. The interaction effect between genotype and plant geometry, along with integrated nutrient management (A × B), was found to be statistically significant. In terms of interactions, $A_1B_5$ significantly achieved the highest seed yield (2441.74 and 2612.66 kg $ha^{-1}$), quality *viz.*, oil content (42.00 and 43.00 %), oil yield (1025.53 and 1101.42 kg $ha^{-1}$) and crude protein content (29.67 and 29.98 %) and nutrient uptake of N (81.27 and 82.82 kg $ha^{-1}$), P (22.13 and 22.55 kg $ha^{-1}$), K (73.41 and 74.80 kg $ha^{-1}$) and S(15.02 and 15.31 kg $ha^{-1}$) sunflower across both the crops. The lowest recorded values for yield, quality and nutrient uptake of sunflower were noted in the genotype KBSH 44 at a spacing of 60×45 cm in conjunction with the control treatment ($A_4B_1$) throughout both the crops.

***Key words:*** *Genotype, Plant geometry, Integrated nutrient management (INM), Yield and nutrient uptake.*

## Introduction

India is recognized as a significant global contributor to the production of oilseeds, which are crucial to the agricultural economy of the nation. Ranking second only to food grains in terms of cultivated land area, production levels, and economic significance (Agriculture Statistics at a Glance, 2024), oilseeds serve as a primary nutritional resource, providing substantial oil content, dietary fiber, essential fatty acids, and critical micronutrients, including vitamin E, niacin, folate, phosphorus, iron, and magnesium. In addition to their role as edible oil, oilseeds constitute essential raw materials for industries engaged in the manufacture of soaps, paints, varnishes, lubricants, perfumes, and hydrogenated fats. Nevertheless, the domestic consumption of edible oil is rising at an annual rate of 6%, while the growth in production remains a mere 2%, thereby exacerbating the supply-demand disparity. In the fiscal year 2021–22, India recorded an edible oil consumption of 22 million metric tonnes juxtaposed against a production output of only 11.1 million tonnes. With the population anticipated to reach 1.5 billion by 2030 and 1.67 billion by 2040, the demand for edible oil is projected to surge to 30 million tonnes by 2030–31 and 33 million tonnes thereafter (Oilseed Division, Department of Agriculture and Farmers Welfare, 2022). Addressing this gap necessitates the expansion of oilseed cultivation through the deployment of high-yielding hybrid and varieties, the application of balanced fertilization, efficient water resource management, and enhanced weed control practices. The potential of rice fallow lands, particularly in Tamil Nadu's Cauvery Delta, could be significantly realized through supplementary irrigation and optimized plant spacing, thereby substantially augmenting production levels. The implementation of integrated nutrient management incorporating both organic and inorganic inputs can guarantee a balanced supply of macro, secondary, and micronutrients, while regionally adapted hybrids can improve nutrient uptake efficiency. Sunflower (*Helianthus annuus* L.), a principal oilseed belonging to the Asteraceae family and indigenous to North America, presents considerable promise within this framework. Tamil Nadu stands out as a prominent sunflower-producing state, cultivating 0.01 million hectares which accounts for 2.65% of total sunflower area, producing 0.01 million tonnes, contributing 2.79% to the total production, and achieving an average yield of 1050 kg per hectare (AgriStat India, 2024). At present, the global per capita availability of oilseeds is 21.4 kg, in contrast to 17.8 kg in India and 16.8 kg in Tamil Nadu. The genotypic variability within sunflower significantly influences yield characteristics such as seed size, oil content, and adaptability to varying agro-climatic conditions, thereby emphasizing the necessity of selecting appropriate genotypes to enhance productivity. Maximizing the productivity of sunflower cultivation is contingent upon the deployment of high-yielding genotypes that are specifically adapted to particular agroecological zones, as such varieties typically exhibit heightened responsiveness to nutrient inputs and exhibit superior tolerance to environmental stresses (Meena, 2017). Equally critical is the configuration of plant geometry, notably row spacing and plant density, which directly influences resource utilization efficiency, encompassing light interception, nutrient absorption, and intra-plant competition, thereby impacting both seed and oil yields. The optimization of spacing, particularly within intercropping frameworks, enhances land use efficiency and contributes to yield stability (Kalaiyarasan *et al*., 2019). Integrated Nutrient Management (INM), which synergistically amalgamates organic manures with chemical fertilizers, assumes a crucial role in augmenting nutrient availability, enhancing soil fertility, and sustaining crop yields over temporal scales, particularly in soils deficient in nutrients (Dambale *et al*., 2018; Kalaiyarasan *et al*., 2019). A judiciously balanced nutrient strategy under the INM framework not only diminishes input costs but also fosters long-term soil health and productivity (Mukherjee *et al*., 2019). Consequently, evaluating sunflower performance across diverse genotypes, planting geometries, and INM regimes is imperative for realizing sustainable yield enhancements and ensuring agricultural resilience (Mahapatra *et al*., 2021). Among the essential nutrients, nitrogen holds paramount importance for sunflower development, influencing seed maturation, protein and oil biosynthesis, and leaf area expansion, thereby facilitating enhanced assimilate translocation to reproductive structures (Deepika *et al*., 2022). Phosphorus, although frequently immobilized in the soil matrix, is vital for root development and energy metabolism; its uptake is notably augmented through the concurrent application of nitrogen and potassium, all of which contribute substantially to yield enhancement (Adhikary *et al*., 2018). Sulphur, now recognized as the fourth primary nutrient following NPK, plays an integral role in chlorophyll synthesis and in the formation of essential compounds such as sulphur-containing amino acids, oils, vitamins, and enzymes. When administered in conjunction with NPK, sulphur has been documented to enhance both oil content and seed yield (Saleem *et al*., 2019; Ravikumar *et al*., 2021; Patel *et al*., 2023). The integration of sulphur with organic nutrient sources under the INM paradigm has demonstrated additional benefits, particularly during the flowering period of sunflower (Kalaiyarasan *et al*., 2019). Nonetheless, investigations centered on INM within rice fallow systems remain sparse, highlighting the necessity for localized research that intertwines genotype selection, optimal spacing, and nutrient strategies to augment yield while preserving soil integrity, particularly in regions deficient in sulphur. The utilization of organic manures, particularly poultry manure, has been empirically shown to significantly enhance sunflower growth parameters such as dry matter accumulation, plant stature, and stem girth throughout all developmental phases (Mokgolo *et al*., 2019). Poultry manure is esteemed for its rich nutrient profile, encompassing considerable quantities of nitrogen, phosphorus, potassium, and essential micronutrients. It is particularly efficacious in the bioavailability of phosphorus relative to other organic sources and contributes to improved soil health by elevating pH, organic matter content, accessible phosphorus, exchangeable cations, and micronutrient concentrations, whilst concurrently mitigating exchangeable aluminium, iron, and bulk density. Notably, poultry manure has the potential to increase soil nitrogen levels by up to 53%, with elevated application rates further enhancing the bioavailability of nitrogen and phosphorus (Alauddin, 2021). Similarly, vermicompost is a nutrient-rich, stable organic amendment produced through earthworm digestion of organic residues, has proven effective in enhancing soil fertility by improving its physical structure, nutrient profile, and biological activity (Anusuyadevi *et al*., 2023). It enhances water retention capacity, boosts microbial populations, and increases nutrient availability, thereby supporting higher crop productivity (Devi, 2024). With the rising demand for sustainable agricultural practices, vermicompost is gaining importance as an eco-friendly alternative to chemical fertilizers, contributing to long-term soil health and sustainable crop production (Thirunavukkarasu *et al*., 2023).In light of these findings, the present investigation was undertaken to evaluate the performance of sunflower genotypes for yield maximization under varied plant geometry and integrated nutrient management strategies.

## Materials and Methods

The field investigations were conducted at the Experimental Farm of Annamalai University, located in Annamalai Nagar, Tamil Nadu, India during February-May 2024 and June-September 2024. The soil characteristics of the experimental site were indicative of the terminal region of the Cauvery delta. The texture of the soil at the experimental site was classified as clay loamy. The nutrient profile of the experimental soil exhibited a deficiency in available nitrogen, a moderate level of available phosphorus, a surplus of available potassium and low available sulphur. The sunflower hybrids selected for the experimentation were KBSH 44 and COSFH4. The experimental design was formulated as a Factorial Randomized Block Design, comprising 20 distinct treatments and 3 replications. The detailed specifications of the treatments integrated into the experiments included; Factor-A (Genotypes and Spacing): $A_1$ - COSFH4 with 60×30 cm, $A_2$ - COSFH4 with 60×45 cm, $A_3$ - KBSH 44 with 60×30 cm, $A_4$ - KBSH 44 with 60×45 cm and Factor-B (Integrated Nutrient Management): $B_1$ – Control, $B_2$ - 100 % RDF + 45 kg S $ha^{-1}$, $B_3$ - 75 % RDN+100 % P K +25 % N through vermicompost (VC) + 45 kg S $ha^{-1}$, $B_4$ - 75 % RDN + 100 % P K +25 % N through poultry manure (PM) + 45 kg S $ha^{-1}$ and $B_5$ - 75 % RDN + 100 % P K +12.5 % N through VC +12.5 N through PM + 45 kg S $ha^{-1}$.The sunflower crop was fertilized in accordance with the treatment schedule. The seeding rate employed was 5 kg $ha^{-1}$ with sowing conducted at a depth of 2-3 cm, utilizing different spatial arrangements of 60×30 cm and 60×45 cm. A recommended dose of fertilizers (RDF) at 60:90:60 kg of NPK $ha^{-1}$was adhered to and administered in the form of urea, DAP, and muriate of potash. Half of the nitrogen dosage, along with the full quantities of phosphorus and potassium, were applied at the base; the remaining nitrogen was supplied as top dressing at 30 days after sowing (DAS). Vermicompost and poultry manure were applied basally to substitute nitrogen as per the treatment schedule. Five representative plants within the net plot were randomly selected and labelled, and observations regarding yield and quality parameters were documented at the harvest stage of the crop. The plant samples collected for dry matter production (DMP) at harvest were ground into a fine powder for subsequent chemical analysis. The experimental data were subjected to statistical analysis as per the methodology proposed by Panse and Sukhate (1978). For determining significant results, the critical difference was calculated at a probability level of 5%.

## Results and Discussion

### Yield (Table 1)

The details of the experiments are furnished in Table 1 indicated that seed and stalk yield were significantly influenced by different genotypes, plant geometry and INM practices. Among the different genotypes and spacing tried, the genotype COSFH4 at 60×30 cm spacing ($A_1$) registered the highest values for yield *viz*., seed yield (1914.45 and 2042.04 kg $ha^{-1}$) and stalk yield (3833.88 and 3906.73 kg $ha^{-1}$) in both crop seasons, which was followed by KBSH44 at 60×30 cm ($A_3$). The lowest values for seed yield (1225.93 and 1311.74 kg $ha^{-1}$) and stalk yield (2838.07 and 2885.40 kg $ha^{-1}$) were recorded in KBSH44 at 60×45 cm ($A_4$) in both crop seasons. The improvement of growth attributes contributes to higher yield attributes which lead to enhanced yield and also absence of crop competition resulting in higher nutrient uptake, higher photosynthetic assimilates production and effective portioning from source to sink. The results are in agreement with the findings of Rahangdale *et al.* (2024); Yasir and Abed (2025).

Regarding various INM practices imposed, the application of 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poultry manure compost ($B_5$) + 45 kg S $ha^{-1}$ significantly registered maximum values for yield *viz*., seed yield (2014.02 and 2146.97 kg $ha^{-1}$) and stalk yield (3964.93 and 4040.26 kg $ha^{-1}$) over the rest of the treatments in both crop seasons. This was followed by 75 % RDN + 100 % PK + 25 % N through poultry manure + 45 kg S $ha^{-1}$($B_4$). The minimum values for seed yield (870.61 and 931.55 kg $ha^{-1}$) and stalk yield (2440.50 and 2478.63 kg $ha^{-1}$) were recorded under control ($B_1$) in both crop seasons. This could be attributed to the availability of nutrients enhanced nutrient absorption, better photosynthetic production, and more efficient distribution of resources from source to sink. The improved movement of photosynthetic products to growth sites contributed to better growth and yield outcomes. The best results were obtained from the combined application of inorganic fertilizer and organic manures. This might be applied to achieve better yield for sunflower plants. These results are in agreement with findings of Sharma *et al.* (2022); Araganji *et al.* (2024); Bahuguna *et al*. (2025).

The interaction effect between genotype and plant geometry and nutrient management (A×B) was found to be statistically significant. Regarding interactions, the genotype COSFH4 with spacing of 60×30 cm along with 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poultry manure + 45 kg S $ha^{-1}$ ($A_1B_5$) significantly registered the maximum values for yield *viz*., seed yield (2441.74 and 2612.66 kg $ha^{-1}$) and stalk yield (4563.79 and 4650.50 kg $ha^{-1}$) in both crop seasons. This was followed by the genotype KBSH44 with the spacing of 60×30 cm along with 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poultry manure + 45 kg S $ha^{-1}$ ($A_3B_5$). The minimum values for seed yield (716.50 and 766.65 kg $ha^{-1}$) and stalk yield (2320.28 and 2331.40 kg $ha^{-1}$) were recorded under the genotype KBSH 44 with the spacing 60×45 cm along with control ($A_4B_1$) in both crop seasons. This might be the result of improved crop growth, which is driven by effective fertilizer and optimum spacing. This allows plants to create more photosynthate, which accumulates in the sink. Higher applications of nitrogen and sulphur are considered to increase seed yield because of the availability of sufficient nutrients and improved growth. In particular, increased seed setting and filling is facilitated by the build-up of amino acids and amides and their effective transfer to reproductive organs. The application of organics such as vermicompost and poultry manure had a notable impact on both the size of the flower head and the number of seeds $head^{-1}$. This might be attributed to increased photosynthetic efficiency during the vegetative phase, which results in higher head dry matter accumulation and increased nutrient availability, particularly in the case of nitrogen and phosphorus supply due to the application of composted poultry manure and vermicompost. Similar finding was observed by Bangaru *et al.* (2024); Manzoor *et al*. (2024); Nandhini *et al.* (2024); Sahu *et al*. (2024).

### Quality parameters (Table 1)

The details of the experiments are furnished in Table 1 indicated that quality parameters such as oil content, oil yield and crude protein content were significantly influenced by different genotypes, plant geometry and INM practices. Among the different genotypes and spacing tried, the genotype COSFH4 at 60×30 cm spacing ($A_1$) registered the highest values for quality parameters *viz*., oil content (39.86 and 41.04 %), oil yield (781.74 and 839.59 kg ha$^{-1}$) and crude protein content (27.58 and 27.73 %)in both crop seasons, which was followed by KBSH44 at 60×30 cm ($A_3$). The lowest values for oil content (36.48 and 38.14 %), oil yield (469.39 and 503.20 kg ha$^{-1}$) and crude protein content (25.14 and 25.26 %) were recorded in KBSH44 at 60×45 cm ($A_4$) in both crop seasons. The superior performance in oil content, oil yield, and crude protein content can be attributed to its genetic potential and optimal plant population achieved under closer spacing. COSFH4 may possess inherently higher metabolic efficiency and resource-use traits, allowing it to accumulate more oil and protein in seeds. The closer spacing (60×30 cm) likely enhanced intraspecific competition to a moderate level, stimulating greater nutrient uptake and more efficient light interception per unit area, which in turn promoted better synthesis of energy-dense compounds such as oil and protein. The results are in agreement with the findings ofAhmad *et al*. (2024); Jamir *et al*. (2025).

Regarding various INM practices imposed, the application of 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poultry manure compost + 45 kg S ha$^{-1}$ ($B_5$) significantly registered maximum values for quality parameters*viz*., oil content (40.20 and 41.93 %), oil yield (815.77 and 876.11 kg ha$^{-1}$) and crude protein content (28.16 and 27.96 %) over the rest of the treatments in both crop seasons. This was followed by 75 % RDN + 100 % PK + 25 % N through poultry manure + 45 kg S ha$^{-1}$ ($B_4$). The minimum values for oil content (34.80 and 36.66 %), oil yield (329.47 and 352.16 kg ha$^{-1}$) and crude protein content (24.16 and 24.26 %) were recorded under control ($B_1$) in both crop seasons.The superior performance in quality characters can be attributed tothe combined benefits of organic and inorganic nutrients, ensuring balanced and sustained nutrient availability. Vermicompost enhances soil health and microbial activity, while poultry manure supplies readily available nutrients. This synergy improves nutrient uptake, boosts metabolic efficiency, and promotes higher oil and protein accumulation in seeds, resulting in improved quality parameters. The results are in agreement with the findings of Ayenew *et al.* (2024); Monika *et al*. (2024); Amanullah Yasir *et al.* (2025).

The interaction effect between genotype and plant geometry and nutrient management (A×B) was found to be statistically significant. Regarding interactions, the genotype COSFH4 with spacing of 60×30 cm along with 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poultry manure + 45 kg S ha$^{-1}$ ($A_1B_5$) significantly registered the maximum values for quality parameters *viz*., oil content (42.00 and 43.00 %), oil yield (1025.53 and 1101.42 kg ha$^{-1}$) and crude protein content (29.67 and 29.98 %) in both crop seasons. This was followed by the genotype KBSH44 with the spacing of 60×30 cm along with 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poul-

**Table 1.** Effect of plant geometry and INM on yield and quality of sunflower.

| Treatments | Seed Yield (Kg ha$^{-1}$) | | Stalk Yield (kg ha$^{-1}$) | | Oil Content (%) | | Oil Yield (kg ha$^{-1}$) | | Crude Protein Content (%) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | I Crop | II Crop | I Crop | II Crop | I Crop | II Crop | I Crop | II Crop | I Crop | II Crop |
| Factor A - Genotypes and Spacings | | | | | | | | | | |
| **$A_1$** | 1914 | 2042 | 3833 | 3906 | 39.86 | 41.04 | 782 | 840 | 27.58 | 27.73 |
| **$A_2$** | 1317 | 1409 | 2967 | 3023 | 37.04 | 38.66 | 505 | 543 | 25.57 | 25.72 |
| **$A_3$** | 1819 | 1934 | 3719 | 3790 | 39.36 | 40.69 | 739 | 794 | 27.24 | 27.38 |
| **$A_4$** | 1226 | 1312 | 2838 | 2885 | 36.48 | 38.14 | 469 | 503 | 25.14 | 25.26 |
| **C. D. (P = 0.05)** | 36.08 | 38.45 | 75.52 | 76.94 | 0.86 | 0.90 | 24.40 | 15.53 | 0.335 | 0.312 |
| **S. Ed** | 17.83 | 18.99 | 37.31 | 38.01 | 0.43 | 0.44 | 12.05 | 7.67 | 0.167 | 0.158 |
| Factor B - Integrated Nutrient Management practices | | | | | | | | | | |
| **$B_1$** | 871 | 932 | 2440 | 2478 | 34.80 | 36.66 | 329 | 352 | 24.16 | 24.26 |
| **$B_2$** | 1481 | 1585 | 3169 | 3229 | 37.80 | 39.13 | 581 | 624 | 26.05 | 26.21 |
| **$B_3$** | 1652 | 1768 | 3429 | 3494 | 38.60 | 40.03 | 660 | 709 | 26.61 | 26.67 |
| **$B_4$** | 1827 | 1939 | 3693 | 3763 | 39.40 | 40.96 | 733 | 787 | 27.15 | 27.31 |
| **$B_5$** | 2014 | 2147 | 3964 | 4040 | 40.20 | 41.93 | 816 | 876 | 27.96 | 28.16 |
| **C. D. (P = 0.05)** | 40.34 | 42.99 | 84.43 | 86.02 | 0.77 | 0.93 | 27.28 | 17.36 | 0.669 | 0.412 |
| **S. Ed** | 19.93 | 21.24 | 41.71 | 42.49 | 0.48 | 0.50 | 13.48 | 8.58 | 0.262 | 0.206 |

try manure + 45 kg S ha$^{-1}$ ($A_3B_5$). The minimum values for oil content(33.60 and 35.50 %), oil yield (269.40 and 282.59 kg ha$^{-1}$) and crude protein content (23.07 and 23.25 %)were recorded under the genotype KBSH 44 with the spacing 60×45 cm along with control ($A_4B_1$) in both crop seasons. The superior performance in quality characters can be attributed tothe high genetic potential of COSFH4, combined with optimal plant density at 60×30 cm, ensured efficient resource utilization. Additionally, the integrated nutrient application provided a balanced and continuous nutrient supply, enhancing plant metabolism, seed filling, and quality parameter expression. This synergy maximized nutrient uptake and biosynthesis, leading to superior seed quality. The results are in agreement with the findings of Jose *et al*. (2021); Meena *et al*. (2022); Asif *et al.* (2023); James *et al*. (2023).

**Nutrient uptake (Table 2)**

The details of the experiments are furnished in Table 2 indicated that nutrient uptake such as N uptake, P uptake and K uptake were significantly influenced by different genotypes, plant geometry and INM practices. Among the different genotypes and spacing tried, the genotype COSFH4 at 60×30 cm spacing ($A_1$) registered the highest values for nutrient uptake *viz*., N uptake (77.00 and 78.46 kg ha$^{-1}$), P uptake (20.74 and 21.14 kg ha$^{-1}$), K uptake (70.34 and 71.67 kg ha$^{-1}$) and S uptake (13.03 and 13.28 kg ha$^{-1}$)in both crop seasons, which was followed by KBSH44 at 60×30 cm ($A_3$). The lowest values for N uptake (71.01 and 72.04 kg ha$^{-1}$), P uptake (18.34 and 18.61 kg ha$^{-1}$), K uptake (65.45 and 66.40 kg ha$^{-1}$) and S uptake (10.22 and 10.37 kg ha$^{-1}$) were recorded in KBSH44 at 60×45 cm ($A_4$) in both crop seasons. The highest nutrient uptake can be attributed to its vigorous growth habit, efficient root system, and better nutrient use efficiency. The closer spacing enhanced plant population per unit area, leading to improved resource capture, while the genotype's genetic potential supported higher nutrient absorption and translocation, resulting in maximum uptake. The results are in agreement with the findings of Pragatheeswaran *et al.* (2021); Gsenan *et al*. (2024).

Regarding various INM practices imposed, the application of 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poultry manure compost + 45 kg S ha$^{-1}$ ($B_5$) significantly registered maximum values for nutrient uptake *viz*., N uptake (77.76 and 79.23 kg ha$^{-1}$), P uptake (21.07 and 21.47 kg ha$^{-1}$), K uptake (71.02 and 72.36 kg ha$^{-1}$) and S uptake (13.45 and 13.71 kg ha$^{-1}$) over the rest of the treatments in both crop seasons. This was followed by 75 % RDN + 100 % PK + 25 % N through poultry manure + 45 kg ha$^{-1}$ ($B_4$). The minimum values for N uptake (68.45 and 69.36 kg ha$^{-1}$), P uptake (16.95 and 17.17 kg ha$^{-1}$), K uptake (62.42 and 63.25 kg ha$^{-1}$), and S uptake (8.75 and 8.87 kg ha$^{-1}$) were recorded under control ($B_1$) in both crop seasons.The superior nutrient uptake is due to the combined application of organic and inorganic nutrient sources, which ensured continuous and balanced nutrient availability throughout the crop growth period.

**Table 2.** Effect of plant geometry and INM on N, P, K and S uptake of sunflower.

| Treatments | N uptake(Kg ha$^{-1}$) | | P uptake(kg ha$^{-1}$) | | K uptake(kg ha$^{-1}$) | | S uptake(kg ha$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|
| | ICrop | IICrop | ICrop | IICrop | ICrop | IICrop | I Crop | II Crop |
| Factor A - Genotypes and Spacings | | | | | | | | |
| **$A_1$** | 77.00 | 78.46 | 20.74 | 21.14 | 70.34 | 71.67 | 13.03 | 13.28 |
| **$A_2$** | 72.02 | 73.39 | 18.80 | 19.16 | 66.51 | 67.77 | 10.60 | 10.80 |
| **$A_3$** | 76.17 | 77.62 | 20.46 | 20.85 | 69.67 | 70.99 | 12.71 | 12.95 |
| **$A_4$** | 71.01 | 72.04 | 18.34 | 18.61 | 65.45 | 66.40 | 10.22 | 10.37 |
| **C.D. (P= 0.05)** | 0.82 | 0.83 | 0.27 | 0.27 | 0.65 | 0.67 | 0.26 | 0.28 |
| **S. Ed** | 0.41 | 0.41 | 0.14 | 0.14 | 0.33 | 0.33 | 0.13 | 0.12 |
| Factor B - Integrated Nutrient Management practices | | | | | | | | |
| **$B_1$** | 68.45 | 69.36 | 16.95 | 17.17 | 62.42 | 63.25 | 8.75 | 8.87 |
| **$B_2$** | 73.12 | 74.51 | 19.39 | 19.76 | 67.72 | 69.01 | 11.28 | 11.49 |
| **$B_3$** | 74.71 | 76.12 | 19.96 | 20.33 | 68.8 | 70.11 | 11.99 | 12.22 |
| **$B_4$** | 76.22 | 77.67 | 20.56 | 20.95 | 69.99 | 71.32 | 12.73 | 12.97 |
| **$B_5$** | 77.76 | 79.23 | 21.07 | 21.47 | 71.02 | 72.36 | 13.45 | 13.71 |
| **C.D. (P = 0.05)** | 1.55 | 1.52 | 0.50 | 0.50 | 1.02 | 1.02 | 0.29 | 0.30 |
| **S. Ed** | 0.78 | 0.76 | 0.24 | 0.25 | 0.51 | 0.51 | 0.15 | 0.15 |

Vermicompost and poultry manure enhanced soil microbial activity, improved nutrient mineralization, and increased nutrient availability and uptake efficiency. This synergy promoted better root development and absorption capacity, leading to significantly higher uptake of essential nutrients.The results are in agreement with the findings of Poonia *et al*. (2022); Ramamoorthy *et al*. (2023); Kumar *et al*. (2025).

The interaction effect between genotype and plant geometry and nutrient management (A×B) was found to be statistically significant. Regarding interactions, the genotype COSFH4 with spacing of 60×30 cm along with 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poultry manure + 45 kg S $ha^{-1}$ ($A_1B_5$) significantly registered the maximum values for nutrient uptake *viz*., N uptake (81.27 and 82.82 kg $ha^{-1}$), P uptake(22.13 and22.55 kg $ha^{-1}$), K uptake (73.41 and 74.80 kg $ha^{-1}$) and S uptake (15.02 and 15.31 kg $ha^{-1}$)in both crop seasons. This was followed by the genotype KBSH44 with the spacing of 60×30 cm along with 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poultry manure + 45 kg S $ha^{-1}$ ($A_3B_5$). The minimum values for N uptake (66.51 and 66.83 kg $ha^{-1}$), P uptake (15.95 and 16.03 kg $ha^{-1}$), K uptake (59.76 and 60.05 kg $ha^{-1}$) and S uptake (8.21 and 8.17 kg $ha^{-1}$) were recorded under the genotype KBSH 44 with the spacing 60×45 cm along with control ($A_4B_1$) in both crop seasons. The superior nutrient uptake is due to the synergistic effect of genotype potential, optimal spacing, and balanced nutrient supply. The high nutrient use efficiency of COSFH4, combined with optimum spacing, promoted better root growth and resource capture. Additionally, the integrated nutrient approach ensured continuous nutrient availability and improved soil health, enhancing overall nutrient absorption and translocation in plants.The results are in agreement with the findings of Pragatheeswaran *et al.* (2021); Ahmad and Tripathi (2022); Aziz *et al*. (2023); Bhargav *et al*. (2024).

## Conclusion

Based on the abovesaid facts, it can be concluded that the genotype COSFH4 with spacing of 60×30 cm along with 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poultry manure ($A_1B_5$) was an Agronomically sound and economically feasible practice to maximize the productivity and profitability of sunflower growing in north-eastern region of Tamil Nadu.

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### Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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