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RESEARCH ARTICLE

Response of sunflower genotypes to varying plant geometries and integrated nutrient management practices on growth and yield of sunflower

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Abstract

Field investigations were conducted at the experimental farm of Annamalai University during February-May and June-September 2024 to examine the combined effects of genotype, plant geometry and integrated nutrient management (INM) on sunflower growth, yield attributes and productivity in the North-Eastern zone of Tamil Nadu. The trial was laid out in a Factorial Randomised Block Design (FRBD) with 20 treatment combinations and three replications. Treatments comprised two factors: Factor-A (genotype and spacing): A_1- COSFH 4 at 60 × 30 cm, A_2- COSFH 4 at 60 × 45 cm, A_3- KBSH 44 at 60 × 30 cm and A_4- KBSH 44 at 60 × 45 cm; and Factor-B (INM levels): B_1- Control, B_2- 100 % RDF + 45 kg S ha^{-1}, B_3- 75 % RDN + 100 % PK + 25 % N through vermicompost + 45 kg S ha^{-1}, B_4- 75 % RDN + 100 % PK + 25 % N through poultry manure + 45 kg S ha^{-1} and B_5- 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poultry manure + 45 kg S ha^{-1}. Results demonstrated that genotype selection, spacing and INM significantly affected morphological, physiological and yield parameters. COSFH 4 at 60 × 30 cm (A_1) recorded superior performance. Among INM strategies, B_5 proved most effective in enhancing yield. Interaction effects were notable, with A_1B_5 achieving the highest seed yield (2441.74 kg ha^{-1}), while A_4B_1 was the lowest. The study underscores the pivotal role of genotype choice, optimum spacing and balanced INM in maximizing sunflower productivity in this region.

Keywords: genotype; growth attributes; INM; plant spacing; yield parameters

Introduction

India is one of the world's leading producer of oilseeds, ranking fourth globally after United States, China and Brazil (1). Oilseeds in India occupy about 13 % of the gross cropped area and contribute significantly to the country's economy. The per capita consumption of edible oil in India is 19.7 kg per year compared to the global average of 25kg per year. Among crops, oilseeds occupy the second position, surpassed only by food grains in terms of cultivated area, production and economic importance (2). Sunflower seeds are rich in oil, dietary fibre, vitamins (such as vitamin E, niacin and folate), minerals (including phosphorus, iron and magnesium) and essential fatty acids. oilseeds serve as vital sources of nutrition. In addition to their role in edible oil production, oilseeds are widely used in various industries for making paints, varnishes, soaps, perfumes, lubricants and hydrogenated oils. However, the domestic demand for vegetable oils and fats is increasing at a rate of 6 % annually, the production rate lags at just 2 % leading to a widening demand-supply gap. In 2021-22, India consumed 22 million metric tonnes of edible oil against a production of only 11.1 million metric tonnes. The population is anticipated to reach 1.5 billion by 2030 and 1.67 billion by 2040, leading to a forecast increase in edible oil demand to 30 million metric tonnes by 2030-31 and subsequently to 33 million metric tonnes by 2040 (3). To address this shortfall, it is imperative to expand oilseed cultivation through the adoption of intensive cropping systems, high-yielding varieties and hybrids, balanced nutrient management, efficient irrigation and effective weed control strategies. Utilizing rice fallow areas, particularly in Tamil Nadu's Cauvery Delta region, through supplemental irrigation and optimized plant geometry, offers significant potential to boost oilseed production. Integrated nutrient management involving the concurrent use of organic and inorganic fertilizers can fulfil the primary, secondary and micronutrient requirements of crops, while utilising location-specific hybrids can improve nutrient utilisation efficiency. Sunflower (*Helianthus annuus L.*) an important oilseed crop from the Asteraceae family and native to the northern United States and Mexico, demonstrates considerable potential in this regard. During 2022-2023, the all-India production of sunflower was 0.363 million metric tonnes, while that of oilseeds was 0.121 million metric tonnes. However, in 2023 - 2024, oilseeds dropped to 0.056 million metric tonnes and sunflower availability declined to 0.169

million metric tonnes (4). Tamil Nadu contributes about 2.65 % of total sunflower area in India with a production of 0.1 lakh tonnes and productivity of 1050 kg ha^{-1}. Per capita availability of oilseed is at 21.4 kg in global level, 17.8 kg in India and 16.8 kg in Tamil Nadu (5).

Maximizing sunflower yield required the selection of high-performing genotypes that were well-suited to specific agroecological conditions. Utilizing genotypes with inherent adaptability to nutrient variations and spacing can enhanced resource-use efficiency. Improved varieties responded better to nutrient management and exhibited greater stress tolerance (6). Plant geometry including optimal row spacing and plant density was equally vital as it influenced light interception, nutrient uptake and intra-specific competition, thereby affecting seed and oil yields. Strategic spacing particularly in intercropping systems, had been shown to improve land use efficiency and yield stability (7). Integrated Nutrient Management (INM), which entailed the synergistic use of organic manures and inorganic fertilizers is pivotal in augmenting nutrient availability, promoting soil health and sustaining crop output particularly in nutrient-deficient regions (8, 9). A balanced and integrated nutrient approach was essential to maintain soil fertility, optimize nutrient supply and maximize yields with minimal input costs (10). Thus, evaluating sunflower genotypes under varied plant geometries and INM practices was crucial for achieving sustainable yield improvements and promoting long-term agricultural sustainability (11). Nitrogen is essential for the growth, yield and productivity of sunflowers markedly affecting seed development, oil and protein content and increase of the photosynthetic surface area, hence improving the transfer of assimilates to reproductive structures (12). Phosphorus, second only to nitrogen in importance is vital for root development and energy transfer. Its efficiency improves in the presence of nitrogen and when combined with potassium and another key nutrient, it contributes positively to yield enhancement (13). Sulphur acknowledged as the fourth important macronutrient facilitates chlorophyll synthesis and the production of sulphur-containing amino acids, lipids, vitamins and enzymes vital to metabolism. Its application can increase oil and seed yields significantly with synergistic effects observed when applied alongside recommended NPK levels (14-16). Integrated Nutrient Management (INM) particularly when sulphur is combined with organic sources has been shown to enhance growth and yield traits of sunflower especially during flowering (7). Rice fallow soils in Tamil Nadu commonly suffer from nutrient depletion and moisture stress after paddy harvest, limiting the availability of nitrogen, phosphorus and other essential nutrients needed for sunflower growth (8). Nevertheless, few studies have concentrated on the implementation INM strategies in rice fallow conditions, underscoring the need for localised research on genotype selection, optimal spacing and inorganic nutrient management practices to enhance productivity and maintain soil health in sulphur-deficient agroecosystems.

The application of organic fertilizers particularly poultry manure significantly enhances plant growth parameters such as dry matter accumulation, plant height and stem diameter across all growth stages of sunflower (17). Poultry manure is highly esteemed for its abundant nutrient composition featuring elevated levels of nitrogen, phosphorous, potassium and vital micronutrients. It is more efficient in releasing phosphorus to plants compared to other organic fertilizers (18). Furthermore, its utilisation enhances soil characteristics by elevating pH, organic matter content, accessible phosphorus, exchangeable cations and micronutrient concentrations, while diminishing exchangeable aluminium, iron and bulk density. Poultry manure significantly elevates soil nitrogen levels by as much as 53 % with increased application rates substantially augmenting the availability of nitrogen and phosphorus (19). Vermicompost, a stable and nutrient-dense organic fertiliser produced through the digestion of organic materials by earthworms, augments soil fertility by enhancing its physical, chemical and biological characteristics (20). It enhances water retention, nutrient accessibility and microbial activity resulting in heightened agricultural productivity (21). With growing interest in organic farming, vermicompost has emerged as a sustainable alternative to synthetic fertilizers, promoting soil health and crop production (22).

This experiment was conducted to assess sunflower genotypes for yield optimisation under different plant arrangements and INM.

Materials and Methods

Experimental site

Field investigations were conducted during February to May and June to September 2024 at the experimental farm, Annamalai University, Annamalai Nagar, Tamil Nadu, India, located at the latitude of 11°23′ N and longitude of 79°43′ E (The images of the experimental field are depicted in Fig. 1). The soil at both experimental sites exhibited a clay loam texture as determined using USDA method. It was characterized by low nutritional status in accessible nitrogen (271.0 and 264.4 kg ha^{-1}), a medium available phosphorus (19.55 and 21.85 kg ha^{-1}), high available potassium (314.80 and 307.50 kg ha^{-1}) and low sulphur (8.8 and 9.2 kg ha^{-1}).

Climatic conditions

The experimental site received a rainfall of 28.0 mm during first crop and 36.7 mm during second crop. The maximum temperature ranges from 31 °C to 39.5 °C and 35.2 °C to 37.5 °C. The minimum temperature for the corresponding period ranges from 18.3 °C to 23.9 °C and 20.8 °C to 23.7 °C.

Planting material

The Sunflower hybrids selected for the experiments, COFSH 4 and KBSH 44 were obtained from Department of oil seeds, TNAU, Coimbatore, Tamil Nadu and GKVK, Bangalore, Karnataka. The features of the hybrids are presented in the Table 1. The implemented seed rate was 5 kg ha^{-1} at a depth of 2-3 cm, with a spacing of 60 × 30 cm and 60 × 45 cm. The gross plot is 5 × 4 m. The net plot area was 3.8 × 3.4 m for 60 × 30 cm spacing and 3.8 × 3.1 m for spacing 60 × 45 cm.

Experimental design and treatments

The experiment was laid out in a FRBD with 20 treatment combinations; each replicated three times. Replications were arranged as blocks to minimize field variability and treatments within each block were randomly assigned to plots using a random number table (23). In total, 60 experimental plots were established. The treatments include A_1 - COSFH 4 with 60 × 30 cm, A_2 - COSFH 4 with 60 × 45 cm, A_3 - KBSH 44 with 60 × 30 cm, A_4 - KBSH 44 with 60 × 45 cm and Factor-B (INM): B_1 - Control, B_2 - 100 %

A. Crop I

B. Crop II

C. Best treatment

D. Least treatment

Fig. 1. General view of fields.

Table 1. Varietal description of genotypes

Cultivars	Parentage	Duration (days)	Plant height (cm)	Head diameter (cm)	100 seed weight (g)	Oil content (%)	Average yield (kg ha^{-1})
COSFH 4	COSF12A x IR 6	90-100	180 -200	26-30	5.5 - 6.4	40-42	2200-2700
KBSH 44	CMS-17A×RHA-95C-1	95-100	178 -186	23- 26	5.4 - 6.2	36-38	2200-2500

recommended dose of fertilizer (RDF) + 45 kg S ha^{-1}, B_3- 75 % RDN + 100 % PK + 25 % N through vermicompost (VC) + 45 kg S ha^{-1}, B_4- 75 % RDN + 100 % PK + 25 % N through poultry manure (PM) + 45 kg S ha^{-1} and B_5- 75 % RDN + 100 % PK + 12.5 % N through VC + 12.5 % N through PM + 45 kg S ha^{-1}.

Agronomic management

The sunflower crop was fertilized as per the treatment schedule. The RDF of 60:90:60 kg of NPK ha^{-1} was adhered to administered in the forms of urea, di-ammonium phosphate and muriate of potash. Nearly fifty percent dose of nitrogen and the full doses of phosphorus and potassium were applied as basal and the remaining nitrogen was applied as top dressing at 25 days after sowing (DAS). Nitrogen was substituted with vermicompost and poultry manure as per the treatment. The nutrient content of organics was given in Table 2. Sulphur was supplied at 45 kg ha^{-1} in the form of gypsum at 300 kg ha^{-1} to the treatment plots (B_2-B_5).

Observations recorded

Five representative plants inside the net plot were randomly tagged and data about growth *viz.* plant height with the help of meter scale, stem girth was measured at 60 DAS and at harvest stage at height of about 20 cm from the base of sampled plants using thread and measuring scale, chlorophyll content of the leaf was measured by chlorophyll meter (SPAD-502), days to 50 % flowering, dry matter production was calculated by sun drying the samples initially for 24 hr and subsequently oven dried at 80 °C to attend constant weight. Leaf area index was calculated by using following formula (24).

$$LAI = \frac{\text{Total leaf area plant}^{-1} \times \text{No. of leaves plant}^{-1} \times 0.73}{\text{Spacing}}$$

where 0.73 is the correction factor for leaf shape.

Yield attributers, *viz.* head diameter was calculated by the distance between two diametrically opposite ends of the capitulum, number of filled seeds were counted and then mean value of plant^{-1} was recorded, percentage of filled seeds per head was calculated by using formula,

$$\text{Percentage of filled seeds per head} = \frac{\text{Number of filled seeds per head} \times 100}{\text{Total number of seeds per head}}$$

Table 2. Nutrient composition of organic fertilizers

Organic fertilizers	Organic carbon (%)	Nitrogen (%)	Phosphorous (%)	Potassium (%)
Vermicompost	9.5-17.98	1.70	1.48	0.58
Poultry manure	27.8	2.49	2.10	2.03

100 seed weight was taken by counting one hundred filled seeds from each plant and weighed, seed yield was recorded at 14 % moisture content and stalk yield was recorded after sun drying the stalk.

Statistical analysis

The experimental data was statistically evaluated according to the previous recommendations (25). The critical difference for significant results was calculated at a 5 % probability level.

Results and Discussion

Effect of genotype and plant geometry on growth attributes

The data presented in Table 3 and 4 indicated that growth attributes were strongly affected by various genotypes and plant geometry. Among the assessed genotypes and spacings, the genotype COSFH 4 at a spacing of 60 × 30 cm (A_1) demonstrated the superior values for growth parameters, including plant height, leaf area index (LAI), dry matter production (DMP), chlorophyll content, 50 % flowering and stem girth per plant followed by KBSH 44 at 60 × 30 cm (A_3) in both the crops. The minimal values for growth qualities were observed in KBSH 44 at 60 × 45 cm (A_4) over both crops. The enhancement in growth features may be attributed to improved resource availability and less interplant competition within the community (26, 27).

Effect of INM on growth attributes

The application of diverse INM practices demonstrated a significant effect on the growth attributes of sunflower. Application of 75 % RDN + 100 % PK + 12.5 % N through VC + 12.5 % N through PM + 45 kg S ha^{-1} (B_5) markedly produced superior values for growth parameters encompassing plant height, LAI, DMP, chlorophyll content, 50 % flowering and stem girth per plant in comparison to alternative treatments across both crop seasons. This was succeeded by 75 % RDN + 100 % PK + 25 % N through PM + 45 kg S ha^{-1} (B_4). The control (B_1) exhibited the lowest growth parameter values in both the crops. The increased growth attributes might be due to the accessibility of all important

Table 3. Effect of genotype, plant geometry and INM on growth attributes of sunflower (crop I)

Treatments	Plant height (cm)			Leaf area index			Dry matter production (kg ha^{-1})			Chlorophyll content	Days to 50 % flowering	Stem girth (cm)	
	30 DAS	60 DAS	harvest	30 DAS	60 DAS	Harvest	30 DAS	60 DAS	Harvest			60 DAS	Harvest
Factor A- Genotypes and spacing													
A_1	77.41	141.60	153.91	2.54	4.48	3.81	799	3143	3550	13.55	54	7.89	9.75
A_2	55.84	97.43	105.90	2.12	4.02	3.46	626	2408	2747	11.70	58	6.06	7.57
A_3	74.16	134.86	146.59	2.48	4.41	3.75	771	3036	3444	13.29	54	7.64	9.43
A_4	52.52	90.23	98.34	2.06	3.94	3.39	598	2326	2640	11.32	58	5.82	7.24
C. D (p=0.05)	1.48	2.67	2.90	0.05	0.07	0.05	15.81	61.88	69.95	0.28	NS	0.16	0.19
S. Ed	0.73	1.32	1.43	0.03	0.05	0.04	7.81	30.57	34.56	0.14	0.65	0.08	0.10
Factor B - Integrated nutrient management													
B_1	39.53	63.82	69.69	1.82	3.64	3.20	485	2115	2275	10.06	61	4.75	5.92
B_2	61.84	109.63	119.16	2.23	4.16	3.55	678	2583	2935	12.24	57	6.55	8.18
B_3	68.16	122.26	132.89	2.36	4.29	3.63	725	2753	3176	12.80	55	7.09	8.82
B_4	74.47	135.04	146.78	2.48	4.42	3.74	775	2971	3420	13.34	54	7.67	9.46
B_5	80.91	149.41	162.40	2.61	4.56	3.88	829	3219	3671	13.88	53	8.20	10.10
CD (p=0.05)	1.66	2.99	3.25	0.06	0.11	0.07	17.68	69.18	78.21	0.31	NS	0.17	0.22
S. Ed	0.82	1.48	1.60	0.03	0.05	0.04	8.74	34.17	38.64	0.15	0.72	0.09	0.11

NS - non significant, A1 - COSFH4 at 60 × 30 cm, A2 - COSFH4 at 60 × 45 cm, A3 - KBSH 44 at 60 × 30 cm, A4 - KBSH 44 at 60 × 45 cm; and Factor-B (INM levels) B1 - Control, B2 - 100 % RDF, B3 - 75 % RDN + 100 % PK + 25 % N through vermicompost, B4 - 75 % RDN + 100 % PK + 25 % N through poultry manure and B5 - 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through poultry manure.

Table 4. Effect of genotype, plant geometry and INM on growth attributes of sunflower (crop II)

Treatments	Plant height (cm)			LAI			DMP (kg ha^{-1})			Chlorophyll content	Days to 50 % flowering	Stem girth (cm)	
	30 DAS	60 DAS	Harvest	30 DAS	60 DAS	Harvest	30 DAS	60 DAS	Harvest			60 DAS	90 DAS
Factor A- Genotypes and spacing													
A_1	80.16	140.94	170.79	2.57	4.54	3.86	813	3197	3617	15.52	54	9.05	10.35
A_2	58.20	94.04	134.26	2.15	4.08	3.50	636	2449	2799	12.95	57	6.97	7.39
A_3	76.81	133.42	165.13	2.51	4.47	3.80	784	3088	3509	15.16	54	8.72	9.97
A_4	54.81	91.02	125.38	2.08	3.98	3.42	606	2356	2679	12.52	57	6.66	6.99
CD (p = 0.05)	1.54	2.46	3.39	0.05	0.07	0.05	16.08	62.91	71.26	0.157	NS	0.18	0.20
S. Ed	0.76	1.22	1.68	0.03	0.05	0.04	7.94	31.07	35.20	0.078	0.01	0.09	0.10
Factor B - Integrated nutrient management													
B_1	41.61	70.56	98.58	1.83	3.67	3.23	484	2139	2305	10.86	60	5.33	5.81
B_2	64.30	105.78	146.41	2.26	4.22	3.59	678	2628	2990	13.75	56	7.53	8.01
B_3	70.72	118.84	156.18	2.39	4.35	3.68	725	2801	3236	14.45	55	8.16	8.93
B_4	77.14	132.35	166.64	2.51	4.48	3.79	775	3022	3484	15.21	54	8.83	9.85
B_5	83.73	146.75	176.64	2.64	4.62	3.93	729	3274	3740	15.93	53	9.40	10.77
CD (p = 0.05)	1.72	2.75	3.79	0.06	0.11	0.08	17.98	70.33	79.67	0.175	NS	0.20	0.22
S. Ed	0.85	1.36	1.87	0.03	0.11	0.05	8.74	34.74	39.36	0.175	0.03	0.10	0.11

elements that facilitate nutrient uptake, transport and absorption resulting in enhanced growth and development of the crop. Addition of sulphur through gypsum improved the solubility of different nutrients, thus enabling better nutrient uptake necessary for cellular increase, elongation and expansion during the entire development stage of the crop (28, 29).

Interactive effect of genotype, plant geometry and INM on growth attributes

The interaction effect between various genotype with varied plant geometry and integrated nutrient management (A × B) was statistically significant. The genotype COSFH 4 spaced at 60 × 30 cm coupled with 75 % RDN + 100 % PK + 12.5 % N through VC + 12.5 % N through PM + 45 kg S ha^{-1} (A_1B_5), exhibited significantly superior growth attributes including plant height, leaf area index, dry matter production, chlorophyll content and 50 % flowering and stem girth per plant in both the crops. This was followed by the genotype KBSH 44 with the spacing of 60 × 30 cm along with 75 % RDN + 100 % PK + 12.5 % N through VC + 12.5 % N through PM + 45 kg S ha^{-1} (A_3B_5). The lowest values for growth parameters were seen in the genotype KBSH 44 with a spacing of 60 × 45 cm alongside the control (A_4B_1) in both the crops. This may be due to enhanced nutritional availability and physiological efficiency due to the simultaneous application of organic and inorganic sources. Vermicompost and poultry manure not only released nutrients gradually but also improved the soil structure, microbial activity and moisture retention. These factors supported sustained leaf development and photosynthetic activity throughout the crop growth period. Sulphur played a key role in chlorophyll synthesis and protein metabolism promoting the active cell division and expansion in leaf tissues. Additionally, the optimum spacing ensured better light interception and minimized inter-plant competition contributing to the enhanced foliage growth (13, 30).

Effect of genotype and plant geometry on yield attributes and yield

The details of the experiments are furnished in Table 5 and 6 indicated that yield attributes and yield were significantly influenced by different genotypes and plant geometry. Among the different genotypes and spacing tried, the genotype COSFH 4 at 60 × 30 cm spacing (A_1) registered the highest values for yield attributes *viz.* Head diameter, number of seeds head^{-1}, no. of filled seeds head^{-1}, percentage of filled seeds head^{-1}, 100 seed weight and yield *viz.* seed yield and stalk yield in both the crops, which was followed by KBSH 44 at 60 × 30 cm (A_3). The minimum values for yield characteristics and yield were observed in KBSH 44 at 60 × 45 cm (A_4) during both crops. The enhancement of growth characteristics results in increased yield qualities and the elimination of crop competition leading to more nutrient absorption, elevated photosynthetic assimilate production and efficient allocation from source to sink (31, 32).

Effect of INM on yield attributes and yield

The application of 75 % RDN + 100 % PK + 12.5 % N through VC + 12.5 % N through PM + 45 kg S ha^{-1} (B_5) significantly resulted in enhanced yield attributes encompassing head diameter, seed

Table 5. Effect of genotype, plant geometry and INM on yield attributes and yield of sunflower (crop I)

Treatments	Head diameter (cm)	No. of filled seeds head^{-1}	Percentage of filled seeds head^{-1}	100 seed weight (g)	Seed yield (kg ha^{-1})	Stalk yield (kg ha^{-1})
Factor A- Genotypes and spacing						
A_1	25.39	713.41	83.60	6.05	1914	3834
A_2	19.30	600.48	78.72	5.10	1317	2967
A_3	24.72	693.72	82.95	5.84	1819	3719
A_4	18.73	577.79	77.63	4.96	1226	2838
CD (p = 0.05)	0.50	14.59	0.53	0.13	36.08	75.52
S. Ed	0.25	7.21	0.45	0.06	17.83	37.31
Factor B -Integrated nutrient management						
B_1	15.96	500.40	74.73	4.36	871	2441
B_2	20.75	632.78	80.15	5.45	1481	3170
B_3	22.95	666.08	81.50	5.59	1652	3430
B_4	24.70	697.89	82.92	5.87	1827	3693
B_5	25.83	734.61	84.33	6.16	2014	3965
CD (p = 0.05)	0.56	16.31	1.25	0.13	40.34	84.44
S. Ed	0.28	8.06	1.09	0.07	19.93	41.72

Table 6. Effect of genotype, plant geometry and INM on yield attributes and yield of sunflower (crop II)

Treatments	Head diameter (cm)	No. of filled seeds head^{-1}	Percentage of filled seeds head^{-1}	100 seed weight (g)	Seed yield (kg ha^{-1})	Stalk yield (kg ha^{-1})
Factor A- Genotypes and spacing						
A_1	25.85	769.08	88.62	6.22	2042	3907
A_2	19.65	647.33	83.45	5.24	1409	3024
A_3	25.16	747.85	87.55	6.00	1934	3790
A_4	19.00	622.87	82.29	5.08	1312	2885
CD (p = 0.05)	0.51	15.73	0.92	0.14	38.45	76.95
S. Ed	0.25	7.77	0.65	0.08	18.99	38.01
Factor B -Integrated nutrient management						
B_1	16.16	539.44	79.13	4.45	932	2479
B_2	21.12	682.15	84.74	5.60	1585	3230
B_3	23.36	718.04	86.39	5.75	1768	3495
B_4	25.14	752.34	87.82	6.04	1939	3764
B_5	26.29	791.93	89.31	6.33	2147	4040
CD (p = 0.05)	0.567	17.586	1.349	0.143	42.99	86.03
S. Ed	0.280	8.687	1.061	0.080	21.24	42.50

count per head, filled seed count per head, filled seed percentage, 100-seed weight, seed yield and stalk yield, in comparison to alternative treatments across both the crops. This was followed by 75 % RDN + 100 % PK + 25 % N through PM + 45 kg S ha^{-1} (B_4). The control treatment (B_1) exhibited the lowest values for yield characteristics and yield in both the crops. This might be because of the availability of nutrients, improved nutrient absorption, higher photosynthetic output and more effective resource distribution from source to sink. The enhanced transport of photosynthetic products to growth sites facilitated superior growth and yield results. The optimal outcomes were achieved through the synergistic use of inorganic fertilizers and organic manures. This may be utilised to enhance yield metrics for sunflower plants (33, 34).

Interactive effect of genotype, plant geometry and INM on yield attributes and yield

The interaction effect between genotype-plant geometry and INM (A × B) was found to be statistically significant. Regarding interactions, the genotype COSFH 4 with spacing of 60 × 30 cm along with 75 % RDN + 100 % PK + 12.5 % N through VC + 12.5 % N through PM + 45 kg S ha^{-1} (A_1B_5) significantly registered the maximum values for yield attributes *viz.* head diameter, Number of seeds head^{-1}, Number of filled seeds head^{-1}, percentage of filled seeds head^{-1} and 100 seed weight and yield *viz.* seed yield and stalk yield in both the crops. This was followed by KBSH 44 at a spacing of 60 × 30 cm incorporating 75 % RDN + 100 % PK + 12.5 % N through VC + 12.5 % N through PM + 45 kg S ha^{-1} (A_3B_5). The lowest yield characteristics and yield was recorded in the treatment A_4B_1 (KBSH 44 at 60 × 45 cm spacing with control) for both the crops respectively. This may come from enhanced crop growth facilitated by efficient fertilizer use and optimal spacing. This allows plants to create more photosynthate, which accumulates in the sink. Optimum applications of nitrogen and sulphur are considered to increase the 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 PM 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 PM and vermicompost (10, 35, 36).

Conclusion

Sunflower growth and yield were significantly influenced by genotype, plant geometry and nutrient management. The genotype COSFH 4 at 60 × 30 cm spacing recorded superior growth and yield parameters, followed by KBSH 44 at 60 × 30 cm spacing, while wider spacing (60 × 45 cm) gave the lowest values. The INM practice of 75 % RDN + 100 % PK + 12.5 % N through vermicompost + 12.5 % N through PM + 45 kg S ha^{-1} (B_5) was most effective. The interaction of optimum genotype, spacing and nutrient management (A_1B_5) ensured maximum plant vigour, chlorophyll content, seed set and yield. Thus, combining efficient genotype, proper geometry and integrated nutrient use can maximize sunflower productivity. Long-term studies on the effect of different INM practices under varying geometries are needed to assess their role in sustaining soil fertility, improving nutrient-use efficiency and enhancing yield stability.

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Authors' contributions

PCR contributed to conceptualization, data curation and writing of the original draft. CK was involved in conceptualization, supervision, funding acquisition, writing, review and editing. SK contributed to methodology, validation and writing of the original draft. PS participated in writing original draft and editing. KD contributed to resources, visualization, methodology, writing, review and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

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

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During the preparation of this article, the effects used "Quill bot" in order to improve language of readability. After that, the author carefully reviewed and edited the content as required and takes full responsibility for the content of the publication.

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