

Effects of plant density, mineral fertilization and effective microorganisms on the development and essential oil yield of *Ocimum basilicum* L.

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Abstract

This study examined the impacts of plant density, mineral fertilizers (NPK), biological fertilizers (effective microorganisms, EM), and their interactions on the growth, essential oil content, and chemical composition of sweet basil (*Ocimum basilicum* L.) using a split-plot design with three replicates. The main factor consisted of three plant density levels: high, medium, and low (90, 60, and 42 plants/10.8 m², equivalent to 33333, 22222 and 15555 plants/feddan, respectively). The secondary factor included five fertilizer treatments: the full NPK recommended dose (100%), EM alone, and combinations of 75%, 50%, and 25% NPK with EM. Results showed that lower plant density enhanced per-plant traits, including branch number, herb and leaf dry weights per cut, seasonal yield per plant, and NPK percentages in dried leaves, but reduced plant height. Conversely, the highest density maximized herb and leaf dry weight yields per feddan = (4200 m²). Essential oil yield per plant per season increased at lower density, while oil yield per fed decreased. The 75% NPK + EM and 100% NPK treatments produced the highest plant height, branch number, dry weights, seasonal yield per plant, and essential oil content across all three cuts during both seasons. The optimal combination for growth parameters, essential oil percentage, oil yield per plant, and NPK percentages in dried leaves was the lowest density (42 plants/10.8 m²) with 75% NPK + EM, while the highest essential oil yield per feddan was achieved with the highest density (90 plants/10.8 m²) combined with 75% NPK + EM.

Keywords: Sweet basil, plant density, effective microorganisms, NPK, essential oil.

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1. Introduction

According to the World Health Organization (2008), approximately 80% of the global population depends on medicinal and aromatic plants for their therapeutic properties, which include bioactive compounds like phenols, tannins, alkaloids, glycosides, saponins, and secondary metabolites (Naguib, 2011). *Ocimum basilicum* L is a herbaceous plant from the Lamiaceae family, the most economically significant species within the diverse *Ocimum* genus, valued for its volatile oil, fresh or dried herbs, and ornamental qualities (El-Gendy *et al.*, 2001). Typically growing to 50 cm, or over one meter under favorable conditions, sweet basil features glossy, oval leaves, square stems, and small white bilabiate flowers in dense spikes, with fine black seeds (USDA, 2008). It is a rich source of bioactive compounds, including monoterpenes, sesquiterpenes, and phenylpropanoids (e.g., linalool, eugenol, estragole, and methyl chavicol), which provide antioxidant, antitussive, diuretic, anthelmintic, tranquilizing, and expectorant properties (Dzida, 2010; Ekren *et al.*, 2012; Esetili *et al.*, 2016; Sharafzadeh and Alizadeh, 2011). The essential oil, constituting up to 1.5% of the plant, is used to treat conditions such as dental issues, respiratory disorders, fungal infections, and digestive problems, while also providing nutritional benefits, including 22 calories per 100 grams, carbohydrates, fiber, protein, fats, and minerals like calcium, potassium, and iron

(Andrea *et al.*, 2007; Telci *et al.*, 2006). Plant spacing is a crucial determinant of yield and quality in sweet basil (*Ocimum basilicum* L.) cultivation, as it affects aeration, light penetration, and photosynthetic efficiency. Optimal spacing maximizes resource utilization (water, air, light, and nutrients) while minimizing competition, thereby enhancing crop productivity (Abbas, 2014; Atghaei *et al.*, 2015; Bekhradi *et al.*, 2014; Chegini *et al.*, 2012; Sadeghi *et al.*, 2009). Inadequate nutrition, particularly deficiencies in nitrogen, phosphorus, and potassium, poses significant challenges to basil production under typical agroclimatic conditions. Research indicates that plant density significantly influences dry matter and essential oil yield, underscoring the importance of determining appropriate spacing to optimize basil cultivation outcomes (Dadvand *et al.*, 2009; Khafi, 2003;). Plant fertilization with essential macronutrients, nitrogen (N), phosphorus (P), and potassium (K), are critical for sweet basil production. Numerous studies have shown that increasing NPK fertilizer levels enhances mineral uptake in plants. However, the continuous application of chemical fertilizers contributes to environmental pollution and undermines the sustainability of agricultural systems (Bagali *et al.*, 2012). In Egypt, the common practice among farmers of applying excessive fertilizers to boost productivity has led to a significant environmental and health concerns, including ecosystem degradation, atmospheric pollution, and risks to human

health (Mostafa *et al.*, 2021). Additionally, the overuse of chemical fertilizers escalates production costs and accelerates soil fertility decline. Consequently, there is an urgent need to explore alternative, safe, and natural sources of plant nutrients, alongside sustainable approaches to enhance crop productivity and ensure food security. Biological fertilization using effective microorganisms (EM) enhances crop yield, soil mineral availability, and essential oil content in aromatic plants while reducing dependence on inorganic fertilizers. EM, a commercial microbial blend, includes photosynthesizing bacteria, actinomycetes, lactic acid bacteria, yeasts, and fermenting fungi like *Aspergillus* and *penicillium*, with specific strains such as *Streptomyces albus* (10^5 cell/ml), *Propionibacterium freudenreichii* (10^5 cell/ml), *Streptococcus lactis* (10^5 cell/ml), *Aspergillus oryzae* (10^5 cell/ml), *Mucor hiemalis* (10^5 cell/ml), *Saccharomyces cerevisiae* (10^5 cell/ml), and *Candida utilis* (10^5 cell/ml), alongside unspecified amounts of *Lactobacillus sp.*, *Rhodopseudomonas sp.*, and *Streptomyces griseus* (Formowitz *et al.*, 2007; Muthaura *et al.*, 2010; Wielgosz *et al.*, 2010). Research on crops like cotton, maize, sweet potatoes, rice, triticale, wheat, and horticultural species such as roses and apples confirm EM positive impact on plant performance, though Mayer *et al.* (2010) noted no significant yield improvements in some instances (Boliłłowa and Gleń, 2008; Górski and Kleiber, 2010; Eissa, 2002; Klama and

Kleiber, 2010; Kengo and Hui-lian, 2000; Khaliq *et al.*, 2006; Sahain *et al.*, 2007; Shah *et al.*, 2001). EM promotes soil microflora proliferation, nutrient availability, and plant growth by fostering favorable microbial conditions, with efficacy influenced by soil fertility, plant species, climate, and ecological factors (Higa, 2003; Janas, 2009; Wielgosz *et al.*, 2010). The primary aim of this study was to investigate the impact of plant density on maximizing herb and essential oil yields of sweet basil (*Ocimum basilicum*) under the environmental conditions of Assiut Governorate. Additionally, the study sought to minimize or eliminate the use of mineral fertilizers by exploring the potential of biofertilizers as a partial or complete substitute. This approach addresses the adverse health impacts and high costs associated with mineral fertilizers.

2. Materials and methods

2.1 Experimental site and treatments description

This research assessed the effects of plant density, mineral fertilizers (N, P and K), and biological fertilizers (effective microorganisms, EM), along with their interactions, on the growth, yield, essential oil production, and chemical composition of sweet basil (*Ocimum basilicum* L.) across two summer growing seasons (2023 and 2024). The experiments were conducted at the agricultural farm of the Faculty of Agriculture, Al-Azhar University, Assiut

Branch, Egypt ($27^{\circ} 12' 16.67''$ N latitude and $31^{\circ} 09' 36.86''$ E longitude). The study employed a completely randomized block design with a split-plot arrangement, comprising three replicates. Three plant density levels were assigned to the main plots, while five fertilizer treatments were allocated to the subplots, resulting in 15 treatment combinations, each replicated three times to ensure robust statistical analysis. Sweet basil seeds, sourced from the Agricultural Research Center in Giza, were sown in a nursery on March 15th of each season. Seedlings were transplanted 45 days later (April 29th) into plots measuring 3.0×3.6 m (10.8 m^2), arranged in six rows spaced 60 cm apart. Basil seedlings were planted in hills with inter-hill spacing's of 20, 30, and 40 cm, corresponding to 90, 60, and 42 plants per plot, equivalent to plant densities of 33333, 22222, and 15555 plants per fed, respectively.

2.2 Soil analysis

The physical and chemical properties of the soil used in both seasons (averaged across the two seasons) were analyzed following the methods outlined by Jackson (1973). The soil exhibited a clay texture, with a composition of 19.4% sand, 27.2% silt, and 53.4% clay. The soil pH was 7.61 (measured in a 1:2.5 soil-to-distilled water suspension), with an electrical conductivity (EC) of 1.03 dS/m (in a 1:5 soil solution). The soil contained 1.97% total CaCO_3 , 0.97% organic matter, 0.70% total nitrogen and 0.21%

total phosphorus. Soluble ions in the soil paste (meq/L) included Cl^- (3.39), HCO_3^- (4.19), SO_4^{2-} (3.05), Ca^{2+} (4.87), Mg^{2+} (0.52), Na^+ (1.38), and K^+ (3.86).

2.3 Treatments

Main Plots (A): consists of three plant densities as follows: 90 plants per 10.8 m^2 , equivalent to 33333 plants per feddan (20 cm spacing between plants, 15 plants per row), 60 plants per 10.8 m^2 , equivalent to 22222 plants per feddan (30 cm spacing between plants, 10 plants per row) and 42 plants per 10.8 m^2 , equivalent to 15555 plants per feddan (40 cm spacing between plants, 7 plants per row). Subplots (B): comprised five fertilizer treatments as follows: 100% of the recommended dose (RD) of NPK, biofertilizer (effective microorganisms, EM) without NPK, 75% NPK RD + EM, 50% NPK RD + EM and 25% NPK RD + EM. NPK Fertilizers: Three NPK fertilizer rates were applied: 100%, 50%, and 25% of the recommended dose. The full recommended dose (100%) consisted of $300 \text{ kg /feddan}^{-1}$ ammonium sulphate (20.5% N), $250 \text{ kg /feddan}^{-1}$ calcium superphosphate (15.5% P_2O_5) and $200 \text{ kg / feddan}^{-1}$ potassium sulphate (48.5% K_2O). Calcium superphosphate was incorporated into the soil during preparation as a single application for each rate. Ammonium sulphate and potassium sulphate were combined and applied in three equal doses: the first on April 29th (transplanting date), the second one month after transplanting, and the third after the first herb cut on July 7th, for

each rate. Effective Microorganisms (EM): comprising photosynthetic and nitrogen-fixing bacteria, were sourced from the Ministry of Environment, Egypt. Each 1 ml of EM contained 10^7 active bacterial cells. The EM solution was prepared at a concentration of 50 ml EM diluted in 500 ml water and applied at 50 ml per plant to the soil near the plant base. Three applications were applied: 2 weeks

after transplanting, 8 days after the first herb cut and one week after the second herb cut during both growing seasons. Plants were irrigated immediately following each application. All treatments adhered to standard agricultural practices. The composition of effective microorganisms (EM), as detailed in Table (1), is based on established formulations described by Daly and Stewart (1999) and Higa (2004).

Table (1): Composition of effective microorganisms (EM) used in the study.

Bio strains	Types
Actinomycetes	<i>Streptomyces albus</i> ; <i>Streptomyces griseus</i>
Yeasts	<i>Saccharomyces cerevisiae</i> ; <i>Candida utilis</i>
Photosynthetic bacteria	<i>Rhodospseudomonas palustris</i> ; <i>Rhodobacter spaeroides</i>
Fermenting fungi	<i>Aspergillus oryzae</i> ; <i>Mucor hiemalis</i>
Lactic acid bacteria	<i>Lactobacillus plantarum</i> ; <i>Lactobacillus casei</i> ; <i>Streptococcus lactis</i>

2.4 Harvesting Times

In each experimental season, sweet basil plants were harvested three times at approximately 50% flowering. For each harvest, plants were cut, leaving approximately 10 cm of stem above the soil surface. The harvests were conducted on July 1st, August 14th, and September 29th during both summer growing seasons.

2.5 Data Recorded

2.5.1 Vegetative growth parameters

The following parameters were measured at each harvest: Plant height (cm), number of branches per plant per cut, herb dry weight per plant per cut (g)/plant, leaf dry

weight per plant per cut (g)/plant, additionally, the following vegetative growth metrics were calculated: Total herb dry weight (g)/plant/season, total herb dry yield (ton)/fed/season, total leaf dry weight (g)/plant/season and total leaf dry yield (ton)/feddan/season.

2.5.2 Essential oil production

The essential oil percentage was determined from random air-dried herb samples for each treatment at every cut during both seasons, following the method outlined in the British Pharmacopoeia (1963). This involved distilling 60 g of herb for 3 hours to extract the essential oil, with yields calculated as ml/plant/cut, ml/plant/season, and l/feddan/season.

2.5.3 Chemical constituents

The N, P and K percentages in the dried leaf samples from the third cut were analyzed using methods described by Horneck and Miller (1998) for nitrogen, Sandell (1950) for phosphorus, and Horneck and Hanson (1998) for potassium.

2.6 Statistical analysis

All data related to growth, essential oil production, and chemical composition were subjected to statistical analysis using Statistic version 9 (Statistix, 2008), following the methodology of Mead *et al.* (1993). Mean comparisons were conducted using the least significant difference (LSD) test at a 5% significance level.

3. Results

3.1 Vegetative growth traits

3.1.1 Plant height (cm)

3.1.1.1 Impact of plant density

Plant density significantly affected plant height across all three cuts during 2023 and 2024 growing seasons. The highest density (90 plants/10.8 m²) resulted in the tallest plants, recording heights of 53.0, 56.6 and 58.7 cm in the 1st, 2nd and 3rd cuts, respectively of the 2023 season, and 54.7, 57.5 and 60.6 cm in the corresponding cuts, respectively of the 2024 season. The medium density (60

plants/10.8 m²) produced plants with heights of 50.8, 54.2 and 56.1 cm in 2023 and 52.4, 55.3 and 58.4 cm, respectively in 2024. The lowest density (42 plants/10.8 m²) yielded the shortest plants, with heights of 49.4, 52.5 and 54.3 cm in 2023, and 50.6, 53.4 and 56.5 cm, respectively in 2024 (Table 2). No significant differences were found between the 60 and 42 plants/10.8 m² density levels in the first cut of the 2023 season.

3.1.1.2 Impact of fertilizer treatments

Data presented in Table 2 demonstrate that all fertilizer treatments combining NPK and effective microorganisms (EM) significantly improved plant height across all three cuts in both the 2023 and 2024 seasons, except the comparison between 100% NPK and 50% NPK + EM in the first cut of 2023, where no significant difference was observed. Among the five fertilizer treatments, the combination of 75% NPK recommended dose with EM yielded the tallest plants, recording heights of 56.9, 60.3, and 62.2 cm in the first, second, and third cuts of 2023, respectively, and 58.4, 61.5, and 64.6 cm in the corresponding cuts of 2024. Conversely, treated plants with EM only exhibited the lowest plant height values across all three cuts in both seasons.

3.1.1.3 Interaction between plant density and fertilizer treatments

The interaction between plant density and

fertilizer treatments had a significant influence on plant height through all three cuts in both seasons (Table 2). The tallest plants were observed in the higher density treatments (90 and 60 plants/plot) combined with 75% NPK RD + EM,

yielding heights of 58.7 and 56.9 cm in the 1st cut, 62.3 and 60.6 cm in the 2nd cut, and 64.3 and 62.6 cm in the 3rd cut of 2023, and 60.5 and 58.8 cm, 63.5 and 61.8 cm, and 66.6 and 64.9 cm in the first, second, and third cuts of 2024, respectively.

Table (2): Impact of plant density, NPK and EM treatments and their interactions on plant height of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
	1 st Cut							
100% NPK _{RD}	54.9	52.6	50.8	52.8	55.7	54.3	52.0	54.0
EM without NPK	46.9	45.4	44.3	45.5	48.8	46.9	45.7	47.1
75% NPK _{RD} + EM	58.7	56.9	54.9	56.9	60.5	58.8	56.1	58.4
50% NPK _{RD} + EM	53.6	50.4	49.5	51.2	55.5	52.1	50.3	52.7
25% NPK _{RD} + EM	51.1	48.4	47.6	49.0	53.2	49.8	48.8	50.6
Mean (A)	53.0	50.8	49.4		54.7	52.4	50.6	
LSD 0.05	A: 2.1 B: 1.7 AB: 3.0				A: 1.6 B: 1.3 AB: 2.2			
	2 nd Cut							
100% NPK _{RD}	57.6	56.1	53.9	55.9	58.8	57.3	55.1	57.1
EM without NPK	50.7	48.8	47.6	49.0	51.9	49.3	48.8	50.0
75% NPK _{RD} + EM	62.3	60.6	58.0	60.3	63.5	61.8	59.2	61.5
50% NPK _{RD} + EM	57.4	54.0	52.2	54.5	57.9	55.2	53.4	55.5
25% NPK _{RD} + EM	55.0	51.7	50.7	52.5	55.5	52.9	50.5	53.0
Mean (A)	56.6	54.2	52.5		57.5	55.3	53.4	
LSD 0.05	A: 1.6 B: 1.3 AB: 2.2				A: 1.8 B: 1.4 AB: 2.4			
	3 rd Cut							
100% NPK _{RD}	59.5	58.1	55.8	57.8	61.9	60.4	58.2	60.2
EM without NPK	52.3	50.7	49.5	50.9	55.0	52.3	51.9	53.1
75% NPK _{RD} + EM	64.3	62.6	59.7	62.2	66.6	64.9	62.3	64.6
50% NPK _{RD} + EM	60.2	55.7	54.1	56.6	61.0	58.3	56.5	58.6
25% NPK _{RD} + EM	57.0	53.5	52.5	54.3	58.6	56.0	53.6	56.1
Mean (A)	58.7	56.1	54.3		60.6	58.4	56.5	
LSD 0.05	A: 1.3 B: 1.1 AB: 1.9				A: 1.8 B: 1.3 AB: 2.3			

3.1.2 Number of branches per plant per cut

3.1.2.1 Impact of plant density

The results indicated that plant density significantly influenced the number of branches per plant per cut (Table 3). The number of branches increased progressively as plant density decreased, with significant differences observed among density treatments across all three cuts in both the 2023 and 2024 seasons. The

lowest plant density (42 plants/ plot) produced the highest branch counts, recording 20.2 and 20.3 branches/plant in the first cut, 22.7 and 23.7 in the second cut and 25.0 and 28.2 in the third cut for the 2023 and 2024 seasons, respectively.

3.1.2.2 Impact of fertilizer treatments

All five fertilizer treatments significantly enhanced the number of branches per plant across all three cuts in the 2023 and

2024 seasons (Table 3). The combination of 75% NPK recommended dose (RD) + effective microorganisms (EM) produced the highest branch counts, recording 21.4 and 21.3 branches/plant in the first cut, 23.7 and 24.7 in the second cut, and 26.1 and 29.5 in the third cut for the 2023 and 2024 seasons, respectively, surpassing all other treatments. The 100% NPK treatment followed, yielding 18.9 and 18.7 branches/plant in the first cut, 21.1 and 22.0 in the second cut, and 23.6 and 26.7 in the third cut for the respective seasons. No significant differences were observed between 100% NPK and 50% NPK + EM, or between EM alone and 25% NPK + EM, in the first and third cuts of both seasons, nor between 100% NPK

and 50% NPK + EM, or EM alone and 25% NPK + EM, in the second cut of the 2024 season. Regardless of other treatments, the lowest branch counts were recorded for the EM-only treatment in both seasons across all three cuts.

3.1.2.3 Interaction between plant density and fertilizer treatments

The interaction between plant density and fertilizer treatments (A×B) significantly affected the number of branches per plant across all three cuts in both seasons (Table 3). The most effective combination was observed with the lowest plant density (42 plants/ plot) paired with 75% NPK RD + EM, resulting in the highest branch counts.

Table (3): Impact of plant density, NPK and EM treatments and their interactions on number of branches of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
	1 st Cut							
100% NPK _{RD}	51.3	54.8	62.7	56.3	53.0	56.3	64.2	57.8
EM without NPK	46.3	47.7	55.7	49.9	47.4	49.3	57.2	51.3
75% NPK _{RD} + EM	55.3	57.3	64.6	59.1	57.1	58.8	66.1	60.7
50% NPK _{RD} + EM	49.1	51.8	61.2	54.1	50.6	53.3	62.7	55.5
25% NPK _{RD} + EM	47.5	50.3	57.8	51.9	49.1	52.2	59.5	53.6
Mean (A)	49.9	52.4	60.4		51.4	54.0	61.9	
LSD 0.05	A: 1.4 B: 2.9 AB: 4.9				A: 1.6 B: 2.8 AB: 4.9			
	2 nd Cut							
100% NPK _{RD}	57.7	61.0	68.9	62.5	57.8	61.3	69.1	62.8
EM without NPK	52.1	54.0	61.9	56.0	52.3	54.2	62.1	56.2
75% NPK _{RD} + EM	61.8	63.5	70.8	65.4	61.9	63.8	71.1	65.6
50% NPK _{RD} + EM	55.3	58.0	67.4	60.2	55.6	58.2	67.6	60.5
25% NPK _{RD} + EM	53.8	56.9	64.2	58.3	54.1	57.1	64.5	58.5
Mean (A)	56.1	58.7	66.6		56.3	58.9	66.9	
LSD 0.05	A: 1.6 B: 2.8 AB: 4.9				A: 1.7 B: 2.7 AB: 4.8			
	3 rd Cut							
100% NPK _{RD}	64.0	67.3	75.1	68.8	62.5	66.0	73.7	67.4
EM without NPK	58.4	60.2	68.1	62.2	57.1	59.0	66.7	60.9
75% NPK _{RD} + EM	68.1	69.7	77.1	71.6	66.7	68.4	75.9	70.3
50% NPK _{RD} + EM	61.5	64.2	73.6	66.4	60.4	63.0	72.4	65.3
25% NPK _{RD} + EM	60.0	63.1	70.4	64.5	58.7	61.9	69.1	63.2
Mean (A)	62.4	64.9	72.8		61.1	63.7	71.5	
LSD 0.05	A: 1.7 B: 2.9 AB: 5.0				A: 1.6 B: 2.8 AB: 4.9			

3.1.3 Herb and leaf dry weights (g/plant/cut)

3.1.3.1 Impact of plant density

Data presented in Tables (4 and 5) indicate that plant density influenced herb and leaf dry weights (g)/plant/cut across all three cuts in both the 2023 and 2024 growing seasons. The lowest plant density (42 plants/plot) yielded the highest herb dry weights, recording 60.4 and 61.9 g/plant in the first cut, 66.6 and 66.9 g/plant in the second cut, and 72.8 and 71.5 g/plant in the third cut for the 2023 and 2024 seasons, respectively (Table 4). Similarly, the highest leaf dry weights were observed at this density, with values of 25.9 and 28.1 g/plant in the first cut, 31.4 and 32.8 g/plant in the second cut, and 37.6 and 37.3 g/plant in the third cut for both seasons, respectively (Table 5). No significant differences were noted between the 90 and 60 plants/10.8 m² density levels in the third cut of the 2023 and 2024 seasons for leaf dry weight g/plant/cut.

3.1.3.2 Impact of fertilizer treatments

Herb and leaf dry weights (g/plant/cut) were significantly increased by the application of NPK and effective microorganism (EM) fertilizer treatments. The combination of 75% NPK recommended dose + EM consistently yielded the highest herb and leaf dry weights across all three cuts in both the 2023 and 2024 seasons. Herb dry weights recorded were 59.1, 65.4, and 77.1 g/plant

in the 1st, 2nd and 3rd cuts of 2023, and 60.7, 65.6, and 70.3 g/plant in the corresponding cuts of 2024 (Table 4). Leaf dry weights were 24.2, 30.3, and 36.6 g/plant in 2023 and 26.8, 31.8, and 36.4 g/plant in 2024 for the respective cuts (Table 5). Conversely, the lowest herb and leaf dry weights were observed with the EM-only treatment through all three cuts in both seasons.

3.1.3.3 Interaction between plant density and fertilizer treatments

The interaction between plant density and fertilizer treatments significantly affected herb and leaf dry weights (g)/plant/cut across all three cuts in both seasons. The highest herb and leaf dry weights were achieved with the lowest plant density (42 plants/10.8 m²) combined with 75% NPK + EM, yielding herb dry weights of 64.6, 70.8, and 77.1 g/plant in 2023 and 66.1, 71.1, and 75.9 g/plant in 2024 and leaf dry weights of 29.7, 35.9 and 42.1 g/plant in 2023 and 32.2, 37.2 and 42.0 g/plant in 2024 for the first, second, and third cuts, respectively. The combination of 42 plants/plot with 100% NPK also performed well, producing herb dry weights of 56.3, 62.5, and 68.8 g/plant in 2023 and 57.8, 62.8, and 67.4 g/plant in 2024 and leaf dry weights of 21.4, 27.6, and 33.7 g/plant in 2023 and 24.1, 29.0, and 33.2 g/plant in 2024 for the respective cuts. These results outperformed other treatment combinations, as shown in Tables (4 and 5).

Table (4): Impact of plant density, NPK and EM treatments and their interactions on herb dry weight (g)/plant/cut of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
	1 st Cut							
100% NPK _{RD}	51.3	54.8	62.7	56.3	53.0	56.3	64.2	57.8
EM without NPK	46.3	47.7	55.7	49.9	47.4	49.3	57.2	51.3
75% NPK _{RD} + EM	55.3	57.3	64.6	59.1	57.1	58.8	66.1	60.7
50% NPK _{RD} + EM	49.1	51.8	61.2	54.1	50.6	53.3	62.7	55.5
25% NPK _{RD} + EM	47.5	50.3	57.8	51.9	49.1	52.2	59.5	53.6
Mean (A)	49.9	52.4	60.4		51.4	54.0	61.9	
LSD 0.05	A: 1.4 B: 2.9 AB: 4.9				A: 1.6 B: 2.8 AB: 4.9			
	2 nd Cut							
100% NPK _{RD}	57.7	61.0	68.9	62.5	57.8	61.3	69.1	62.8
EM without NPK	52.1	54.0	61.9	56.0	52.3	54.2	62.1	56.2
75% NPK _{RD} + EM	61.8	63.5	70.8	65.4	61.9	63.8	71.1	65.6
50% NPK _{RD} + EM	55.3	58.0	67.4	60.2	55.6	58.2	67.6	60.5
25% NPK _{RD} + EM	53.8	56.9	64.2	58.3	54.1	57.1	64.5	58.5
Mean (A)	56.1	58.7	66.6		56.3	58.9	66.9	
LSD 0.05	A: 1.6 B: 2.8 AB: 4.9				A: 1.7 B: 2.7 AB: 4.8			
	3 rd Cut							
100% NPK _{RD}	64.0	67.3	75.1	68.8	62.5	66.0	73.7	67.4
EM without NPK	58.4	60.2	68.1	62.2	57.1	59.0	66.7	60.9
75% NPK _{RD} + EM	68.1	69.7	77.1	71.6	66.7	68.4	75.9	70.3
50% NPK _{RD} + EM	61.5	64.2	73.6	66.4	60.4	63.0	72.4	65.3
25% NPK _{RD} + EM	60.0	63.1	70.4	64.5	58.7	61.9	69.1	63.2
Mean (A)	62.4	64.9	72.8		61.1	63.7	71.5	
LSD 0.05	A: 1.7 B: 2.9 AB: 5.0				A: 1.6 B: 2.8 AB: 4.9			

Table (5): Impact of plant density, NPK and EM treatments and their interactions on leaf dry weight (g)/plant/cut of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
	1 st Cut							
100% NPK _{RD}	16.4	20.0	27.8	21.4	19.2	22.5	30.5	24.1
EM without NPK	11.2	14.9	20.8	15.7	13.8	15.5	23.3	17.5
75% NPK _{RD} + EM	20.5	22.5	29.7	24.2	23.3	24.9	32.2	26.8
50% NPK _{RD} + EM	14.3	17.0	26.4	19.2	16.8	19.4	28.8	21.7
25% NPK _{RD} + EM	12.7	16.2	24.9	17.9	15.3	18.4	25.9	19.8
Mean (A)	15.0	18.1	25.9		17.7	20.1	28.1	
LSD 0.05	A: 1.5 B: 2.3 AB: 4.0				A: 2.3 B: 2.2 AB: 4.0			
	2 nd Cut							
100% NPK _{RD}	22.8	26.1	33.7	27.6	24.2	27.5	35.3	29.0
EM without NPK	17.1	19.1	26.7	21.0	18.6	20.3	28.3	22.4
75% NPK _{RD} + EM	26.7	28.4	35.9	30.3	28.2	30.0	37.2	31.8
50% NPK _{RD} + EM	20.4	23.1	32.4	25.3	21.5	24.3	33.2	26.4
25% NPK _{RD} + EM	18.9	21.9	28.1	23.0	20.1	22.8	29.8	24.3
Mean (A)	21.2	23.7	31.4		22.5	25.0	32.8	
LSD 0.05	A: 2.3 B: 2.4 AB: 4.1				A: 2.2 B: 2.6 AB: 4.6			
	3 rd Cut							
100% NPK _{RD}	29.0	32.3	39.7	33.7	28.8	31.7	39.1	33.2
EM without NPK	23.6	25.2	33.1	27.3	23.0	25.1	32.5	26.9
75% NPK _{RD} + EM	33.1	34.7	42.1	36.6	32.7	34.5	42.0	36.4
50% NPK _{RD} + EM	26.5	29.2	38.6	31.4	26.5	29.2	38.0	31.2
25% NPK _{RD} + EM	25.0	28.1	34.7	29.3	24.9	27.8	35.1	29.3
Mean (A)	27.4	29.9	37.6		27.2	29.7	37.3	
LSD 0.05	A: 2.7 B: 2.5 AB: 4.3				A: 2.8 B: 2.2 AB: 3.9			

3.1.4 Total herb and leaf dry weights (g/plant/season and ton/feddan/season)

3.1.4.1 Impact of plant density

Data in Tables (6, 7, 8, and 9) reveal that plant density significantly impacted total herb and leaf dry weights (g)/plant/season and (ton)/feddan/season. The lowest plant density (42 plants/10.8 m² or 15555 plants/fed) produced the highest dry weights per plant, with herb dry weights of 199.85 and 200.34 g/plant/season and leaf dry weights of 94.94 and 98.25 g/plant/season in the 2023 and 2024 seasons, respectively, compared to higher densities (33333 and 22222 plants/fed) (Tables 6 and 7). In contrast, the highest density (90 plants/plot or 33333 plants/fed) resulted in the greatest yields per unit area, recording 5.61 and 5.63 ton/fed/season for herb dry weight and 2.12 and 2.25 ton/fed/season for leaf dry weight in 2023

and 2024, respectively, compared to lower densities (15555 and 22222 plants/feddan) (Tables 8 and 9).

3.1.4.2 Impact of fertilizer treatments

All five fertilizer treatments, combining NPK and effective microorganisms (EM), significantly increased total herb and leaf dry weights (g/plant/season and ton/fed/season) across the 2023 and 2024 seasons (Tables 6, 7, 8, and 9). The 75% NPK recommended dose (RD) + EM treatment yielded the highest values, recording herb dry weights of 196.04 and 196.54 g/plant/season and 4.57 and 4.58 ton/feddan/season and leaf dry weights of 91.20 and 95.03 g/plant/season and 2.08 and 2.18 ton/feddan/season in the 2023 and 2024 seasons, respectively, surpassing all other treatments. In contrast, the EM-only treatment resulted in the lowest values for these parameters across all three cuts in both seasons.

Table (6): Impact of plant density, NPK and EM treatments and their interactions on total herb dry weight (g)/plant/season of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
100% NPK _{RD}	173.01	183.20	206.60	187.60	173.41	183.60	207.00	188.00
EM without NPK	156.80	161.87	185.60	168.09	156.80	162.53	186.00	168.44
75% NPK _{RD} + EM	185.17	190.50	212.47	196.04	185.67	190.93	213.03	196.54
50% NPK _{RD} + EM	165.97	174.10	202.17	180.74	166.57	174.60	202.60	181.26
25% NPK _{RD} + EM	161.30	170.27	192.43	174.67	161.90	171.13	193.07	175.37
Mean (A)	168.45	175.99	199.85		168.87	176.56	200.34	
LSD 0.05	A: 4.81 B: 8.60 AB: 14.90				A: 5.00 B: 8.51 AB: 14.82			

3.1.4.3 Interaction between plant density and fertilizer treatments

The interaction between plant density and fertilizer treatments (A×B) influenced

total herb and leaf dry weights (g/plant/season and ton/feddan/season) in both seasons (Tables 6, 7, 8, and 9). The most effective combination for per-plant dry weights (g/plant/season) was the

lowest density (42 plants/plot or 15555 plants/fed) paired with 75% NPK + EM (Tables 6 and 7). For yields per unit area (ton/feddan/season), the highest values were obtained with the highest density (90 plants/10.8 m² or 33333 plants/feddan) combined with 75% NPK RD + EM (Tables 8 and 9).

Table (7): Impact of plant density, NPK and EM treatments and their interactions on total leaf dry weight g /plant/season of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
100% NPK _{RD}	68.24	78.47	101.30	82.67	72.24	81.73	104.93	86.30
EM without NPK	51.93	59.17	80.63	63.91	55.37	60.90	84.07	66.78
75% NPK _{RD} + EM	80.30	85.57	107.73	91.20	84.23	89.40	111.47	95.03
50% NPK _{RD} + EM	61.20	69.30	97.37	75.96	64.87	72.93	100.03	79.28
25% NPK _{RD} + EM	56.57	66.13	87.67	70.12	60.33	69.00	90.73	73.36
Mean (A)	63.65	71.73	94.94		67.41	74.79	98.25	
LSD 0.05	A: 6.30 B: 7.01 AB: 12.10				A: 6.71 B: 6.82 AB: 11.82			

Table (8): Impact of plant density, NPK and EM treatments and their interactions on total herb dry weight ton/feddan/season of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
100% NPK _{RD}	5.77	4.07	3.21	4.35	5.78	4.08	3.22	4.36
EM without NPK	5.23	3.60	2.89	3.90	5.23	3.61	2.89	3.91
75% NPK _{RD} + EM	6.17	4.23	3.30	4.57	6.19	4.24	3.31	4.58
50% NPK _{RD} + EM	5.53	3.87	3.14	4.18	5.55	3.88	3.15	4.19
25% NPK _{RD} + EM	5.38	3.78	2.99	4.05	5.40	3.80	3.00	4.07
Mean (A)	5.61	3.91	3.11		5.63	3.92	3.12	
LSD 0.05	A: 0.15 B: 0.18 AB: 0.32				A: 0.14 B: 0.17 AB: 0.31			

Table (9): Impact of plant density, NPK and EM treatments and their interactions on total leaf dry weight ton/feddan/season of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
100% NPK _{RD}	2.27	1.74	1.58	1.86	2.41	1.82	1.63	1.95
EM without NPK	1.73	1.31	1.25	1.43	1.85	1.35	1.31	1.50
75% NPK _{RD} + EM	2.68	1.90	1.68	2.08	2.81	1.99	1.73	2.18
50% NPK _{RD} + EM	2.04	1.54	1.51	1.70	2.16	1.62	1.56	1.78
25% NPK _{RD} + EM	1.89	1.47	1.36	1.57	2.01	1.53	1.41	1.65
Mean (A)	2.12	1.59	1.48		2.25	1.66	1.53	
LSD 0.05	A: 0.21 B: 0.16 AB: 0.28				A: 0.20 B: 0.17 AB: 0.29			

3.2 Essential oil production

3.2.1 Essential oil percentage

3.2.1.1 Impact of plant density

Data in Table (10) reveal that plant density influenced essential oil percentage at a 5% significance level. A decrease in plant density was associated with a

significant increase in essential oil percentage across all three cuts in both the 2023 and 2024 seasons. The lowest plant density (42 plants/10.8 m², equivalent to 15555 plants/feddan) yielded the highest essential oil percentages, recording 1.026, 1.115 and 1.173% in the first, second, and

third cuts of 2023, and 1.065, 1.123 and 1.139% in the corresponding cuts of 2024. No significant differences were observed between the higher density levels (90 and 60 plants/plot, equivalent to 33333 and 22,222 plants/feddan) through all cuts in both seasons.

Table (10): Impact of plant density, NPK and EM treatments and their interactions on essential oil percentage/plant/cut of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
	1 st Cut							
100% NPK _{RD}	1.017	1.053	1.058	1.042	0.997	1.030	1.090	1.039
EM without NPK	0.898	0.930	0.964	0.931	0.880	0.936	1.023	0.947
75% NPK _{RD} + EM	1.029	1.038	1.060	1.042	0.988	1.067	1.107	1.054
50% NPK _{RD} + EM	1.010	1.011	1.027	1.016	0.964	1.024	1.067	1.018
25% NPK _{RD} + EM	1.007	1.008	1.022	1.012	0.960	0.998	1.038	0.999
Mean (A)	0.992	1.008	1.026		0.958	1.011	1.065	
LSD 0.05	A: 0.044 B: 0.047 AB: 0.081				A: 0.100 B: 0.046 AB: 0.079			
	2 nd Cut							
100% NPK _{RD}	1.047	1.080	1.140	1.089	1.020	1.080	1.163	1.088
EM without NPK	0.930	0.986	1.073	0.997	0.943	0.963	1.060	0.989
75% NPK _{RD} + EM	1.038	1.117	1.157	1.104	1.027	1.097	1.180	1.101
50% NPK _{RD} + EM	1.014	1.074	1.117	1.068	1.004	1.074	1.133	1.070
25% NPK _{RD} + EM	1.010	1.048	1.088	1.049	1.020	1.050	1.077	1.049
Mean (A)	1.008	1.061	1.115		1.003	1.053	1.123	
LSD 0.05	A: 0.100 B: 0.046 AB: 0.080				A: 0.055 B: 0.070 AB: 0.122			
	3 rd Cut							
100% NPK _{RD}	1.070	1.130	1.213	1.138	1.071	1.104	1.164	1.113
EM without NPK	0.993	1.013	1.110	1.039	0.954	1.010	1.097	1.021
75% NPK _{RD} + EM	1.077	1.147	1.230	1.151	1.062	1.141	1.181	1.128
50% NPK _{RD} + EM	1.054	1.124	1.183	1.120	1.038	1.098	1.141	1.092
25% NPK _{RD} + EM	1.070	1.100	1.127	1.099	1.034	1.072	1.112	1.073
Mean (A)	1.053	1.103	1.173		1.032	1.085	1.139	
LSD 0.05	A: 0.056 B: 0.071 AB: 0.123				A: 0.099 B: 0.045 AB: 0.078			

3.2.1.2 Impact of fertilizer treatments

All fertilizer treatments significantly enhanced the essential oil percentage across all three cuts in both the 2023 and 2024 seasons. Among the five treatments, the combination of 75% NPK recommended dose (RD) + effective microorganisms (EM) yielded the highest essential oil percentages, recording 1.042,

1.104, and 1.151% in the first, second, and third cuts of 2023, respectively, and 1.054, 1.101, and 1.128% in the corresponding cuts of 2024. The 100% NPK treatment followed closely, with values of 1.042, 1.089, and 1.138% in 2023 and 1.039, 1.088, and 1.113% in 2024 for the respective cuts, outperforming the remaining treatments (Table 10). Conversely, the EM-only

treatment resulted in the lowest essential oil percentages in both seasons through all three cuts.

3.2.1.3 Interaction between plant density and fertilizer treatments

The interaction between plant density and fertilizer treatments (A×B) significantly affected essential oil percentage across all three cuts in both seasons (Table 10). The highest essential oil percentages were achieved with the lowest plant density (42 plants/10.8 m²) combined with either 75% NPK + EM or 100% NPK, demonstrating the most effective treatment combinations for maximizing essential oil %.

3.2.2 Essential oil yield (ml/plant/cut)

3.2.2.1 Impact of plant density

Plant density significantly influenced essential oil yield (ml/plant/cut) through both the 2023 and 2024 seasons, as shown in Table (11). A reduction in plant density led to an increase in essential oil yield per plant per cut. No significant differences were observed between the density levels of 90 and 60 plants/10.8 m² (equivalent to 33333 and 22222 plants/feddan) in the third cut of the 2023 season. The lowest density (42 plants/plot or 15555 plants/feddan) consistently produced the highest essential oil yield ml per plant per cut in both seasons.

Table (11): Impact of plant density, NPK and EM treatments and their interactions on essential oil yield ml/plant/cut of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
	1 st Cut							
100% NPK _{RD}	0.168	0.211	0.295	0.224	0.192	0.231	0.331	0.251
EM without NPK	0.101	0.138	0.200	0.146	0.121	0.143	0.236	0.166
75% NPK _{RD} + EM	0.210	0.232	0.314	0.252	0.230	0.264	0.356	0.284
50% NPK _{RD} + EM	0.144	0.172	0.271	0.196	0.162	0.200	0.309	0.224
25% NPK _{RD} + EM	0.128	0.163	0.254	0.182	0.147	0.184	0.268	0.200
Mean (A)	0.150	0.183	0.267		0.170	0.204	0.300	
LSD 0.05	A: 0.012 B: 0.023 AB: 0.041				A: 0.033 B: 0.027 AB: 0.046			
	2 nd Cut							
100% NPK _{RD}	0.239	0.281	0.384	0.301	0.247	0.298	0.410	0.318
EM without NPK	0.159	0.186	0.284	0.210	0.174	0.193	0.299	0.222
75% NPK _{RD} + EM	0.277	0.315	0.415	0.336	0.288	0.328	0.439	0.352
50% NPK _{RD} + EM	0.207	0.249	0.364	0.273	0.216	0.263	0.378	0.286
25% NPK _{RD} + EM	0.191	0.230	0.305	0.242	0.205	0.240	0.321	0.255
Mean (A)	0.215	0.252	0.350		0.226	0.264	0.369	
LSD 0.05	A: 0.033 B: 0.030 AB: 0.052				A: 0.038 B: 0.037 AB: 0.065			
	3 rd Cut							
100% NPK _{RD}	0.310	0.367	0.481	0.386	0.309	0.349	0.455	0.371
EM without NPK	0.233	0.253	0.366	0.284	0.219	0.252	0.354	0.275
75% NPK _{RD} + EM	0.355	0.398	0.518	0.423	0.347	0.392	0.496	0.412
50% NPK _{RD} + EM	0.280	0.331	0.458	0.356	0.275	0.322	0.435	0.344
25% NPK _{RD} + EM	0.267	0.309	0.391	0.322	0.258	0.298	0.390	0.315
Mean (A)	0.289	0.331	0.443		0.282	0.323	0.426	
LSD 0.05	A: 0.047 B: 0.037 AB: 0.065				A: 0.039 B: 0.031 AB: 0.054			

3.2.2.2 Impact of fertilizer treatments

Data in Table (11) demonstrate that all five fertilizer treatments involving NPK and effective microorganisms (EM) significantly enhanced essential oil yield (ml/plant/cut) in both seasons. The combination of 75% NPK recommended dose + EM resulted in the highest essential oil yield ml per plant through all three cuts in both the 2023 and 2024 seasons, outperforming other treatments.

3.2.2.3 Interaction between plant density and fertilizer treatments

The interaction between plant density and fertilizer treatments ($A \times B$) significantly increased essential oil yield (ml/plant/cut) in both seasons. The highest yields were achieved with the lowest plant density (42 plants/10.8 m²) combined with either 75% NPK RD + EM or 100% NPK, as detailed in Table (11).

3.2.3 Total essential oil yield (ml/plant/season and l/feddan/season)

3.2.3.1 Impact of plant density

Data presented in Table (12) show that total essential oil yield (ml/plant/season) increased with decreasing plant density. The yields were 0.654, 0.767, and 1.060 ml/plant in the 2023 season and 0.678, 0.792, and 1.095 ml/plant in the 2024 season for densities of 90, 60, and 42 plants/plot (equivalent to 33333, 22222 and 15555 plants/feddan), respectively. Conversely, essential oil yield per unit

area (l/feddan/season) increased with higher plant density. The highest density (33333 plants/feddan) produced the greatest yields, recording 21.79 and 22.60 l/feddan/season in the 2023 and 2024 seasons, respectively, compared to 17.04 and 17.59 l/fed/season for 22222 plants/feddan and 16.49 and 17.04 l/feddan/season for 15555 plants/fed in the respective seasons (Table 13).

3.2.3.2 Impact of fertilizer treatments

Data in Tables (12 and 13) indicate that all fertilizer treatments including NPK and effective microorganisms significantly enhanced total essential oil yield (ml/plant/season and l/feddan/season) compared to EM without NPK. The 75% NPK recommended dose + EM treatment resulted in the highest yields, with 1.011 and 1.047 ml/plant/season and 22.83 and 23.61 l/feddan/season in the 2023 and 2024 seasons, respectively, outperforming other treatments through all three cuts.

3.2.3.3 Interaction between plant density and fertilizer treatments

The interaction between plant density and fertilizer treatments ($A \times B$) significantly influenced total essential oil yield (ml/plant/season and l/feddan/season) in both seasons. The highest yield per plant (ml/plant/season) was achieved with the lowest density (42 plants/10.8 m² or 15555 plants/feddan) combined with 75% NPK + EM, recording 1.246 and 1.291 ml/plant in the 2023 and 2024 seasons, respectively (Table 12). For yield

(1/feddan/season), the highest values were obtained with the highest density (90 plants/plot or 33333 plants/fed) paired with 75% NPK + EM, yielding 28.08 and 28.85 l/feddan/season in the 2023 and 2024 seasons, respectively (Table 13).

Table (12): Impact of plant density, NPK and EM treatments and their interactions on total essential oil yield ml/plant/season of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
100% NPK _{RD}	0.718	0.859	1.159	0.912	0.748	0.878	1.196	0.941
EM without NPK	0.493	0.577	0.850	0.640	0.514	0.588	0.889	0.663
75% NPK _{RD} + EM	0.843	0.945	1.246	1.011	0.866	0.985	1.291	1.047
50% NPK _{RD} + EM	0.630	0.751	1.093	0.825	0.653	0.785	1.122	0.853
25% NPK _{RD} + EM	0.586	0.702	0.950	0.746	0.610	0.722	0.979	0.770
Mean (A)	0.654	0.767	1.060		0.678	0.792	1.095	
LSD 0.05	A: 0.087 B: 0.086 AB: 0.150				A: 0.104 B: 0.085 AB: 0.148			

Table (13): Impact of plant density, NPK and EM treatments and their interactions on total essential oil yield l/feddan/season of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
100% NPK _{RD}	23.92	19.08	18.03	20.34	24.93	19.52	18.61	21.02
EM without NPK	16.42	12.81	13.22	14.15	17.13	13.06	13.82	14.67
75% NPK _{RD} + EM	28.08	21.01	19.39	22.83	28.85	21.89	20.09	23.61
50% NPK _{RD} + EM	21.01	16.69	17.01	18.24	21.76	17.44	17.45	18.89
25% NPK _{RD} + EM	19.54	15.59	14.78	16.64	20.32	16.04	15.23	17.20
Mean (A)	21.79	17.04	16.49		22.60	17.59	17.04	
LSD 0.05	A: 2.34 B: 2.04 AB: 3.52				A: 2.72 B: 2.02 AB: 3.49			

3.3 Chemical Constituents

3.3.1 Nitrogen, phosphorus, and potassium percentages

3.3.1.1 Impact of plant density

Data presented in Table (14) indicate that sweet basil planted at the lowest density (42 plants/10.8 m² equivalent to 15555 plants/fed) exhibited the highest percentages of nitrogen (2.13 and 2.20), phosphorus (0.272 and 0.269), and potassium (2.31 and 2.27) in dry leaf

samples for the 2023 and 2024 seasons, respectively, compared to higher densities (90 and 60 plants/10.8 m² equivalent to 33333 and 22222 plants/feddan). No significant differences in nitrogen percentage were observed between the 90 and 60 plants/plot density levels in either season.

3.3.1.2 Impact of fertilizer treatments

All fertilizer treatments (100% NPK, EM without NPK, 75% NPK + EM, 50% NPK + EM, and 25% NPK + EM) increased the percentages of nitrogen, phosphorus, and

potassium in dry leaf samples across both seasons (Table 14). The treatments of 100% NPK and 75% NPK + EM resulted in the highest N, P, and K percentages compared to other treatments, with no significant differences between these two treatments.

3.3.1.3 Interaction between plant density and fertilizer treatments

The interaction between plant density and fertilizer treatments significantly influenced the percentages of nitrogen, phosphorus, and potassium in both seasons (Table 14). The most effective combination was the lowest plant density (42 plants/10.8 m²) paired with 100% NPK, followed closely by 75% NPK + EM, which yielded the highest N, P, and K percentages in both the 2023 and 2024 seasons.

Table (14): Impact of plant density, NPK and EM treatments and their interactions on dry leaf N, P and K percentages of sweet basil (*Ocimum basilicum* L.) during 2023 and 2024 seasons.

Treatments (B)	Plant densities per 10.8 m ² (A)							
	2023 season				2024 season			
	90	60	42	Mean (B)	90	60	42	Mean (B)
	N%							
100% NPK _{RD}	2.20	2.24	2.32	2.25	2.16	2.20	2.29	2.22
EM without NPK	1.96	1.99	2.03	1.99	2.03	2.09	2.14	2.09
75% NPK _{RD} + EM	2.09	2.12	2.15	2.12	2.14	2.18	2.22	2.18
50% NPK _{RD} + EM	2.03	2.06	2.09	2.06	2.07	2.11	2.18	2.12
25% NPK _{RD} + EM	2.00	2.03	2.05	2.02	2.06	2.11	2.15	2.11
Mean (A)	2.06	2.09	2.13		2.09	2.14	2.20	
LSD 0.05	A: 0.06 B: 0.05 AB: 0.08				A: 0.10 B: 0.04 AB: 0.07			
	P%							
100% NPK _{RD}	0.271	0.276	0.286	0.278	0.265	0.278	0.283	0.275
EM without NPK	0.254	0.257	0.263	0.258	0.249	0.256	0.260	0.255
75% NPK _{RD} + EM	0.269	0.274	0.278	0.274	0.263	0.267	0.273	0.268
50% NPK _{RD} + EM	0.260	0.264	0.269	0.264	0.253	0.260	0.265	0.260
25% NPK _{RD} + EM	0.257	0.260	0.266	0.261	0.249	0.258	0.262	0.257
Mean (A)	0.262	0.266	0.272		0.256	0.264	0.269	
LSD 0.05	A: 0.004 B: 0.006 AB: 0.011				A: 0.005 B: 0.005 AB: 0.009			
	K%							
100% NPK _{RD}	2.28	2.33	2.37	2.33	2.20	2.27	2.33	2.22
EM without NPK	2.17	2.23	2.25	2.22	2.13	2.15	2.20	2.09
75% NPK _{RD} + EM	2.26	2.33	2.36	2.32	2.18	2.24	2.33	2.18
50% NPK _{RD} + EM	2.22	2.26	2.29	2.26	2.17	2.21	2.25	2.12
25% NPK _{RD} + EM	2.19	2.24	2.27	2.23	2.14	2.17	2.22	2.11
Mean (A)	2.22	2.28	2.31		2.16	2.21	2.27	
LSD 0.05	A: 0.03 B: 0.04 AB: 0.07				A: 0.04 B: 0.03 AB: 0.05			

4. Discussion

4.1 Impact of plant density on parameter traits

Plant density plays a crucial role as an agronomic factor in intercropping systems, significantly affecting crop performance and overall yield. According

to Sattler and Bartelheimer (2018), poor management of planting density can lead to unfavorable outcomes in intercropping. For instance, low plant densities may restrict yield potential, whereas overly high densities can cause increased plant stress and heightened competition for

essential resources such as light, water, and nutrients, ultimately resulting in reduced yields (Adeniyi and Omotunde, 2001). In line with this, Alemu *et al.* (2018) observed that higher basil population densities intensify competition for sunlight and nutrients, leading to longer stem lengths. Similarly, Pereira *et al.* (2015) noted that increased plant density promotes stem elongation because of stronger competition for light, which favors vertical growth over other developments. On the other hand, Fallah *et al.* (2018) found that wider spacing between plants encourages a higher number of branches, as there is more room for lateral expansion. However, Sadeghi *et al.* (2009) emphasized basil's sensitivity to plant density, pointing out that very low densities do not maximize fresh herb yield per unit area. At higher densities, individual plant weight often decreases due to limited growth and development from competition, which aligns with findings by Faridvand *et al.* (2021), who reported that reduced competition in basil allows better access to light, enhancing chlorophyll accumulation and aboveground biomass. Wider spacing improves individual plant growth by lessening rivalry for light, water, and nutrients, but this benefit for single plants does not fully compensate for the fewer plants per area, leading to lower total biomass. As a result, higher densities tend to increase dry matter yield, which positively influences essential oil yield per feddan. Comparable results were seen in studies on *Ocimum spp.* by Ram *et al.* (2002) and Arabasi and

Bayran (2004), as well as on *Melissa officinalis* by Katar and Gurbuz (2008). Furthermore, the percentage of essential oil decreases as plant density rises, consistent with observations by El-Gendy *et al.* (2001) and Atghaei *et al.* (2015) for *Ocimum basilicum*. Plants under high light conditions exhibit greater essential oil content than those in low light, since light availability strongly affects essential oil biosynthesis (Gavrić *et al.*, 2021). This suggests that denser populations can elevate total essential oil content in basil. Supporting evidence comes from Akbari *et al.* (2018), Alemu *et al.* (2018), and Lin *et al.* (2021), who indicated that plant population density impacts growth by modifying nutrient uptake and light exposure, thereby influencing photosynthesis and essential oil production. The drop in essential oil yield at lower densities is attributed to reduced herbal biomass. The study highlights plant density's importance in improving basil's chemical constituents (*Ocimum basilicum* L.), with lower densities linked to higher NPK percentages in dry leaves. These findings match those of El-Shaer (1986) for fennel, showing increases in NPK in dry herbs as density decreases.

4.2 Impact of NPK on parameter traits

Long-term use of chemical fertilizers like NPK can degrade soil, lower its fertility, and cause heavy metal accumulation in plant tissues, which harms the nutritional quality and safety of edible produce (Tamara *et al.*, 2005). Nutrition is widely recognized to profoundly influence plant

growth, yield, and fruit quality (Kassem and Marzouk, 2002), but the high cost of mineral fertilizers poses a major hurdle for farmers. Recent research also highlights health and environmental risks from these fertilizers, including soil depletion that necessitates higher chemical inputs, leading to substantial pollution over time. In sweet basil (*Ocimum basilicum* L.), NPK fertilizers notably affect growth parameters, essential oil content and chemical constituents, as evidenced in Tables 1-13 of the original study. Increasing NPK rates led to improvements in plant height, branch count, herb and leaf dry weights, essential oil content and leaf chemical constituents, peaking at 100% of the recommended dose. This boost is likely from NPK's stimulation of vegetative growth. Similar patterns were reported by Kamrozzman *et al.* (2016) in coriander. Ghatas and Mohamed (2018) also observed NPK's positive effects on growth, including higher total plant dry weight. The 100% recommended NPK dose significantly increased basil height, aligning with Alhasan *et al.* (2020) and Abbas *et al.* (2020) for sweet basil, Yousuf *et al.* (2014) and Kamrozzman *et al.* (2016) for coriander, and Abbas and Ali (2011) for roselle. Nitrogen, phosphorus, and potassium (NPK) are indispensable macronutrients that play pivotal roles in the physiological and biochemical processes underpinning plant growth, development, and secondary metabolite production, including essential oils in medicinal plants. The following

sections provide an in-depth analysis of their functions, supported by seminal research, with a focus on their influence on vegetative growth and essential oil yield. Nitrogen is a fundamental nutrient critical for plant growth and development, serving as a structural and functional component of amino acids, enzymes, and energy transfer molecules such as chlorophyll, adenosine diphosphate (ADP), and adenosine triphosphate (ATP). According to Bidwell (1974), nitrogen is essential for the synthesis of proteins and nucleic acids, which are vital for cell division and the formation of new tissues. The availability of nitrogen directly correlates with plant growth rates, as it facilitates the proliferation of meristematic cells and supports the expansion of vegetative structures (Thompson and Troch, 1975). Phosphorus is a vital element for plant cellular processes, particularly in cell division, the development of meristematic tissues, and carbohydrate metabolism. Lambers *et al.* (2000) highlight its involvement in numerous phosphorylation reactions, where it forms energy-rich phosphate bonds in molecules such as ATP and ADP, driving glycolysis, photosynthesis, and the metabolism of amino acids and lipids. Additionally, phosphorus contributes to biological oxidation processes and the structural integrity of membranes and nucleic acids. Devlin (1972) notes that a deficiency in phosphorus disrupts the conversion of sugars into starch and cellulose, impairing cell wall formation and energy storage, which can severely

limit plant growth and reproductive development. Potassium plays a significant role in supporting plant growth and elongation, primarily through its function in osmoregulation, which maintains turgor pressure and facilitates cell expansion. Mengel and Kirkby (1987) suggest that potassium may interact synergistically with indole acetic acid (IAA), a key plant hormone, to promote growth. Furthermore, potassium enhances carbon dioxide (CO₂) assimilation during photosynthesis and aids in the efficient translocation of carbohydrates from source leaves to storage tissues and developing organs. This nutrient's activation of enzymes involved in metabolic pathways further supports biomass accumulation and overall plant vigor. The combined availability of nitrogen, phosphorus, and potassium (NPK) has a synergistic effect on vegetative growth and biomass production. Mohammed (2020) and Ahmed *et al.* (2019) demonstrated that elevated NPK application rates correlate with maximum biomass yields across various crops, attributing this to the comprehensive nutritional support provided by these macronutrients. Abdelraouf *et al.* (2013) specifically observed optimal vegetative growth in black cumin with the application of mineral NPK fertilizers, underscoring their efficacy in enhancing shoot and root development. As outlined by Tiessen (2008) and Fageria (2009), nitrogen is integral to the synthesis of nucleic acids, amino acids, enzymes, proteins, chlorophyll, and cell wall

components; phosphorus supports nucleic acid formation, membrane stability, and energy transfer; and potassium activates enzymatic reactions while maintaining cellular water balance. These functions collectively bolster plant structural and metabolic capacity. The availability of NPK not only enhances vegetative growth but also influences the synthesis and yield of essential oils in medicinal plants. Onofrei *et al.* (2018) established a direct relationship between these macronutrients and the production of secondary metabolites, including essential oils, which are often concentrated in sweet basil. A positive correlation exists between vegetative biomass and essential oil yield, as increased vegetation provides a larger substrate for oil synthesis. Pariari and Bhattacharya (2001) observed this trend in ginger, where higher NPK levels resulted in greater foliage and correspondingly higher essential oil content. Nitrogen promotes the synthesis of proteins and carbohydrates, serving as building blocks for oil-producing tissues; phosphorus facilitates the movement of amino acids for protein synthesis; and potassium maintains turgor pressure, enhancing metabolic efficiency (Patra *et al.*, 2002, in Japanese mint). El-Nagar *et al.* (2015) further linked nutrient application rates to increased essential oil content in basil, potentially due to improved plant growth, higher oil gland density, or enhanced monoterpene production. These findings align with Ghatas and Mohamed (2018), who reported that elevated NPK-induced

vegetative growth significantly boosts essential oil yields, reflecting a robust metabolic response to nutritional enrichment.

4.3 Impact of effective microorganisms (EM) on parameter traits

Effective microorganisms (EM) serve as an affordable, eco-friendly biofertilizer, providing substantial benefits to crops and soil. As a sustainable nutrient source, EM reduces reliance on inorganic fertilizers and supports eco-agriculture (Hedga *et al.*, 1999; Hauwaka, 2000). EM promotes growth via nitrogen fixation, hormone production, and better nutrient access, while enhancing soil properties and minimizing environmental damage (Correa, 2002). Kengo and Hui-Lian (2000) reported that EM inoculation improves crop growth, yield, quality, and soil health in plant-soil systems. EM includes over 60 microbes, such as lactic acid bacteria (e.g., *Lactobacillus plantarum*, *Lactobacillus casei*, and *Streptococcus lactis*), photosynthetic bacteria, yeasts, and algae, producing lactic acids (Formowitz *et al.*, 2007). It enhances yield and quality in ornamental plants, increasing key chemical constituents (Javaid, 2006; Singh, 2007). For apple trees, EM led to longer/thicker shoots, larger leaves, and higher chlorophyll (Sahain *et al.*, 2007). EM also boosts nutrient status, especially NPK, iron, manganese, and zinc (Khaliq *et al.*, 2006). However, Abdou *et al.* (2011) on basil, Barbara *et al.* (2012) on basil, and Cezary (2015) on *Chamomilla recutita* found no significant benefits in some

practices. EM speeds organic matter breakdown, improving element availability and protecting against pathogens for better development and yields (Joshi *et al.*, 2019; Nayak *et al.*, 2020). Borowiak *et al.* (2021) noted EM increases soil activity and photosynthesis, potentially cutting fertilizer needs for sustainability. Olle and Williams (2013) found 70% of EM studies positive for growth, yield, quality, and protection. EM suppresses pathogens, solubilizes minerals, conserves energy, balances ecology, and improves photosynthesis/nitrogen fixation (Hidalgo *et al.*, 2022; Rastogi *et al.*, 2020). Szewczuk *et al.* (2016) showed EM strains positively affect plant features, functions, and substrates. Yet, some studies report limited or negative effects: Bajwa (2005), Javaid (2006), and Okorski *et al.* (2008) saw minimal/adverse impacts; Priyadi *et al.* (2005) and van Vliet *et al.* (2006) found none; Mayer *et al.* (2010) suggested growth suppression from nitrogen competition; Javaid *et al.* (2008) noted no effect on rye; and Javaid (2006) observed pea yield drops. Nitrogen levels matched Markiewicz (2000) (0.78-2.8% N) and Jadcak *et al.* (2006) (2.44-3.07% N). Khaliq *et al.* (2006) and Sahain *et al.* (2007) confirmed EM's positive effect on nitrogen, magnesium, and zinc in apples, while Golcz and Bosiacki (2008) saw higher nitrogen in thyme with mycorrhizae. EM sometimes reduced phosphorus uptake, despite improvements noted by Khaliq *et al.* (2006) and Sahain *et al.* (2007). Basil phosphorus matched (Seidler-Łożykowska *et al.*, 2006, 2009).

Potassium varied with EM methods, with increases in apples (Sahain *et al.*, 2007) and cotton (Khaliq *et al.*, 2006).

5. Conclusion

To improve sweet basil productivity, it is recommended to use a high plant density (33333 plants/feddan) to achieve maximum herb and leaf dry and essential oil yields per feddan, which is ideal for commercial production, or a low density (15555 plants/fed) to increase branches, herb and leaf dry weights/plant, oil percentage, and leaf nutrient content (NPK), which is suitable for high-quality oil production. Use a reduced dose of NPK (75%) with effective microorganisms (EM), administered several times during the season, to achieve peak growth, branch number, dry weight, and essential oil content. EM promotes soil health, reducing the use of mineral fertilizers. Future research should investigate the long-term effects of EM.

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