Indian Journal of Experimental Biology
Vol. 64, June 2026, pp. 572-578
DOI: 10.56042/ijeb.v64i06.27965

Synergistic effects of nano urea and PSB on oil quality, production and crop productivity of *Monarda citriodora* in Jammu region

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Received 27 January 2026; revised 30 January 2026

Limited quantitative information is available on the integrated use of Nano Urea and phosphate-solubilizing bacteria (PSB) for improving essential oil yield and composition in aromatic crops under subtropical conditions. This study aimed to generate statistically robust, stage-specific evidence on the effects of Nano Urea–PSB integration on growth, biomass, essential oil yield and thymol content of *Monarda citriodora*. A two-year field experiment (Rabi 2022–23 and 2023–24) was conducted at CSIR–IIIM, Jammu, using a randomized block design with five treatments and three replications. Data were analyzed at $P \leq 0.05$ and oil composition was determined by GC–MS at pre-flowering (75 Days After Transplanting) and full bloom (90 Days After Transplanting). Integrated Nano Urea and PSB application significantly improved vegetative growth, biomass accumulation, and oil recovery over conventional fertilization. At 90 DAT, thymol, the principal oil constituent ranged from 80.08–83.74% during the first year and 70.98–76.59% during the second year, confirming sustained thymol dominance under integrated nutrient management. Enhanced levels of *P*-cymene and carvacrol further indicated improved oil compositional diversity. This study provides quantified, stage-specific GC–MS evidence linking Nano Urea–PSB integration to thymol-rich essential oil production in *Monarda citriodora*, suggesting a sustainable nutrient strategy to enhance productivity and oil quality in aromatic crops in subtropical climates.

Keywords: Essential oil, Fertilizer, Lemon bee balm, PSB culture, Recommended dose of Fertilizer

Introduction

Monarda citriodora Cerv. ex Lag., commonly known as bee balm or lemon horse mint, is an important medicinal and aromatic crop valued for its thymol-rich essential oil, widely used in pharmaceutical, perfumery and food industries[1]. Despite its commercial potential, cultivation of *Monarda citriodora* in subtropical regions such as Jammu remains constrained by low biomass production, inconsistent essential oil yield and variable oil quality, which directly affect farmer profitability and crop marketability, as evidenced by significant phenological variations in essential oil content and composition[2]. Conventional cultivation practices depend heavily on chemical fertilizers, particularly nitrogenous inputs. Nitrogen plays a critical role in plant growth, chlorophyll synthesis and metabolic activity; however, its inefficient use results in economic losses and environmental degradation[3]. Excessive fertilizer application has been linked to soil fertility decline, nutrient leaching and environmental pollution, while rising fertilizer costs limit adoption by small and marginal farmers[4].

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Recent advances emphasize nano-fertilizers and plant growth-promoting rhizobacteria (PGPR) as sustainable nutrient management alternatives. Nano urea, characterized by nanoscale nitrogen particles (20–50 nm), improves nitrogen use efficiency through rapid foliar uptake, enhanced photosynthesis and reduced loss[5,6]. Phosphate-solubilizing bacteria (PSB) enhance phosphorus availability by converting insoluble forms into plant-accessible nutrients, promoting root growth, biomass accumulation and secondary metabolite synthesis[7].

Although individual benefits of nano fertilizers and PSB have been reported in various crops, quantitative, stage-specific studies integrating Nano Urea and PSB for improving essential oil yield and GC–MS-based oil composition of *Monarda citriodora* under subtropical conditions are scarce. Moreover, evidence on reducing recommended fertilizer doses without compromising oil quality remains limited.

Therefore, the present study aimed to evaluate the integrated effects of Nano Urea and PSB, with partial substitution of conventional fertilizers, on growth, biomass, essential oil yield and chemical composition of *M. citriodora* under Jammu agro-climatic conditions, to establish a cost-effective and sustainable nutrient management strategy for the farmers.

Material and Method

The study was conducted at the Research Farm, Chatha, CSIR-IIIM, Jammu, located at 32°59'57" N latitude and 74°34'41" E longitude. The experiment followed a randomized block design (RBD) with five treatments and three replications. Treatments included various combinations of recommended doses (RD) of NPK fertilizers, Nano urea and PSB culture. The treatments were: T_1 (Recommended Dose of NPK), T_2 (Half RD + 1 Spray Nano Urea), T_3 (2 Sprays of Nano Urea + PSB), T_4 (3 Sprays of Nano Urea) and T_5 (No Fertilizer Application). The PSB culture suspension was prepared by mixing the culture with water in a 1:10 ratio and applied as per the treatment protocol of (Department of Agriculture, Cooperation & Farmers Welfare, GoI, 2008). Nano urea spray solution (4%) was applied at recommended intervals (Table 1). The plot details included net plot size of 9 m², plant spacing of 30 × 30 cm. The crop was managed with a seed rate of 200-300 g/ha, variety IIIM (J) MC-02 and grown during the Rabi season (2022-23 and 2023-24). Data were recorded for growth parameters, yield attributes and essential oil content across two years, observing parameters such as plant height (cm), number of branches, leaf area (cm²), fresh weight (g), dry weight (g), root length (cm) and oil recovery in %, all taken on 75 and 90 days after transplanting. The two year (2022-23 and 2023-24) data mean values were subjected to a one-way ANOVA and statistical analysis was performed using OPSTAT software to determine the significance of treatment effects.

Leaf area Measurement

The leaf area of Monarda was estimated using the graph paper method (Pandey and Singh, 2011)[8]. Fresh leaves were detached from the plant and their outlines were drawn on millimeter graph paper. The graph paper covered by the leaf outline was cut and weighed (x, g). A one cm² area of the graph paper was also cut and weighed (y, g). The leaf area was calculated using the formula:

Leaf Area (cm²) = x / y

where x is the weight of the graph paper covered by the leaf outline (g) and y is the weight (g) of the cm² area of the graph paper.

Essential oil Extraction

The technique which is used for oil extraction is Clevenger method for determining essential oil content in plant material. It involves steam distillation of the plant material using a Clevenger apparatus, where the plant sample is heated with water at 80 degree Centigrade to release its essential oils. The distillate, containing the essential oil and water, is collected in a graduated tube and allowed to separate into two layers. The volume of the essential oil is then measured, and the oil content is calculated as % v/w (volume of oil per weight of plant material)[9].

Result

Plant Height (cm)

The study evaluated the synergistic effects of Nano Urea and phosphate-solubilizing bacteria (PSB) on the oil quality, production and crop productivity of *M. citriodora* in Jammu region. Significant variations were observed in plant height and flowering response across different treatments. At the pre flowering stage i.e. 75 DAT (Table 2), the plant height ranged from 17.98 cm to 30.44 cm, with the highest height recorded in T_3 (30.44 ± 2.60 cm), followed by T_2 (24.77 ± 0.78 cm). The recommended dose of NPK resulted in a plant height of 20.03 ± 0.49 cm, whereas T_5 recorded the lowest (17.98 ± 0.61 cm). At the full bloom stage (90 DAT), the plant height was significantly higher in T_3 (77.86 ± 1.07 cm), followed by T_2 (67.81 ± 1.11 cm), while the lowest was observed in T_5 (60.66 ± 1.22 cm). These results suggest that the combination of Nano

Table 1 — Detail of the treatments

Treatment	Details	Dose	Spray Timing (Days After Planting)
T_1	Recommended Dose of NPK (Farmer's Fertilizer Practices)	100:50:50 (Urea: 157.32 g/9 m², Diammonium Phosphate (DAP): 97.82 g/9 m², Muriate of Potash (MOP): 74.97 g/9 m²)	Not Applicable
T_2	Half RD + 1 Spray Nano Urea + PSB Culture	40 ml/L Nano Urea + Phosphate Solubilizing Bacteria (PSB) (1:10)	20
T_3	2 Sprays of Nano Urea + PSB Culture	40 ml/L Nano Urea + PSB (1:10)	20, 50
T_4	3 Sprays of Nano Urea	40 ml/L Nano Urea/Spray	20, 50, 80
T_5	Control (No Fertilizer Application)	NIL	NIL

DAP- Diammonium Phosphate, MOP- Muriate of Potash, PSB- Phosphate Solubilizing Bacteria, RD- Recommended dose

Urea and PSB can positively influence plant growth parameters, potentially improving oil yield and overall productivity.

No. of Branches per Plant

At the pre flowering stage (75 DAT) (Table 2), the number of branches varied significantly among treatments, ranging from 17.46 to 37.23). The highest number of branches was recorded in T_3 (37.23 ± 2.52), followed by T_2 (26.20 ± 0.30), while the lowest was observed in T_5 (17.467 ± 0.996). At the full bloom stage (90 DAT), T_3 had the highest branch count (69.43 ± 1.41), followed by T_2 (65.20 ± 0.36), while T_5 had the lowest (50.63 ± 0.24). In comparison, the standard NPK dose yielded significantly fewer branches, with 19.96 ± 0.27 at flowering and 52.46 ± 0.63 at full bloom.

Leaf Area

At the pre flowering stage (75 DAT) (Table 2), the leaf area ranged from 4.84 cm² to 9.32 cm², with the highest value observed in T_3 (9.32 ± 0.03 cm²), followed by the T_1 (9.06 ± 0.06 cm²) and T_4 (8.32 ± 0.17 cm²) while, the lowest leaf area was recorded in T_5 (4.84 ± 0.38 cm²).

At the full bloom stage (90 DAT), the leaf area was highest in T_3 (7.36 ± 0.69 cm²), followed by T_2 (6.14 ± 0.23 cm²) and T_1 (4.27 ± 0.12 cm²). The lowest value was observed in T_5 (3.81 ± 0.10 cm²). This suggests the application of Nano Urea and PSB, especially in T_3, significantly enhances leaf area, which plays a crucial role in photosynthetic efficiency and overall crop productivity.

Fresh Weight of plant (g)

At the pre flowering stage (75 DAT), the fresh weight ranged from 9.38 g to 22.89 g, with the highest value recorded in T_3 (22.89 ± 1.70 g), followed by T_2 (17.47 ± 0.40 g) and T_4 (15.49 ± 1.03 g). However, T_5 (9.38 ± 1.05 g) recorded the lowest fresh weight (Table 3).

At the full bloom stage (90 DAT), the highest fresh weight was again found in T_3 (231.04 ± 1.36 g), followed by T_2 (212.83 ± 3.04 g) and minimum was recorded in T_5 (108.91 ± 3.04 g). T_2 resulted in a fresh weight of 12.63 ± 0.54 g at the flowering stage and 146.33 ± 9.96 g at full bloom. T_3 improves plant biomass, which is crucial for enhanced crop yield and oil production.

Dry weight (g)

At the pre flowering stage (75 DAT), the dry weight ranged from 1.93 g to 5.45 g, with the greater value recorded in T_3 (5.45± 0.25 g), followed by T_2 (4.03 ± 0.16 g) and T_4 (3.44 ± 0.15 g).

Table 2 — Effect of different treatment on agronomic traits of *Monarda citriodora* at different growth stages using pooled data (2022-23 & 2023-24)

Treatments	Plant Hight (cm)		No. of Branches		Leaf Area (cm)	
	Flowering stage (75 DAT)	Full Bloom Stage (90 DAT)	Flowering stage (75 DAT)	Full Bloom Stage (90 DAT)	Flowering stage (75 DAT)	Full Bloom Stage (90 DAT)
T_1	20.03 ± 0.49	65.46±2.22	19.96 ± 0.27	52.46 ± 0.63	9.06 ± 0.069	4.27 ± 0.12
T_2	24.77 ± 0.78	67.81± 1.11	26.20 ± 0.30	65.20 ± 0.36	6.99 ± 0.427	6.14 ± 0.23
T_3	30.44 ± 2.60	77.86 ± 1.07	37.23 ± 2.52	69.43 ± 1.41	9.32 ± 0.038	7.36 ± 0.69
T_4	21.14 ± 0.30	67.24 ± 1.20	21.93 ± 0.73	57.80 ± 1.22	8.32 ± 0.176	5.50 ± 0.06
T_5	17.98 ± 0.61	60.66 ± 1.22	17.46 ± 0.99	50.63 ± 0.24	4.84 ± 0.384	3.81 ± 0.10
Critical Difference at 5%	3.49	4.67	4.45	3.25	0.99	1.12

DAT- Days After Transplanting, Values are presented as mean ± Standard Deviation (SD)

Table 3 — Effect of different treatment on agronomic traits of *Monarda citriodora* at different growth stages.

Treatments	Fresh Weight (g)		Dry Weight (g)		Root length (cm)
	Flowering stage (75 DAT)	Full Bloom Stage (90 DAT)	Flowering stage (75 DAT)	Full Bloom Stage (90 DAT)	Flowering stage (75 DAT)
T_1	12.63 ± 0.54	146.33 ± 9.96	2.53 ± 0.07	27.25 ± 0.50	5.45 ± 0.10
T_2	17.47 ± 0.40	212.83 ± 3.04	4.03 ± 0.16	30.29 ± 0.97	6.16 ± 0.03
T_3	22.89 ± 1.70	231.04 ± 1.36	5.45 ± 0.25	36.37 ± 1.83	6.71 ± 0.34
T_4	15.49 ± 1.03	184.58 ± 0.22	3.44 ± 0.15	28.29 ± 0.18	5.80 ± 0.03
T_5	9.38 ± 1.05	108.91 ± 3.04	1.93 ± 0.20	22.46 ± 0.46	4.75 ± 0.14
Critical Difference at 5%	3.52	17.33	0.64	3.58	0.48

DAT- Days After Transplanting, Values are presented as mean ± Standard Deviation (SD)

The lowest dry weight was observed in T_5 (1.93 ± 0.20 g) (Table 3).

At the full bloom stage (90 DAT), T_3 (36.37 ± 1.83 g) performs better followed by T_2 (30.29 ± 0.97 g), while the lowest was recorded in T_5 (22.46 ± 0.46 g). T_1 (recommended dose of NPK) resulted in a dry weight of 2.53 ± 0.07 g at the pre flowering stage and 27.25 ± 0.50 g at full bloom. These results indicate that the application of Nano Urea and PSB, especially in T_3, significantly enhances dry biomass accumulation, which is essential for improved crop productivity and oil yield.

Root Length (cm)

The root length varied significantly among treatments, ranging from 4.75 cm to 6.71 cm. (Table 3). The highest root length was recorded in T_3 (6.71 ± 0.34 cm), followed by T_2 (6.16 ± 0.03 cm) and T_4 (5.80 ± 0.03 cm). The lowest root length was observed in T_5 (4.75 ± 0.14 cm).

T_1 resulted in a root length of 5.45 ± 0.10 cm. These findings suggest that the application of Nano Urea and PSB, particularly in T_3, enhances root development, which is crucial for better nutrient uptake, water absorption and overall plant growth, ultimately leading to improved crop productivity.

Oil Recovery (%)

The study also evaluated the impact of Nano Urea and PSB on the oil recovery percentage of *M. citriodora* across two cropping seasons (2022–23 and 2023–24) at different growth stages (Table 4) (Fig. 1).

During the 2022–23 cropping season, oil recovery at the pre flowering stage (75 DAT) ranged from 0.60% to 1.60%, with the highest recovery recorded in T_3 (1.60 ± 0.04%), followed by T_2 (1.30 ± 0.01%). The lowest oil recovery was observed in T_5 (0.60 ± 0.00%). At the full bloom stage (90 DAT), oil recovery was highest in T_3 (2.30 ± 0.05%), followed by T_2 (2.10 ± 0.02%), while the lowest was recorded in T_5 (1.10 ± 0.024%).

Similarly, in the cropping season of 2023–24, oil recovery at the pre flowering stage (75 DAT) ranged from 0.70% to 1.40%, with the highest recovery again observed in T_3 (1.40 ± 0.01%), followed by T_2 (1.20 ± 0.02%). At the full bloom stage (90 DAT), oil recovery peaked in T_3 (2.20 ± 0.03%), whereas the lowest was recorded in T_5 (0.80 ± 0.00%).

GC-MS Based Chemical Profiling of Essential Oil of *Monarda citriodora*

To identify the components present in the essential oil of Monarda obtained from different treatments was done through GC-MS analysis at two stages, one at pre-flowering stage (75 DAT) (Table 5) and other at full bloom stage (90 DAT) (Table 6). The major compounds identified were Thymol, Carvacrol, Terpinen-4-ol, α-Terpineol, p-Cymene, β-Caryophyllene, γ-Terpinene, beta-Myrcene, α-Pinene, Benzene, 2-methoxy-1-methyl-4-(1-methylethyl) (Table 5 and 6). Thymol being the primary constituent of Monarda essential oil was recorded to be highest in all the treatments at all the stages during both the years followed by p-Cymene and Carvacrol (Fig. 2). During the first year of the study, at 75 DAT, T_4 recorded the highest thymol content of 82.92% followed by T_2 (82.44%), T_1 (82.16%), T_3 (81.21%) and T_5 (80.70%) After thymol, p-Cymene content was recorded highest in the treatments with maximum in T_5 (9.32%) followed by T_3 (8.85%), T_4

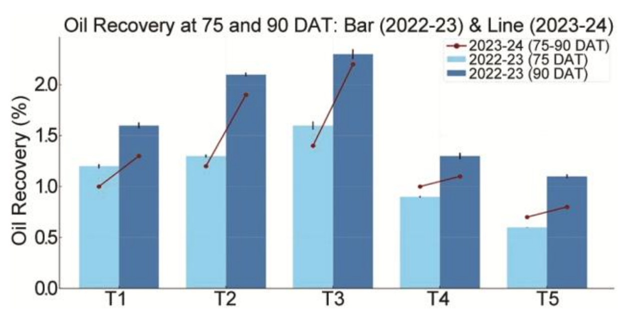

Fig. 1 — Oil Recovery % at 75 and 90 DAT.

Table 4 — Effect of different treatment on Percent of oil recovery of *Monarda citriodora* at different growth stages using pooled data (2022-23 & 2023-24)

Treatments	Cropping Season 2022-23		Cropping Season 2023-24	
	Oil Recovery % (75 DAT)	Oil Recovery % (90 DAT)	Oil Recovery % (75 DAT)	Oil Recovery % (90 DAT)
T_1	1.20 ± 0.02	1.60 ± 0.03	1.0 ± 0.02	1.30 ± 0.01
T_2	1.30 ± 0.015	2.10 ± 0.02	1.20 ± 0.02	1.90 ± 0.02
T_3	1.60 ± 0.04	2.30 ± 0.05	1.40 ± 0.01	2.20 ± 0.03
T_4	0.90 ± 0.009	1.30 ± 0.03	1.0 ± 0.006	1.10 ± 0.01
T_5	0.60 ± 0.003	1.10 ± 0.02	0.70 ± 0.01	0.80 ± 0.009
Critical Difference at 5%	0.071	0.111	0.057	0.065

DAT- Days After Transplanting, Values are presented as mean ± Standard Deviation (SD)

Table 5 — Effect of different treatment on chemical components of *Monarda citriodora* essential oil at 75 DAT (2022-23 & 2023-24)

75 DAT at Pre Flowering stage

Compound (Area %)	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
	1st Year (2022-23)					2nd Year (2023-24)				
Thymol	82.16	82.44	81.21	82.92	80.7	75.39	80.26	79.72	76.85	78.1
Carvacrol	3.86	3.5	4.01	4.77	4.9	2.21	3.35	2.65	1.76	3.39
Terpinen-4-ol	0.89	0.93	0.61	0.77	0.85	0.54	0.37	0.46	0.28	0.54
α-Terpineol	-	-	0.08	-	-	-	-	-	-	-
p-Cymene	5.23	0.24	8.85	6.62	9.32	5.58	4.11		4.86	6.46
β-Caryophyllene	0.08	-	-	-	0.13	-	-	-	-	-
γ-Terpinene	3.67	3.5	0.52	1.28		6.96	4.88	5.02	6.67	4.06
beta-Myrcene	1.11	1.04	0.88	0.96	0.83	1.95	1.68	1.44	1.92	1.51
α-Pinene	0.08	0.29	-	0.29	0.32	0.92	0.78	0.63	1.14	0.83
Benzene, 2-methoxy-1-methyl-4-(1-methylethyl)-	0.65	0.82	0.7	0.51	0.89	0.97	0.1	0.79	0.85	0.15

DAT- Days After Transplanting

Table 6 — Effect of different treatment on chemical components of *Monarda citriodora* essential oil at 90 DAT using pooled data (2022-23 & 2023-24)

90 DAT at Flowering stage

Compound (Area %)	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
	1st Year (2022-23)					2nd Year (2023-24)				
Thymol	83.57	82.6	81.02	83.74	80.08	76.59	70.98	76.31	75.71	71.71
Carvacrol	3.81	4.22	4.57	3.37	3.58	2.33	2.67	2.73	3.32	2.87
Terpinen-4-ol	1.37	1.07	0.76	1.47	0.95	0.57	0.44	0.32	0.67	0.61
α-Terpineol	-	-	0.1	-	0.1	-	-	-	-	-
p-Cymene	4.89	6.86	8.96	7.21	7.91	6.99	7.33	7.98	7.18	7.62
β-Caryophyllene	-	-	-	-	-	-	-	-	-	-
γ-Terpinene	0.47	1.5	0.91	0.92	-	4.95	6.8	4.13	4.13	7.25
beta-Myrcene	0.35	0.89	0.88	0.62	0.98	1.54	2.39	1.49	1.71	1.96
α-Pinene	-	-	-	-	0.32	0.79	1.64	0.72	0.89	1.1
Benzene, 2-methoxy-1-methyl-4-(1-methylethyl)-	1.18	0.33	0.33	0.69	0.73	0.82	0.66	0.4	0.53	0.77

DAT- Days After Transplanting

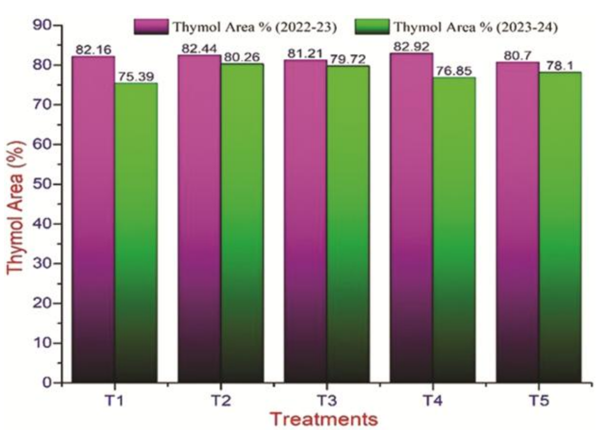

Fig. 2 — Effect of different treatments on Thymol content during 2022-23 & 2023-24.

(6.62%), T_1 (5.23%), while the lowest was in T_2 having 0.24%. Carvacrol, which was also recorded in good amount found to be highest in T_5 (4.90%) followed by 4.77, 4.01, 386 and 3.50% in T_4, T_3, T_4 and T_2, respectively. Two components β-Caryophyllene and α-Terpineol recorded the minimum percentage. β-Caryophyllene was found only in two treatments i.e. T_1 and T_5 with 0.08 and 0.13%, respectively. Whereas α-Terpineol was found only in one treatment i.e. T_3 (0.08%). During the second year, the percentage of Thymol was dominating over all the other major compounds identified. It was found highest in T_2 having 80.26% followed by 79.72, 78.10, 76.85 and 75.39% in T_3, T_5, T_4 and T_1, respectively. Among 5 treatments, p-Cymene was found in four treatments with highest percentage in T_5 (6.46%) followed by T_1 (5.58%), T_4 (4.86%) and T_2 (4.11%), while T_3 did not record any traces of p-Cymene. T_5 with Carvacrol percentage of 3.39 was found superior over rest of the treatments. While T_4 (1.76%) recorded minimum Carvacrol percentage followed by T_1 (2.21%), T_3 (2.65%) and T_2

(3.35%). However, during this year, β-Caryophyllene and α-Terpineol were not identified in any of the treatments.

At 90 DAT, a slight variation in the percentage of Thymol was observed in the first year. Compared to data at 75 DAT, thymol percentage was observed highest at 90 DAT. It was recorded highest in T_4 (83.74%) followed by T_1 (83.57%), T_2 (82.60%), T_3 (81.02%) and T_5 (80.08%). p-Cymene percentage of 8.96 was observed to be highest in T_3 followed by T_5 (7.91%), T_4 (7.21%), T_2 (6.86%), while T_1 recorded the lowest percentage of 4.89. Carvacrol, another important component present in Monarada essential oil was found maximum in T_3 (4.57%) and minimum in T_4 (3.37%) followed by T_5 (3.58%), T_1 (3.81%) and T_2 (4.22%). Components α-Terpineol was found in T_3 and T_5 constituting similar percentage i.e. 01%. while α-Pinene was found in one treatment only i.e. T_5 (0.32%). In the second year, highest Thymol percentage of 76.59 was recorded in T_1 followed by 76.31, 75.71, 71.71 and 70.98% in $T_{3,}$ $T_{4,}$ $T_{5,}$ and $T_{2,}$ respectively. Highest percentage of p-Cymen was recorded in $T_{3,}$ $T_{5,}$ $T_{2,}$ T_4 and T_1 having 7.98, 7.62, 7.33, 7.18 and 6.99%, respectively. Carvacrol was found to be maximum in T_4 with 3.32% followed by 2.87, 2.73, 2.67 and 2.33% in $T_{5,}$ $T_{3,}$ T_2 and $T_{1,}$ respectively. α-Terpineol was not found in any of the treatment in the second year, while β-Caryophyllene was not identified during both the years in any treatment.

Discussion

The study demonstrates that the combined application of Nano Urea and PSB significantly enhances plant growth, biomass accumulation and oil recovery in *M. citriodora*. The increase in plant height, number of branches and leaf area, particularly in T_3, suggests improved nitrogen use efficiency and microbial activity, leading to better vegetative growth. Similar trends have been reported in aromatic and medicinal crops where Nano Urea enhances nitrogen uptake and PSB promotes root growth and nutrient absorption[10-13].

The significant improvements in fresh and dry weight further support the role of these bio-inputs in enhancing biomass production. The highest values recorded in T_3 indicate improved chlorophyll content and photosynthetic efficiency, aligning with findings by Fattahi *et al.*[11] and Verma *et al.*[14] Gayathri *et al.* [15]. Additionally, increased root length in T_3 highlights the contribution of PSB in enhancing root proliferation and nutrient uptake, which has been previously observed in oil crops[16].

Oil recovery was highest in T_3 across both cropping seasons, with greater values observed at full bloom, indicating enhanced secondary metabolite biosynthesis. These results corroborate the findings of Koli *et al.*[12], who reported that biofertilizers and foliar nutrients improve essential oil yield and quality.

Thymol is considered as the major component in essential oil of Monarda that determines the quality of the oil in national and international markets[17-19]. Quality essential oil plays a vital role in industry i.e. aromatherapy[18], skincare[20], insect repellent[21] and perfumery[22]. The study underscores the potential of integrating Nano Urea and PSB on quality of essential oil. Thymol was found to be highest in T_2 and T_4 while T_3 showed superiority in other valuable compounds in the oil like Carvacrol and p-Cymene at full bloom stage. Hence, T_3, which involved two sprays of Nano Urea combined with Phosphate Solubilizing Bacteria (PSB), was found to be effective, demonstrating a 0.99% increase in essential oil content during the first year at the full bloom stage (90 DAT). As a result, the plant's physiological processes such as photosynthesis, enzymatic activity and secondary metabolite biosynthesis are positively impacted, leading to an overall improvement in biomass accumulation and a significant enhancement in both the quality and quantity of essential oils produced in the crop[23,24].

Conclusion

The findings clearly demonstrate that the integrated application of Nano Urea and Phosphate-solubilizing bacteria (PSB) markedly enhances growth, biomass production and essential oil yield of *Monarda citriodora*. Among the evaluated treatments, T_3 comprising two foliar sprays of Nano Urea in combination with PSB consistently outperformed other treatments across growth stages and achieved a 0.99% increase in essential oil content at full bloom (90 DAT) during the first year. Although T_4 and T_2 recorded marginally higher thymol concentrations at specific stages, T_3 emerged as the most effective treatment by maintaining stable thymol dominance while simultaneously enhancing key bioactive constituents such as *p*-cymene and carvacrol, thereby producing a more balanced and enriched essential oil profile. An important practical outcome of this study is the reduction in dependence on conventional fertilizers, thereby lowering input costs for farmers using low-dose nano fertilizers and bio-inoculants. While the study was conducted under a single agro-climatic condition, it highlights the need for multi-location validation and long-term economic evaluation. Overall, the results position Nano Urea and PSB integration as a cost-effective, resource-efficient and sustainable nutrient management strategy for improving productivity and essential oil quality in aromatic crop cultivation.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgement

The authors would like to express their sincere gratitude to Dr. Zabeer Ahmed, Director, CSIR-Indian Institute of Integrative Medicine, Jammu, for providing the necessary facilities, infrastructure and support that enabled the successful completion of this research work.

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