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Synergistic Effect of Seaweed Extract, Humic, and Fulvic Substances on Growth, Essential Oil Yield, and Quality of Patchouli in a Semi-arid Tropical Region

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Abstract

The cultivation of patchouli in semi-arid tropical regions is affected by various abiotic factors that hinder the production of biomass and the oil that patchouli yields. This research quantified the impact of individual and all possible combinations of seaweed extracts, humic acid, and fulvic acid on patchouli (cv. CIM-Samarth) growth, yield, essential oil quality, and economic potential. A field experiment was conducted in Hyderabad, India, from 2023 to 2025, utilizing a randomized complete block design with eight treatments and three repetitions. The treatment T8, which included triple biostimulants, showed the best performance for each of the measured parameters due to its synergistic effects. T8 surpassed all control parameters about plant height (35.5%), number of leaves (62.1%), fresh herbage yield (54.5%), and oil yield (105.7%). The T8 treatment also improved the oil quality as the oil content increased from 1.93% to 2.56%, and the patchoulol concentration increased from 19.5% to 20.2%. The principal component analyzed confirmed the symmetry of the yield with growth, as it maintained closely cohesive structures ($r = 0.84$-1.0). The T8 treatment provided its economic potential with the net return of 5,440.7/ha and benefit-cost ratio of 3.73, nearly doubling the profitability of the control. This integrated biostimulants approach effectively mitigates multiple abiotic stress bottlenecks, offering a sustainable and highly profitable strategy to improve patchouli production in marginal environments.

Keywords

Seaweed extractant; Humic acid; Fulvic acid; Patchouli alcohol; CIM-Samarth

1. Introduction

In today's world, modern agriculture faces the dilemma of increasing agricultural production while combating the negative impact of environmental degradation. Excessive use of synthetic agrochemicals has degraded soil, excessively depleted groundwater [1, 2], and possibly led to environmental losses. Losses are most evident in semi-arid tropical ecoregions, where agricultural stakeholders face low water availability, extreme temperatures, and low soil

fertility. The combination of these factors makes the use of conventional agriculture with high production factors economically and environmentally unsustainable [3].

In these increasingly challenging environmental conditions, aromatic and medicinal crops present a unique agricultural opportunity. For example, patchouli (*Pogostemon cablin* (Blanco) Benth.) is a high-value aromatic crop, and its essential oil is highly valued in the international market. The economic returns are sufficient to make patchouli cultivation worthwhile, even on marginal lands [4, 5]. However, it is essential to move away from traditional agronomic approaches to realize such potential.

The CIM-Samarth type of patchouli shows great potential, yet has considerable limitations with production under abiotic stressors. High temperatures, lack of water, and nutrient deficiencies all undercut patchouli biomass. The reduction of biomass directly leads to the reduction of patchouli essential oil and alters the phytochemical profile that the market is based on [6, 7]. With climate change projections indicating a gradual increase of these stressors, the viability of economically patchouli production in these vulnerable regions is economically unsustainable.

Increasing economic costs, coupled with the negative consequences of synthetic fertilizers and pesticides, such as environmental pollution, have directed researchers to the use of biological alternatives [2, 8]. In this regard, plant biostimulants have emerged as one of the most promising alternatives. Unlike the usual inputs that just give nutrients and help to manage pests, the biostimulants help in improving the physiological functions of plants and help in getting and assimilating more resources and managing to cope with stress [9, 10].

Biostimulants can be classified into a few main types, which have been repeatedly shown to be successful across many cropping systems. Chemical compounds, which can be obtained from seaweed, can improve the rooting and quality of the plantlets of garden plant species such as 'Bush green bean' and 'Jade plant'. Planting these plants with added seaweed can be beneficial. Humic acids mainly work through altering the physical, chemical, and biological properties of soils, which result in better water retention, improved soil structure, and a good microbial community [11, 12]. Smaller compounds such as fulvic acids can enter plant tissues to help the transport of nutrients and prevent oxidative damage at a cellular level [13, 14].

The unique significance of these biostimulants depends upon the mechanism of action. Biostimulants do not target one pathway but rather a network of interacting pathways such as hormone signalling, photosynthesis, antioxidant systems, and beneficial microbes [11, 15]. Researchers have found that different biostimulants can offer synergistic effects greater than additive when used together. Evidence from aromatic crops shows it. The mixture of different treatments brings more biomass accumulation and yield of essential oil and metabolites than each treatment applied separately [16, 17].

However, there remains a significant gap in our knowledge. The patchouli plant has reportedly responded positively to biostimulants when applied individually [5, 18]. However, the effect of multiple biostimulants applied together is not systematically documented. Semi-arid tropical agro ecosystems are important environments from an ecological and economic point of view. In these environments, integrated biostimulants can increase farm profitability and reduce environmental damage [3, 19].

The objective of this study is to fill this knowledge gap by evaluating the effect of seaweed extract, humic acid, and fulvic acid applied individually and in combination on patchouli cv. CIM-Samarth under semi-arid tropical conditions. We evaluate several parameters such as growth, physiology, nutrient absorption, essential oil yield, and chemical composition. This system will evaluate the effectiveness of these biostimulants and how they interact with each other. The aim of this work is twofold: to decipher the mechanistic basis of biostimulants synergies and to provide empirically derived guidelines for agronomists and practitioners to increase sustainable productivity in resource-poor environments.

2. Materials and Methods

2.1 Experimental Site and Climate

In the Kharif seasons (June-October) of 2023-2024 and 2024-2025, a two-year field experiment was conducted at the experimental farm of CSIR-Central Institute of Medicinal and Aromatic Plants Research Centre, Hyderabad, India (17°25′ N, 78°33′ E; 530 meters above mean sea level). The experimental site, located in the Deccan Plateau, is characterized by a semi-arid tropical climate with hot summers (30-40°C), mild winters (15-25°C), and seasonal variation in relative humidity. The predominant soil type was red sandy loam with medium organic matter content and limited nutrient availability. Physico-chemical properties of the soil at 0-15 cm depth and meteorological data during the experimental period are depicted in Table 1.

Table 1. Climate and soil (physical and chemical soil properties) of the experimental site (CSIR-CIMAP, RC., Boduppal, Hyderabad, Telangana State, India)

Parameters	Details
Latitude	17° 25´N
Longitudes	78° 33´E
Mean sea level	530 m above
Climate	Semi-arid tropical
Average annual rainfall	800 mm
Rainfall during this experiment year	810.7 mm
Soil	(72.2 % sand, 12.02 % silt, 15.78 % clay)
pH	7.35
EC	0.47 dS/m
Organic carbon (%)	0.28
Available N	172.4 kg/ha
Available P	15.2 kg/ha
Available K	258.6 kg/ha
Avg. Ann. Temp. (Long term) (◦ c)	30
Max. Temp. (Long term) (◦ c)	38.9
Min. Temp. (Long term) (◦ c)	23.6

2.2 Plant Material and Propagation

The patchouli cultivar 'CIM-Samarth' (*Pogostemon cablin* (Blanco) Benth.) was obtained from the germplasm repository of CSIR-CIMAP Research Centre, Hyderabad. In April 2023, healthy terminal cuttings (10–12 cm length, 4–5 nodes, 2–3 leaves) were collected from disease-free mother plants for vegetative propagation. Before planting, cuttings were treated with Bayer's Aliette solution (0.3 g L^{-1}) by dipping for 15 minutes to prevent root rot and fungal infections. Treated cuttings were planted in polyethylene bags (15 × 20 cm) filled with a potting mixture of soil, sand, and compost (1:1:1, v/v/v). The cuttings were initially maintained under shade with gradual exposure to evening sunlight for hardening to prevent transplant shock. Regular irrigation was provided to maintain adequate moisture until the cuttings developed sufficient root systems after 30–35 days.

2.3 Field Preparation and Experimental Design

The experimental field was prepared by ploughing with a mould board plough, followed by two harrows to achieve fine tilth. Weeds and crop residues were removed, and the field was leveled using a wooden plank. Well-decomposed farmyard manure (FYM) at 4 t ha^{-1} was incorporated into the soil before transplanting to improve fertility. Pendimethalin 30% EC was applied as a pre-emergence herbicide to suppress early weed growth. Individual experimental plots measuring 4 m × 4 m (16 m^2 gross area) were prepared manually. The experiment was laid out in a randomized complete block design (RCBD) with eight treatments and three replications. Thirty-five-day-old rooted saplings were transplanted into the main field in the first week of June 2023 and June 2024 at a spacing of 45 × 45 cm. Biostimulant treatments were incorporated into the soil three days before transplanting.

2.4 Crop Management

At transplanting, a basal application of 25 kg N, 50 kg P_2O_5, and 50 kg K_2O ha^{-1} was done. Throughout the growing season, nitrogen top-dressing (25 kg N ha^{-1}) was applied 5 times at two-month intervals. Transplanting took place in the evening, and the plots were irrigated immediately for establishment. The crops were watered every day for the first 3-4 days. After that, they were watered every other day for a period of 10-15 days. After that, irrigation frequency was modified to once or twice weekly based on soil moisture status and climate conditions. Weeding was

done manually four times to maintain weed-free conditions in the field. The leaves were harvested four months after the transplants were grown, when they turned yellowish. From the upper recommended bud section, branches 15–20 cm with cuts made from top to bottom are taken for harvesting every 3–4 months, depending on growth conditions.

2.5 Bio stimulant treatments

Commercially available products were used for the biostimulants in the study. The seaweed extract was IFFCO Sagarika Natural Seaweed Extract Fertilizer, which is derived from marine algae and is rich in natural growth-promoting substances. Utkarsh Huminoz-98 Humic Acid, a powdered product with 98% humic acid, was the source of the humic acid. Fulfill bio-stimulant of Agrolaunch is a liquid formulation of fulvic acid from Agrolaunch.

The Experiment consists of eight treatments in a Randomized Complete Block Design (RCBD) with three replications. The treatments were as follows.

- **T1:** Control (No biostimulant application)
- **T2:** Seaweed extract @ 3 ml/plant
- **T3:** Humic acid @ 0.16 g/plant
- **T4:** Fulvic acid @ 0.8 ml/plant
- **T5:** Seaweed extract @ 3 ml/plant + Humic acid @ 0.16 g/plant
- **T6:** Seaweed extract @ 3 ml/plant + Fulvic acid @ 0.8 ml/plant
- **T7:** Humic acid @ 0.16 g/plant + Fulvic acid @ 0.8 ml/plant
- **T8:** Seaweed extract @ 3 ml/plant + Humic acid @ 0.16 g/plant + Fulvic acid @ 0.8 ml/plant

The biostimulants were applied at the time of transplanting, with subsequent applications every 30 days.

Post-Harvest Processing

The finely chopped herbage was spread in thin layers over the plastic nets and shade dried for 7 was turned appeared. The material days till a characteristic smell discarded because intermittently to maintain even drying. Old, thick stems were for two months before of their low oil content. The dried herbage was kept essential oil extraction in order to develop and mature the aroma.

2.6 Essential Oil Extraction

The essential oil was Clevenger-type obtained from 300 g of dried herb by hydrodistillation in a apparatus (5 L capacity) for 9 h to ensure complete oil extraction. The resulting essential oil was dried over anhydrous sodium sulfate to remove any dark, cool conditions, remaining moisture, kept in amber glass containers under and subjected to analysis.

2.7 Growth, Yield, and Quality Parameters

The plant's height (cm) was taken as the distance from the soil surface to the top of the main stem by was using a meter scale. The number of Primary and Secondary branches and the Number of Leaves per plant were counted manually. Leaf width (cm) was measured using a measuring scale, and Collar diameter (mm) was measured using a Vernier caliper at 5 cm above ground level. These observations were recorded before the first harvest. Fresh herbage yield was recorded immediately after harvest, and dry herbage yield was determined after shade drying. Essential oil content (%) and Essential oil yield were calculated using the formula:

Essential oil content (%) = (Volume of essential oil (mL) / Weight of dry herb (g)) × 100

Essential oil yield per hectare was calculated by multiplying the oil content by the dry herbage yield.

Essential Oil Yield (kg/ha) = (Fresh or Dry Plant Biomass Yield (kg/ha)) × (Essential Oil Content (%)).

2.8 Gas Chromatography-Mass Spectrometry (GC-MS) Analysis

The extracted and dried patchouli Essential oil samples were analyzed using a Varian CP-3800 gas chromatograph, which features a flame ionization detector and split/split less capillary injectors, in conjunction with a Varian Galaxie chromatography data system (version 1.9 SP 1a) and a 100% dimethylpolysiloxane bonded phase Varian CP-Sil 5CB column, which has a 50 m length, 0.25 mm internal diameter, and 0.25 µm film thickness, to identify the relative peak area percentages of the oil's constituents. The GC operating conditions comprised an injector temperature of 250°C and an FID temperature of 300°C. Injections of the oil samples, each of 0.2 µL, were made neatly. RRIs were generated using a standard solution of n-alkanes (C6-C19) under the same conditions. The relative proportions of individual compounds were determined from GC peak areas by normalisation.

2.9 Statistical Analysis

The mean data from the experiment were analyzed using the statistical software IBM SPSS Statistics Version 19 [20]. The variance (F) ratio was used to determine the significance of treatment variation versus error variance. To assess the significance of any difference between any two treatment averages, LSD values were computed at the percent probability level (P = 0.05).

3. Results and Discussion

3.1 Bio stimulants on the growth parameters of Patchouli

Differences in the growth parameters of patchouli (CIM-Samarth) due to applied bio-stimulants were presented in Figures 1 and 2. The application of bio stimulants induced significant improvements in the plant's morphological characteristics, with the most pronounced effects observed in the triple-combination treatment, T8. The growth parameters, including plant height and number of leaves in the humic acid (T8) were combined treatment with seaweed extract + fulvic acid + significantly higher than all other treatments. This was accompanied by the highest values recorded for plant height (88.33 cm), number of primary branches (16.77), number of secondary branches (184.33), Number of leaves (402), and widest leaf width (4.11 cm). The lowest values for all traits, plant height (68.67 cm), primary branches (12.77), secondary branches (140.43), number of treatment leaves (245), and leaf width (3.6 cm) were recorded in the control group.

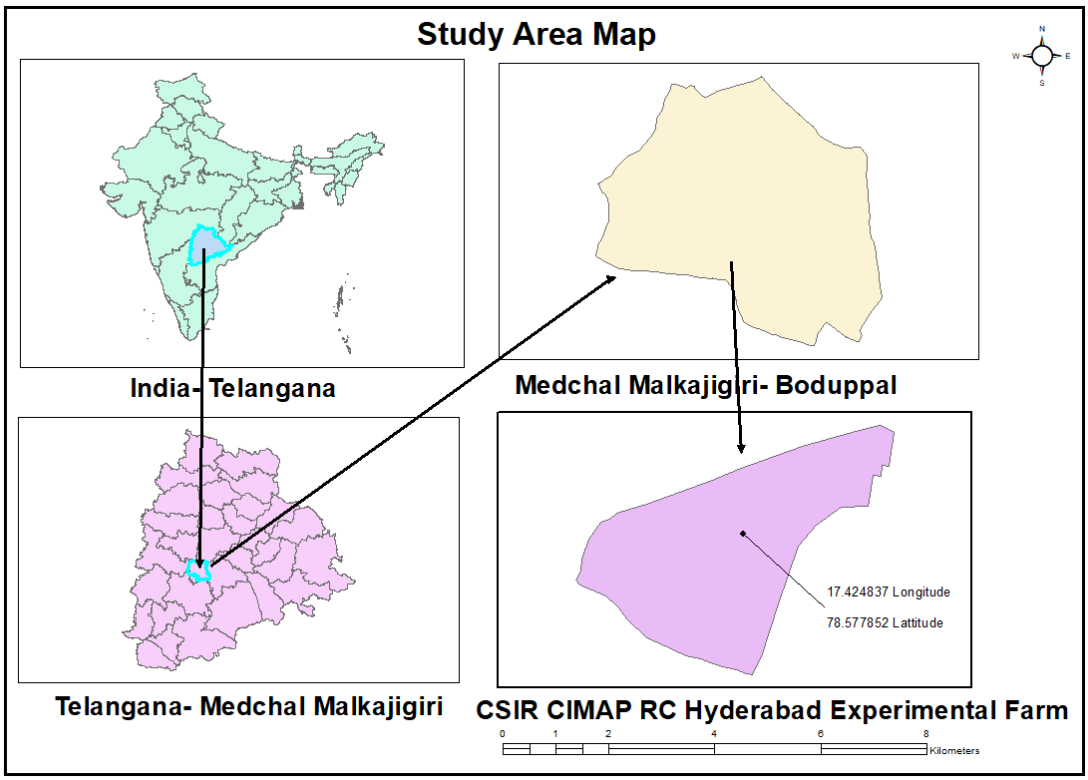

Figure 1. Experimental location map for the patchouli crop.

Plant height increased by 35.5%, from 68.4 cm in the control group to 92.7 cm with T8 treatment. This benefit was much greater than that of single applications (T2-T4), which saw an average improvement of 12.6%, and dual combinations (T5-T7), which saw an average improvement of 24.8%. The number of primary branches also increased by 32 %. In contrast, leaf width remained fairly constant across treatments (3.6 to 4.7 cm), suggesting that this trait is less affected by biostimulants and may be determined mostly by genetics or plant structure. The strong performance of the triple-combination treatment (T8) probably comes from the way its components work together, affecting multiple plant processes at the same time. Seaweed extracts provide a mixture of phytohormones – such as auxins, cytokinins, and betaines – that stimulate cell division, cell expansion, and overall plant metabolism [14].

Humic acid helps improve the physical and chemical properties of soil by increasing cation exchange capacity (CEC), water retention, and aggregate structure [21]. This creates a better environment for the roots, making the nutrients more available for plant utilization, along with the benefits of the seaweed extract [5, 22]. Fulvic acids act as effective chelators and transporters of nutrients. Due to their low molecular weight, they form complexes with minerals and transport them directly into plant cells, thereby ensuring that the nutrients released by humic acids are properly absorbed and distributed [23].

Figure 2. Field view of Patchouli experiment with varied biostimulants treatments in Patchouli.

In semi-arid tropical areas, where high temperatures, droughts, and poor soils are common, plants deal with multiple stresses at the same time [24]. A single biostimulant tends to solve only one problem. The triple combination offers a more complete solution: humic acids help reduce water and nutritional stress, seaweed extracts promote growth and resilience, and fulvic acids improve nutrient efficiency [25]. By covering different needs at the same time, this mixture helps plants break through several barriers at the same time and make the most of their genetic potential. Sharp increases in branch number and leaf count are especially important for patchouli, since its essential oil is produced and stored primarily in the leaves. A 64% increase in the number of leaves, from 245 to 402, means there is more leaf mass to support higher essential oil yields. This gives a strong base for greater harvest potential. The steady leaf width observed across all treatments supports the idea of phenotypic plasticity – while biostimulants can strongly affect traits like branch growth and stem length, features like leaf width are usually controlled by genetics and don't change as easily in response to environmental or biochemical inputs. These results are in line with those reported by Anzuay et al. [26] in Argentina, where biostimulant treatment led to a maize grain yield of 8.9 t ha-1, compared to 7.96 t ha^{-1} in controls, representing an 11.8% (0.94 t ha^{-1}) increase.

3.2 Bio stimulants on herbage yield, oil content, and oil yield

As shown in Figures 3a-d, the use of bio-stimulants substantially increased both biomass and essential oil yields in the patchouli variety CIM-Samarth. The differences in response indicate potential agronomic benefits due to the synergetic effects of the combined treatments. The combined use of seaweed extracts, fulvic acid, and humic acid (T8) has been concluded to achieved the highest patchouli fresh yield (17.08 t/ha), dry herbage yield (4.44 t/ha), oil content (0.85 %), and oil yield (145.2 kg/ha) compared to all other treatments, While the lowest fresh herbage yield (11.36 t/ha), dry herb yield (2.95 t/ha), oil content (0.64 %), and oil yield (72.7 kg/ha) was recorded in the control. In terms of fresh herbage yield, there was a 54.5 % increase, from 11.2 t/ha in control plants (T1) to 17.3 t/ha in the triple combination treatment (T8). The use of the individual bio stimulants (T2-T4) achieved modest results,

generating an average increase of 15.6 % in fresh herbage yield. The control dry herbage yield was 2.9 t/ha, and with the combination treatment (T8), this was increased to 4.5 t/ha, an increase of 55.2%. The simultaneous increase of fresh and dry herbage, which implies the stimulants improved the herbage production and merely altered the herbage water content, suggests an increase in the photosynthetic activity and carbon fixation. Although the essential oil content fluctuated more modestly, increasing 32.6% from the control treatment (0.64%) to T8 (0.85%), the essential oil yield showed a strong response. It increased from 72.7 kg/ha @ T1 to 145.2 kg/ha @ T8, resulting in an almost doubling of productivity with a gain of 99.7% (Figure 4a-d). Such a notable increase in yield can be attributed to a combination of more biomass and higher oil content and further highlights how biostimulants can trigger plant growth while also promoting the synthesis of secondary metabolites.

The especially high increase in biomass indicates significantly improved photosynthetic efficiency. Seaweed extracts, which have been well documented to be particularly rich in cytokinins, likely facilitated chlorophyll synthesis and delayed senescence, thus prolonging the period of photosynthetic activity [27]. The additional biomass itself creates a stronger 'sink' for the photosynthetic products. This strong sink strength in turn triggers more carbon fixation, thereby amplifying growth. Importantly, the results show that plants under the T8 treatment sustained high levels of biomass without losing essential oil production. This indicates that biostimulants allow for a more efficient metabolic 'shunting' – rerouting excess photo-assimilates towards the production of valuable secondary metabolites like patchouli oil rather than wastefully channeling these products into structural growth or only a handful of primary metabolites. Patchouli essential oil is mostly made up of sesquiterpenes. These chemicals are dependent on native metabolites (Isopentenyl diphosphate and Dimethylallyl diphosphate) originating from primary metabolism for their biosynthesis [28]. The need for humic and fulvic acids in improving nutrient uptake (specifically for phosphorus and sulfur that are tied to the energy transfer and enzyme functionality in terpenoid pathways) guarantees that plants have the necessary substrates and energy (ATP) to support both strong growth and parallel synthesis of essential oils [29]. Beyond mere growth promotion, the phytohormones in seaweed extracts may be directly stimulating the genes and enzymes responsible for the terpenoid pathway [30]. For instance, certain seaweed compounds can double as elicitors: mildly stressing plants and provoking a defense response that results in an upsurge of secondary metabolites like essential oils. In stressful conditions, plants typically need to make a call to channel resources either towards growth or protection/secondary metabolites. The combination of all three bio-stimulants, however, seems to reconcile this trade-off by essentially fortifying the plant's resource base and metabolizing capacity [31-33]. This way, the plant can start moving from a defensive, survival-oriented physiology that prioritizes growth to one that is more inclined to do both growth and oil production simultaneously, as abiotic stresses are being addressed (via better water and nutrient transmission).

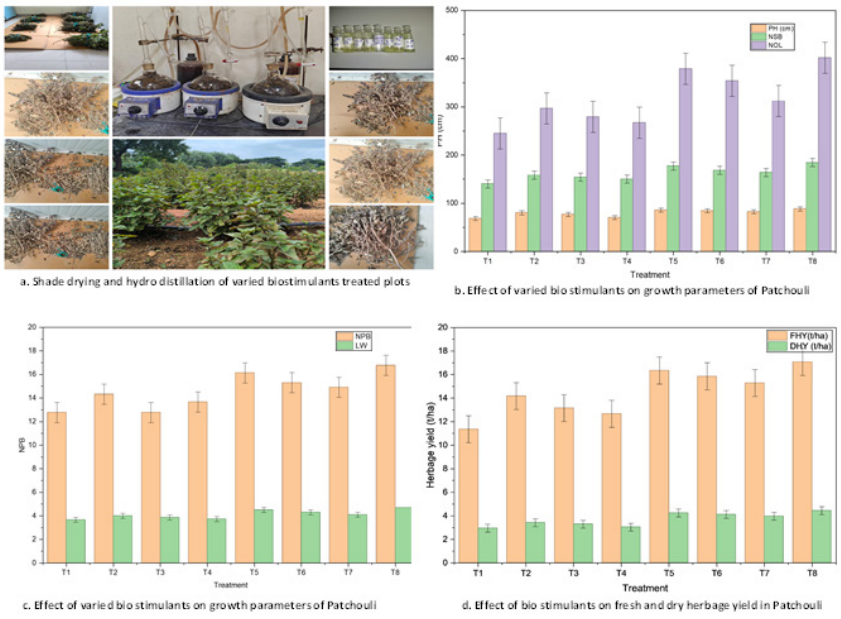

Figure 3a-d. a. drying and hydro distillation of varied biostimulants treated plots, b. Effect of varied bio stimulants on growth parameters, c. Effect of varied bio stimulants on growth parameters, and d. Effect of bio stimulants on fresh and dry herbage yield in Patchouli.

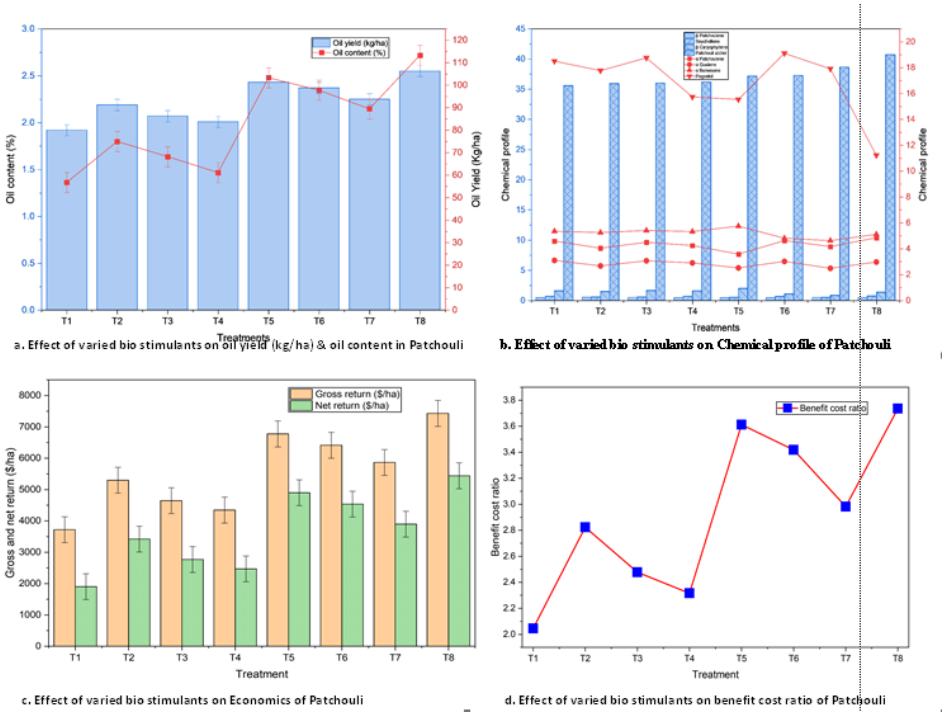

Figure 4a-d. a. Effect of varied bio stimulants on oil yield (kg/ha) and oil content (%), b. Effect of varied bio stimulants on Chemical profile, c. Effect of varied bio stimulants on Economics, and d. Effect of varied bio stimulants on benefit cost ratio of Patchouli.

3.3 Effect of Bio stimulants on the chemical profile of the patchouli oil

Biostimulant applications notably affected the chemical profile of patchouli essential oil (Figure 4a-d), primarily influencing the commercially important patchoulol concentration, with a lesser effect on other sesquiterpene components. The key compound, patchoulol, displayed significant sensitivity to the treatments, increasing from roughly 19.5% in the control group (T1) to 20.2% in the combined treatment (T8). This represents a small, but economically relevant, 3.6% elevation, potentially leading to considerable financial advantages due to patchoulol's high market value. Single treatments with biostimulants (T2-T4) resulted in small increases (19.8-20.0%), while double combinations (T5-T7) produced intermediate values around 19.2-20.5%, with T5 showing maximum patchoulol concentration at approximately 20.8%. The smaller sesquiterpenes – α-bulnesene, α-guaiene, seichelene, α-patchoulene, β-patchoulene, and norpatchoulenol – showed relative consistency across treatments, maintaining stable proportions with minimal variation (typically <0.5 percentage points). α-Bulnesene remained stable at approximately 5.5-6.0% across all treatments, while α-guaiene, seychelene, and patchoulene isomers demonstrated comparable consistency at 3.5-4.5%, 4.0-4.5%, and 2.8-3.5%, respectively, and norpatchoulenol maintained values close to 3.0-3.5%. This distinct response pattern, notable modification of the parent compound, along with preservation of proportions of minor components, suggests that biostimulants preferentially increase flux through the sesquiterpene biosynthetic pathway, leading to patchoulol, without fundamentally altering the enzymatic network that governs overall terpenoid diversity. The underlying mechanism likely involves increased expression of rate-limiting enzymes specific to patchoulol biosynthesis, especially patchoulol synthase, potentially mediated by hormonal signaling pathways initiated by seaweed-derived cytokinins and auxins, while improved nutrient availability from humic and fulvic substances ensures an adequate supply of precursors (acetyl-CoA and mevalonate pathway intermediates) without creating metabolic imbalances. That would alter smaller proportions of components. The selective accumulation of patchoulol in the T5 and T8 treatments, together with the previously documented increase in biomass, means an optimal result for commercial production: high total oil production combined with an improved quality profile, free from the chemical profile distortions that can accompany stress-related metabolic changes. Similar results were also obtained in EO of parsley (*Petroselinum crispum* Mill.) by Ahmed et al. [34]. Furthermore, the application of seaweed extracts to *Mentha* × *piperita* L. and *Ocimum basilicum* L. was proven to increase the content of the main compounds [35-38]. This observation has important implications for the commercialization of essential oils, since

international standards prescribe minimum patchoulol content requirements, and even modest percentage increases can improve product classification and market price, making the application of the triple biostimulant economically viable, despite the additional costs.

3.4 Effect of bio stimulants on Economics

Use of bio stimulants made a great impact on the economics of patchouli production. Gross return, net return, and the B: C ratio showed significant differences among treatments. The results also indicated that a combination of seaweed extracts, fulvic acid, and humic acid application (T8) gave the highest gross return, 7430.9 $/ha, net return, 5440.7 $/ha, and B: C ratio 3.73, respectively. This treatment was not statistically different from T5, which recorded 6775.8 $/ha, 4899.4 $/ha, and 3.61 gross return, net return, and B: C ratio in that order. However, the control treatment had a significantly weaker economic contribution with gross return 3720.6 $/ha, net return 1900.9 $/ha, and B: C ratio 2.05 (Figures 4c-d). The economic aspect confirms agronomic efficiency through growth and yield parameters since biological efficacy becomes priced in monetary terms. The T8 treatment yielded a net income that was higher by as much as 186% compared to the control (from $1900.9 to $5440.7 / ha). This stellar performance can be attributed directly to the synergistic yield enhancement noted earlier. Therefore, the following paragraph discusses why the primary essential oil showed a significant increase in this aspect. Comparative to it, absolute returns less significant; more dependable returns is significance of B: C ratio even when viewed from perspective of smallholder sector those farmers need support same way better money circulation possible at these environments pair ways getting financial stability besides adaptation process taking share against climatic factors Gives ideal way to improve revenue stream risk management system including biostimulants yet relatively affordable for resource-poor farmers make it easier manage alternative solution climate variability

3.5 Principal Component Analysis and Treatment Clustering

The analysis of the principal components showed distinct clusters between the biostimulant treatments. PC1 and PC2 accounted for 97.54% and 2.46% of the total variance, respectively (Figure 5a), which indicates that the outcome of the treatment was primarily influenced by one of the main axes of physiological change. The binary plot clearly classified the treatments into three functional categories based on their agronomic performance and results. Control and individual biostimulant treatments (T1, T3, T4) were grouped into the left quadrants, characterized by a low PC1 score and a relationship with low levels of all monitored parameters. Application of a single seaweed extract (T2) showed a midpoint, indicating some degree of improvement. The double combination treatments T5, T6, and T7 formed a transitional group with moderately positive PC1 scores, while the triple combination treatment T8 was at the strongly positive end of PC1, showing maximum deviation from the control. Its noteworthy that all growth and production parameters including plant height (PH), number of primary branches (NPB), number of buds (NSB), number of leaves (NOL), leaf width (LW), fresh and dry herb yield (FHY, DHY), oil content (OC%) and oil yield (OY) load highly and uniformly in the positive direction of PC1, and the vector dimensions collectively exceed this variable. The coordinated response pattern suggests that the integrated biostimulant approach enhanced essential physiological processes that simultaneously favored multiple agronomic traits, as described in our interpretation of synergistic resource mobilization and stress resolution through interconnected metabolic networks.

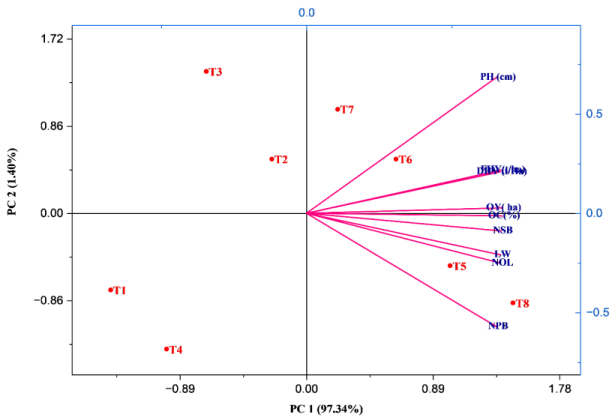

Figure 5a. Principal component analysis of Patchouli on varied bio stimulant.

3.6 Correlation Matrix and Trait Associations

The correlation heat map showed an exceptionally strong positive correlation between all the measured factors; the correlation coefficients ranged from 0.84 to 1.0 (Figure 5b), which suggests that the improvement induced by biostimulants did not occur through changes in individual characteristics but through interrelated physiological processes. The correlation between plant height and a bunch of parameters was statistically significant. A strong correlation can be detected in the measurements between r = 0.84 and r = 0.98, and a particularly strong positive correlation with the number of leaves (r = 0.93) and biomass yields (r = 0.96-0.98), indicating that it was based on the increased photosynthetic capacity. The morphological traits showed an almost perfect correlation (r = 0.95-0.99) that suggests that shoot growth, branching, and leaf production all responded in a coordinated manner to the effects of the treatment. It's noteworthy that essential oil production was closely correlated with both plant characteristics (r = 0.96-0.97) and biomass accumulation (r = 0.99), which suggests that the significant improvement in oil production was caused by increased plant, plant growth, and secondary metabolism synchronized with each other rather than resource shifts, shifts between competing physiological processes. Uniformly high correlation coefficients indicate minimal occurrence of antagonistic polymorphisms, a finding with significant implications for breeding and agriculture, implying that selection for a single trait can improve correlated traits without reducing fitness [37-38]. An integrated approach to biostimulants gains importance based on these relationships; By improving essential processes such as hormonal nutrient absorption, homeostasis, and stress resistance, co-treatments create an environment in which plants can simultaneously optimize vegetative growth and essential oil production, thereby eliminating growth defense trade-offs that typically limit crop performance under resource-scarce conditions.

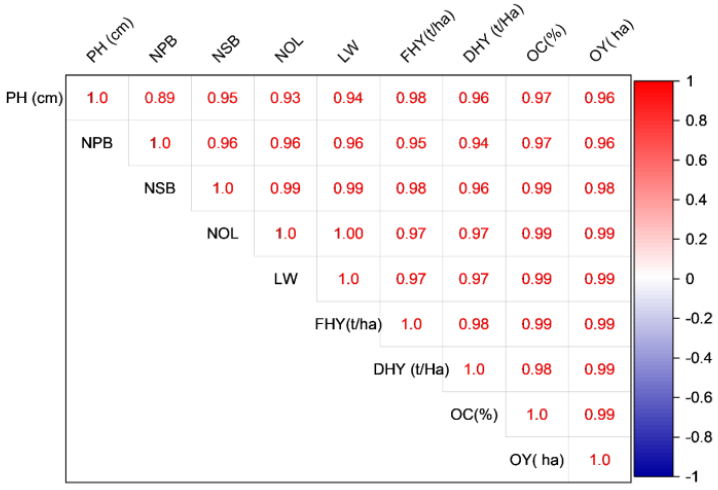

Figure 5b. Correlation plot of Patchouli.

4. Conclusion

This research shows that the combination of seaweed extract, humic acid, and fulvic acid will greatly help farmers improve their agronomic practices for growing patchouli in the semi-arid tropical region. The combination of the three treatments (T8) performed better than all other treatments and provided considerable synergistic benefits relating to the morphological, physiological, and economic attributes of patchouli. The treatment's success is rooted in its ability to simultaneously address multiple stress-induced limitations: humic acids improved the rhizosphere environment, fulvic acids improved nutrient translocation, and seaweed extracts boosted plants' intrinsic metabolism and stress resilience. This multifaceted action resulted in a profound increase in biomass, which, together with a targeted stimulation of the sesquiterpenoid biosynthesis pathway, led to a near doubling of essential oil yield without compromising quality. In fact, selectively increasing patchoulol content increases the market value of the oil. The strong, positive correlations among all growth and yield parameters, as revealed by PCA and correlation analysis, confirm that this approach promotes a harmonious enhancement of plant performance, effectively bypassing the typical growth-defense trade-offs. The remarkable economic returns and high benefit-cost ratio solidify the practical viability of this strategy for farmers. Therefore, the adoption of this integrated biostimulant regimen is highly recommended as a sustainable, productive, and economically rewarding practice for securing the future of patchouli production in challenging agro-ecosystems.

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Author Contribution Statement

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Conflict of Interest

The authors declare no conflicts of interest related to this work.

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References

[1] Jiang Y, Yue Y, Wang Z, Lu C, Yin Z, Li Y, et al. Plant biostimulant as an environmentally friendly alternative to modern agriculture. J Agric Food Chem. 2024;72(10):5107-21.

[2] Sharma M, Suma R, Chowdhury N, Borgohain T, Hiremath S, Chikkaputtaiah C, et al. In vitro and in silico analysis of broad-spectrum bio-activity of essential oils derived from medicinal and aromatic plants against microbial phytopathogens. Eur J Plant Pathol. 2024;170(4):955-71.

[3] Singh M, Sharma S, Ramesh S. Herbage, oil yield and oil quality of patchouli [Pogostemon cablin (Blanco) Benth.] influenced by irrigation, organic mulch and nitrogen application in semi-arid tropical climate. Ind Crops Prod. 2002;16(2):101-7.

[4] Huang H, Wu D, Guo T, Zhang D, Wang X, Zhuang J, et al. The PcbZIP44 transcription factor inhibits patchoulol synthase gene expression and negatively regulates patchoulol biosynthesis in Pogostemon cablin. Ind Crops Prod. 2022;188(Pt A):115561.

[5] Narayasamy S, Jalloh MB. Using seaweed-based organic fertilizer as a yield booster at volcanic soil: Effect on soil quality and yield of patchouli (Pogostemon Cablin). Adv Agric Food Res J. 2020;1(2):a0000120.

[6] Fatima S, Farzeen I, Ashraf A, Aslam B, Ijaz MU, Hayat S, et al. A comprehensive review on pharmacological activities of pachypodol: A bioactive compound of an aromatic medicinal plant Pogostemon cablin Benth. Molecules. 2023;28(8):3469.

[7] Nabila CT, Rahmawati M, Kesumawati E. PengaruhKonsentrasi 2,4-Dichlorophenoxyacetic Acid dan Benzyl Amino Purin terhadapInduksi Tunas Tanaman Nilam (Pogostemoncablin Benth.) Varietas Tapak Tuan secara In Vitro. JurnalIlmiah Mahasiswa Pertanian. 2022;7(4):193-200.

[8] Zhang X, Yin J, Ma Y, Peng Y, Fenton O, Wang W, et al. Unlocking the potential of biostimulants derived from organic waste and by-product sources: Improving plant growth and tolerance to abiotic stresses in agriculture. Environ Technol Innov. 2024;34:103571.

[9] Rouphael Y, Colla G. Synergistic biostimulatory action: Designing the next generation of plant biostimulants for sustainable agriculture. Front Plant Sci. 2018;9:1655.

[10] Kaviya T, Ramah K, Sakthivel N, Sivasakthivelan P, Senthilvalavan P. Impact of biostimulants on crop growth and soil health - A review. Plant Sci Today. 2025;12(sp1).

[11] Sani Md NH, Amin M, Bergstrand K-J, Caspersen S, Prade T, Yong JWH, et al. Harnessing biostimulants from biogas digestates for high-value resource recovery: a review. Environ Chem Lett. 2024;23(1):139-164. https://doi.org/10.1007/s10311-024-01801-8.

[12] Ramadan KMA, El-Beltagi HS, Al Saikhan MS, Almutairi HH, Al-Hashedi SA, Saudy HS, et al. β-carotene supply to dill plants grown in sulphur and humic acid-amended soil improves salinity tolerance via quenching the hazard molecules. Russ J Plant Physiol. 2024;71(1). https://doi.org/10.1134/s1021443724602441.

[13] Capstaff NM, Morrison F, Cheema J, Brett P, Hill L, Muñoz-García JC, et al. Fulvic acid increases forage legume growth, inducing preferential up-regulation of nodulation and signalling-related genes. J Exp Bot. 2020;71(18):5689-5704. https://doi.org/10.1093/jxb/eraa283.

[14] Ali O, Ramsubhag A, Jayaraman J. Biostimulant properties of seaweed extracts in plants: implications towards sustainable crop

production. Plants. 2021;10(3):531. https://doi.org/10.3390/plants10030531.

[15] Hernández-Figueroa KI, Sánchez E, Ramírez-Estrada CA, Anchondo-Páez JC, Ojeda-Barrios DL, Pérez-Álvarez S. Efficacy and differential physiological–biochemical response of biostimulants in green beans subjected to moderate and severe water stress. Crops. 2024;4(1):27-42. https://doi.org/10.3390/crops4010003.

[16] Cristofano F, El-Nakhel C, Rouphael Y. Biostimulant substances for sustainable agriculture: origin, operating mechanisms and effects on cucurbits, leafy greens, and nightshade vegetables species. Biomolecules. 2021;11(8):1103. https://doi.org/10.3390/biom11081103.

[17] Farruggia D, Di Miceli G, Licata M, Leto C, Salamone F, Novak J. Foliar application of various biostimulants produces contrasting response on yield, essential oil and chemical properties of organically grown sage (Salvia officinalis L.). Front Plant Sci. 2024;15:1397489. https://doi.org/10.3389/fpls.2024.1397489.

[18] Singh R, Divya S, Awasthi A, Kalra A. Technology for efficient and successful delivery of vermicompost colonized bioinoculants in Pogostemon cablin (patchouli) Benth. World J Microbiol Biotechnol. 2012;28(1):323-333. https://doi.org/10.1007/s11274-011-0823-2.

[19] Oyebamiji YO, Adigun BA, Shamsudin NAA, Ikmal AM, Salisu MA, Malike FA, et al. Recent advancements in mitigating abiotic stresses in crops. Horticulturae. 2024;10(2):156. https://doi.org/10.3390/horticulturae10020156.

[20] Panse VG, Sukhatme PV. Statistical methods for agricultural workers. 2nd ed. New Delhi: Indian Council of Agricultural Research; 1967. 361 p.

[21] Nabi F, Sarfaraz A, Kama R, Kanwal R, Li H. Structure-based function of humic acid in abiotic stress alleviation in plants: a review. Plants. 2025;14(13):1916. https://doi.org/10.3390/plants14131916.

[22] Prakhyath KM, Yogendra ND, Padalia RC, Anand KGV, Veeragurunathan V, Prasad K, et al. Seaweed extract of Solieria chordalis (C. Agardh) J. Agardh) improves growth, yield and essential oil production and economics of patchouli (Pogostemon cablin (Blanco) Benth.). J Appl Phycol. 2025;37(4):2921-2932. https://doi.org/10.1007/s10811-025-03537-6.

[23] Liang Y, Wang Z, Shi Q, Li F, Zhao Z, Han Y, et al. The varying promotion effects of fulvic acid with different molecular weights on the enhancement of grain yield and quality of winter wheat. Plant Soil Environ. 2023;69(4):141-151. https://doi.org/10.17221/391/2022-PSE.

[24] Hussain S, Shaukat M, Ashraf M, Zhu C, Jin Q, Zhang J. Salinity stress in arid and semi-arid climates: effects and management in field crops. In: Climate change and agriculture. IntechOpen; 2019. https://doi.org/10.5772/intechopen.87982.

[25] Johnson R, Joel JM, Puthur JT. Biostimulants: the futuristic sustainable approach for alleviating crop productivity and abiotic stress tolerance. J Plant Growth Regul. 2024;43(3):659-674. https://doi.org/10.1007/s00344-023-11144-3.

[26] Lal RK, Chanotiya CS, Lahiri R. Insights into genotype × environment interactions affecting essential oil yield and quality stability in Cymbopogon species and genotypes. Biochem Syst Ecol. 2025;123:105068. https://doi.org/10.1016/j.bse.2025.105068.

[27] Górka B, Korzeniowska K, Lipok J, Wieczorek PP. The biomass of algae and algal extracts in agricultural production. In: Algae biomass: characteristics and applications: towards algae-based products. Cham: Springer International Publishing; 2018. p. 103-114.

[28] Tang Y, Zhong L, Wang X, Zheng H, Chen L. Molecular identification and expression of sesquiterpene pathway genes responsible for patchoulol biosynthesis and regulation in Pogostemon cablin. Bot Stud. 2019;60(1):11. https://doi.org/10.1186/s40529-019-0259-9.

[29] Ampong K, Thilakaranthna MS, Gorim LY. Understanding the role of humic acids on crop performance and soil health. Front Agron. 2022;4:848621. https://doi.org/10.3389/fagro.2022.848621.

[30] Rathod SG, Bhushan S, Mantri VA. Phytohormones and pheromones in the phycology literature: benchmarking of data-set and developing critical tools of biotechnological implications for commercial aquaculture industry. Phycology. 2023;4(1):1-36. https://doi.org/10.3390/phycology4010001.

[31] Kumar A, Sharma N, Jnanesha AC, VenkateshKT, Gupta AK, Chanotiya CS, et al. Estimation of stability and correspondence between location × environmental factors on the essential oil yield and chemical composition of rosemary variety 'CIM-Hariyali (Rosmarinus officinalis L.). Explor Agric Biol Sci Res (EABSR). 2025;1(1):1-15. https://dx.doi.org/10.47204/EABSR.1.1.2025.001-015.

[32] Kumar A, Sharma N, Singh M, Chanotiya CS, Semwal M, Lal RK. Recent advancements and the potential for growing Rosmarinus officinalis L., a new fragrant, medicinal, and industrial crop: a review. J Food Nutr Diet Sci. 2025;3(1):91-106. https://doi.org/10.55976/fnds.32025142891-106.

[33] Kumar V, Lal RK, Singh VR, Tiwari N, Chanotiya CS, Swamy YVVVS, et al. Unlocking the intra-specific differentiation and patterns of genetic diversity in the germplasm of the opium poppy (Papaver somniferum L.). Explor Agric Biol Sci Res (EABSR). 2025;1(1):45-61. https://dx.doi.org/10.47204/EABSR.1.1.2025.045-061.

[34] Ahmed A, Elkady F, Khalid KAT. Morphological and chemical characters of Petroselinum crispum (Mill) subjected to some biostimulants. Asian J Plant Sci. 2018;17(2):96-106. https://doi.org/10.3923/ajps.2018.96.106.

[35] Elansary HO, Yessoufou K, Shokralla S, Mahmoud E, Skalicka-Woźniak K. Enhancing mint and basil oil composition and antibacterial activity using seaweed extracts. Ind Crops Prod. 2016;92:50-56. https://doi.org/10.1016/j.indcrop.2016.07.048.

[36] Chen D, Li Z, Yang J, Zhou W, Wu Q, Shen H, et al. Seaweed extract enhances drought resistance in sugarcane via modulating root configuration and soil physicochemical properties. Ind Crops Prod. 2023;194:116321. https://doi.org/10.1016/j.indcrop.2023.116321.

[37] Kumar V, Singh VR, Singh N, Lal RK, Kishor R, Siddiqui S, et al. Dissection of genetic variability, correlations and character contribution in opium poppy (Papaver somniferum L.). J Agric Res Adv. 2025;7(3):15-24.

[38] Kumar V, Singh VR, Singh N, Lal RK, Kishor R, Siddiqui S, et al. Quantification of variability, character association and path analysis for opium poppy (Papaver somniferum L.). Bioscan. 2025;20(4):189-206. https://doi.org/10.63001/tbs.2025.v20.i04.pp189-206.