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Biochar–NPK–Seaweed Integration as a Sustainable Strategy to Boost Productivity of Spearmint in Sandy Soils

Yassin M. Soliman [1], Wagdi Saber Soliman [2,*] and Ahmed M. Abbas [3,4]

[1] Department of Horticulture, Faculty of Agriculture, Sohag University, Sohag 82524, Egypt; yassinsoliman240@gmail.com
[2] Horticulture Department, Faculty of Agriculture and Natural Resources, Aswan University, Aswan 81528, Egypt
[3] Department of Biology, College of Science, King Khalid University, Abha 61321, Saudi Arabia; ahhassan@kku.edu.sa
[4] Prince Sultan Bin Abdelaziz for Environmental Research and Natural Resources Sustainability Center, King Khalid University, Abha 61421, Saudi Arabia
* Correspondence: wagdi79@agr.aswu.edu.eg

Abstract

Sandy soils in arid and semi-arid regions of Egypt are characterized by poor structure, low fertility, and a limited capacity to retain irrigation water, which collectively constrain nutrient availability and crop productivity under arid conditions. Despite these limitations, improving the performance and sustainability of sandy soils has become essential to meet increasing agricultural demands. Therefore, this study aimed to evaluate the individual and combined effects of biochar, mineral NPK fertilization, and seaweed extract on the growth performance, biomass production, nutrient status, and overall productivity of spearmint (*Mentha spicata* L.) cultivated in sandy soil. Field experiments were conducted over two successive growing seasons (2024 and 2025) at the Agricultural Research Station, Al-Marashda, Qena Governorate, Egypt, using a split-plot design with biochar application (0 and 12.5 ton ha^{-1}) as the main factor and foliar growth stimulants (control, NPK, NPK + 2 mL L^{-1} seaweed extract, and NPK + 4 mL L^{-1} seaweed extract) as sub-factors. Results revealed that biochar application significantly improved all vegetative growth parameters, herbage fresh and dry yields, essential oil percentage, oil yield per plant, photosynthetic pigment concentrations, and leaf N, P, and K contents compared with untreated soil. Foliar application of NPK fertilizer, particularly when combined with seaweed extract, further enhanced plant performance. The greatest improvements across all measured traits were consistently obtained from the integrated application of biochar at 12.5 ton ha^{-1} combined with foliar spraying of NPK (5 g L^{-1}) and seaweed extract 4 mL L^{-1}. This treatment produced the highest biomass accumulation, essential oil yield, chlorophyll content, and nutrient uptake during both seasons. The findings conclude that integrating biochar with balanced mineral fertilization and natural biostimulants represents an effective and sustainable strategy for improving productivity and essential oil yield of spearmint grown in nutrient-poor sandy soils.

Keywords: *Mentha spicata* L.; biochar; NPK; seaweed extract; essential oil; sustainable agriculture

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1. Introduction

Sandy soils account for more than 6% of the Earth's land surface and occur across a wide range of climatic conditions [1]. Their distribution is particularly extensive in arid and semi-arid regions, where they constitute a substantial proportion of cultivated lands. These soils are dominated by coarse sand fractions and are typically classified as sand, loamy sand, or sandy loam. Owing to their coarse texture, sandy soils generally exhibit inferior hydrological properties compared with fine-textured soils. Consequently, they are often regarded as problematic and low-productivity soils in agricultural systems due to their limited available water capacity and weak nutrient retention [2].

Over the past decade, biochar has been widely recognized as an effective soil amendment capable of improving the available water capacity of sandy soils, thereby contributing to more sustainable management of coarse-textured soils [3,4]. Biochar is a carbon-rich product generated from the thermal decomposition of biomass under limited or no oxygen conditions. Typically containing 65–90% carbon, biochar exhibits a large surface area, high porosity, and strong adsorption capacity [5,6]. In agricultural systems, biochar is widely used as a soil amendment due to its ability to improve soil structure, enhance microbial activity, increase nutrient availability, and support plant growth [6–8]. Biochar application also increases soil organic carbon, which plays a critical role in soil fertility but continues to decline due to unsustainable agricultural practices and climate change [9,10]. Numerous studies have shown that biochar enhances nutrient uptake, particularly nitrogen (N), phosphorus (P), and potassium (K). It also improves soil moisture retention, photosynthesis, and overall biomass production [11–14].

However, the effect of biochar varies according to application rate and material characteristics [15]. Moderate rates typically enhance plant growth, while excessive levels may negatively affect soil properties and crop performance [6,16,17]. Biochar has been shown to lower the incidence of several soil-borne diseases by enhancing soil microbial diversity, boosting plant systemic resistance, and decreasing pathogen populations [18–21]. Optimal application levels typically range between 1 and 4%, whereas higher doses (>5%) may hinder germination, reduce microbial biomass, or limit nutrient availability [22,23].

Sandy soils, in particular, suffer from poor structure, low nutrient retention, and weak aggregation because of their low organic matter content. Thus, incorporating organic materials such as biochar or compost is essential to improve moisture retention, soil microbial activity, and nutrient availability [24,25]. Recent studies have highlighted the beneficial effects of biochar on improving soil physicochemical properties and enhancing the growth of medicinal and aromatic plants, including *Mentha longifolia* [26] and forage crops [27].

Alongside soil amendments, mineral nutrients also play a fundamental role in the growth and productivity of aromatic plants. Nitrogen is an essential component of amino acids, proteins, and enzymes, and significantly enhances herbage biomass and essential oil yield in various medicinal species [28,29]. Phosphorus is indispensable for energy transfer, photosynthesis, and nucleic acid synthesis, and its application has been shown to enhance leaf biomass and essential oil production in mint and sage [30,31]. Potassium regulates enzymatic activity, nitrogen metabolism, and synthesis of essential metabolites and has been documented to improve yield and essential oil content in several aromatic crops [32].

Seaweed extract is another promising natural biostimulant due to its micronutrient content, growth-promoting hormones (cytokinins, auxins, and gibberellins), vitamins, and amino acids. Foliar application of seaweed extract has been reported to enhance plant height, chlorophyll content, and nutrient uptake in peppermint and other aromatic plants [33–35].

Spearmint (*Mentha spicata* L.) is a perennial aromatic herb in the Lamiaceae family widely cultivated across many regions of the world, including Egypt. It is considered one of the most economically important essential-oil crops due to its diverse commercial and medicinal uses [36]. Fresh and dried spearmint leaves are commonly used as herbal

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teas, spices, and flavoring agents in foods and beverages, while the herbage, extracts, and essential oil (EO) have long been applied in traditional medicine to relieve various ailments [37]. Spearmint EO is also employed as a natural aromatic ingredient in chewing gum, toothpaste, mouthwash, confectionery, fragrances, and pharmaceutical formulations, in addition to its antimicrobial and pesticidal applications [38]. Chemically, the EO of spearmint contains several bioactive compounds, including natural phenolic antioxidants, cholinesterase inhibitors, and antifungal and antiproliferative agents [39–41].

Although biochar and NPK have been studied separately, few studies have examined their combined effect with seaweed extract on *Mentha spicata* in sandy soil. This study evaluates the individual and combined effects of these treatments on the growth, productivity, essential oil content, and chemical composition of *Mentha spicata* under sandy soil conditions.

2. Materials and Methods

2.1. Growth and Experimental Conditions

A field experiment was conducted during the 2024 and 2025 growing seasons at the Agricultural Research Station, Al-Marashda, Qena Governorate, Egypt. Before the experiment, random soil samples were collected from the site and analyzed for physical and chemical properties using the methods described by Jackson [42]. The soil characteristics are shown in Table 1. Uniform seedlings of *Mentha spicata* L. were obtained from a private medicinal plant nursery in Qena Governorate and transplanted on 15 February in both experimental seasons. The experiment was laid out in a split-plot arrangement within a randomized complete block design (RCBD) with three replicates. Biochar treatments (without biochar and biochar applied at 12.5 ton ha^{-1}) were allocated to the main plots, while four growth stimulant treatments were assigned to the sub-plots: control, NPK at 5 g L^{-1}, NPK at 5 g L^{-1} combined with 2 mL L^{-1} seaweed extract (SW), and NPK at 5 g L^{-1} combined with 4 mL L^{-1} SW.

Table 1. Physical and chemical properties of the soil under study.

Character	Value	Character	Value
Texture analysis		Soluble cations (meq/100 g soil)	
Clay %	8.5	Ca^{++}	1.84
Silt %	6.5	Mg^{++}	0.86
Sand %	85.0	Na^{+}	2.92
Texture grade	sandy	K^{+}	1.43
Total **$CaCO_3$** (%)	1.51	Soluble anions (meq/100 g soil)	
E.C. dS/m (1:5) soil extract	3.13	Cl^{-}	3.19
pH (1:2.5 soil suspension)	8.2	HCO_3^{-}	2.45
Organic matter (%)	1.35	SO_4^{-}	1.41
		Total nitrogen (%)	0.33
		Total phosphorus (%)	0.13
		Total potassium (%)	0.24

The used biochar is a porous, sponge-like organic carbon produced by the pyrolysis of olive and rice residues at a temperature of 350–400 °C. Biochar, supplied by Power Tech Company (Cairo, Egypt), was incorporated into the soil prior to transplanting; its chemical composition is presented in Table 2. A balanced NPK fertilizer (20–20–20) was applied as a foliar spray either alone or in combination with seaweed extract (Power Max, Egyptian Fertilizers Company, Cairo, Egypt). The seaweed extract (Power Max) was produced by CHEMA Company, Cairo, Egypt. The extract included different algae types, such as Laminaria, Sargassum, Ascophyllum, Fuscus, and *Rasenvinga intricate*, and contained minerals, vitamins, enzymes, amino acids, sugars, and plant hormones. The nutrient composition of the seaweed extract is shown in Table 3. Each sub-plot measured 1.8 × 1.8 m and consisted of three rows containing 18 mint seedlings (approximately 7 cm in height). Plant spacing was maintained at 60 cm between rows and 30 cm within rows.

Table 2. Chemical analysis of the used biochar in the study.

Component	Value (%)
pH	7.8
EC	2.5 dS m^{-1}
Total N	0.8%
Organic carbon	42.5%
Ash	1.7%
K_2O	26.0%
P_2O_5	3.6%
SiO_2	25.0%

Table 3. Composition of Power max as source of seaweed extract.

<table>
<tr><th rowspan="2">Density (g cm^3)</th><th rowspan="2">OM (g L^{-1})</th><th rowspan="2">pH</th><th colspan="3">Macronutrients Content (g L^{-1})</th><th rowspan="2">Cytokines, Auxins and Gibberellins (g L^{-1})</th><th rowspan="2">Free Amino Acids (mg kg^{-1})</th></tr>
<tr><th>N</th><th>P</th><th>K</th></tr>
<tr><td>0.65</td><td>410</td><td>6.5</td><td>18</td><td>8</td><td>110</td><td>570</td><td>20.0</td></tr>
<tr><th colspan="2">Algenic acid (%)</th><th colspan="2">Manitol (%)</th><th colspan="2">Water solubility (%)</th><th colspan="2">Appearance</th></tr>
<tr><td colspan="2">11.0</td><td colspan="2">5.0</td><td colspan="2">100</td><td colspan="2">Black powder</td></tr>
</table>

Foliar applications of NPK, with or without seaweed extract, were carried out three times per cutting across the three harvesting cycles. The first spray was applied 21 days after transplanting or immediately following each cutting, followed by two additional applications at 10-day intervals. During soil preparation, compost was incorporated at a rate of 15,000 kg ha^{-1}. Phosphorus was applied as calcium superphosphate (15.5% P_2O_5) at 500 kg ha^{-1}, while nitrogen was supplied as ammonium sulfate (20.5% N) at 375 kg ha^{-1} in three equal splits: two weeks after transplanting and immediately after the first and second cuttings.

Mint plants were harvested three times per season at 45-day intervals. The first harvest took place in mid-April, the second in late May, and the third in mid-July during both seasons.

2.2. Measurements

2.2.1. Growth Parameters

Vegetative growth data were collected at each of the three cuttings, including plant height (cm), number of leaves per plant, number of branches per plant, and leaf area (cm^2).

2.2.2. Yield Components

Herb yield was determined as fresh and dry weights per plant and per hectare. Plant samples were oven-dried at 70 °C until a constant weight was achieved to determine dry matter.

2.2.3. Essential Oil Extraction and Yield

Essential oil was extracted from 100 g of fresh herb by hydro-distillation for 2 h. The essential oil percentage was calculated as milliliters of oil per 100 g fresh weight (%), and essential oil yield per plant per cutting was estimated according to Guenther [43].

2.2.4. Photosynthetic Pigments

Chlorophyll a, chlorophyll b, and carotenoid contents were extracted from fresh mint leaves with dimethyl formamide [$HCON(CH_3)_2$] and stored overnight at 5 °C. Absorbance was measured using a spectrophotometer (Shimadzu UV-1800, Shimadzu Corporation, Tokyo, Japan) at 63, 647, and 470 nm. Pigment concentrations were calculated according to Nornai [44]:

Chlorophyll a = 12.70 A_{663} − 2.79 A_{647}

Chlorophyll b = 20.76 A_{647} − 4.62 A_{663}

Total carotenoids = [1000 A_{470} − (3.72 Chl a + 104 Chl b)]/229

2.2.5. Nitrogen, Phosphorus, and Potassium Content

Leaf nitrogen (N), phosphorus (P), and potassium (K) percentages were determined following the procedures outlined by ICARDA [45].

2.3. Statistical Analysis

Data collected from the two growing seasons were statistically analyzed using Statistix software (version 8.1). Data were subjected to statistical analysis using two-way ANOVA. The F-test and *p* value were used to analyze significance among the mean values of these parameters. Treatment means were compared with the least significant difference (LSD) test at the specified significance level, as described by Dowdy and Wearden [46].

3. Results

3.1. Plant Growth Characteristics

Tables 4 and 5 present the effects of biochar, foliar NPK application with or without seaweed extract (SW), and their interaction on vegetative growth parameters of *Mentha spicata* during the 2024 and 2025 seasons. All treatments significantly influenced plant height, branch number, leaf number, and leaf area across all three cuts in both seasons.

Table 4. Plant height (cm) and number of branches per plant of spearmint (*Mentha spicata* L.) plants as affected by biochar and mineral NPK fertilizer with seaweed extract (SW) during the 2024 and 2025 seasons. The values represent the mean value of three cuts.

	Plant Height (cm)		**Number of Branches per Plant**	
	Control	**Biochar at 12.5 ton ha^{-1}**	**Control**	**Biochar at 12.5 ton ha^{-1}**
		1st season		
Control	30.14 a	36.81 cd	26.95 a	51.87 e
5 g L^{-1} NPK	31.73 a	39.70 d	31.19 ab	62.02 f
5 g L^{-1} NPK + 2 mL L^{-1} SW	32.93 ab	43.1 e	35.46 bc	69.78 g
5 g L^{-1} NPK + 4 mL L^{-1} SW	34.96 bc	46.45 f	39.35 cd	77.08 h
		2nd season		
Control	30.36 a	37.31 d	25.26 a	45.96 e
5 g L^{-1} NPK	32.79 ab	40.00 e	30.05 b	60.63 f
5 g L^{-1} NPK + 2 mL L^{-1} SW	33.92 bc	43.52 f	35.52 c	68.69 g
5 g L^{-1} NPK + 4 mL L^{-1} SW	36.13 cd	46.10 g	39.01 d	77.14 h

Different letters represent significant differences among interaction treatments.

Application at 12.5 ton ha^{-1} significantly improved all measured growth traits compared with untreated soil. Biochar-treated plants recorded the highest mean values of plant height (41.52 and 42.98 cm), number of leaves per plant (1172 and 1195), number of branches per plant (65 and 66), and leaf area (4.58 and 4.52 cm^2) during the first and second seasons, respectively, averaged across the three cuts.

Foliar application of growth stimulants significantly enhanced vegetative growth (Tables 4 and 5). All NPK treatments, whether applied alone or with seaweed extract, outperformed the control. The combination of 5 g L^{-1} NPK and 4 mL L^{-1} SW, produced the highest mean plant height (40.70 and 41.12 cm), branch number per plant (58 and 58), leaf number per plant (982 and 977), and leaf area (4.03 and 3.81 cm^2) during the first and second seasons, respectively.

Table 5. Number of leaves per plant and leaf area (cm^2) of spearmint (*Mentha spicata* L.) plants as affected by biochar and mineral NPK fertilizer with seaweed extract (SW) during the 2024 and 2025 seasons. The values represent the mean value of three cuts.

	Number of Leaves per Plant		**Leaf Area (cm^2)**	
	Control	**Biochar at 12.5 ton ha^{-1}**	**Control**	**Biochar at 12.5 ton ha^{-1}**
		1st season		
Control	421.7 a	918.7 e	1.64 a	4.01 e
5 g L^{-1} NPK	499.8 b	1136.9 f	2.09 b	4.21 ef
5 g L^{-1} NPK + 2 mL L^{-1} SW	547.8 c	1272.3 g	2.37 bc	4.75 g
5 g L^{-1} NPK + 4 mL L^{-1} SW	605.4 d	1358.8 h	2.69 cd	5.37 h
		2nd season		
Control	390.3 a	804.3 e	1.65 a	3.45 c
5 g L^{-1} NPK	473.1 b	1011.5 f	1.91 ab	4.09 de
5 g L^{-1} NPK + 2 mL L^{-1} SW	548.5 c	1236.2 g	2.20 b	4.55 ef
5 g L^{-1} NPK + 4 mL L^{-1} SW	597.9 d	1356.3 h	2.48 b	5.15 f

Different letters represent significant differences among interaction treatments.

The interaction between biochar and foliar treatments was statistically significant for all growth parameters. Plants treated with 12.5 ton ha^{-1} biochar and sprayed with 5 g L^{-1} NPK plus 4 mL L^{-1} SW consistently achieved the highest growth values across all three cuts in both seasons. Untreated plants, without biochar or foliar fertilization, showed the lowest growth values.

3.2. Herb Yield Characteristics

The effects of biochar, growth stimulants, and their interaction on herb fresh and dry weights per plant are shown in Table 6. Both main factors and their combinations significantly influenced herb yield parameters during the two growing seasons.

Table 6. Herb fresh and dry weights per plant (g) of spearmint (*Mentha spicata* L.) plants as affected by biochar and mineral NPK fertilizer with seaweed extract during the 2024 and 2025 seasons. The values represent the mean value of three cuts.

	Herb Fresh Weight per Plant (g)		**Herb Dry Weight per Plant (g)**	
	Control	**Biochar at 12.5 ton ha^{-1}**	**Control**	**Biochar at 12.5 ton ha^{-1}**
		1st season		
Control	45.10 a	65.53 e	12.22 a	20.11 c
5 g L^{-1} NPK	47.57 ab	76.13 f	13.26 a	26.65 de
5 g L^{-1} NPK + 2 mL L^{-1} SW	50.57 bc	81.27 g	14.80 a	29.18 e
5 g L^{-1} NPK + 4 mL L^{-1} SW	52.73 cd	87.63 h	15.72 b	33.22 f
		2nd season		
Control	45.07 a	61.23 e	12.72 a	19.87 c
5 g L^{-1} NPK	48.07 b	72.37 f	13.97 a	24.70 d
5 g L^{-1} NPK + 2 mL L^{-1} SW	50.57 cd	79.47 g	15.27 a	29.27 e
5 g L^{-1} NPK + 4 mL L^{-1} SW	51.57 d	87.40 h	16.03 b	32.90 f

Different letters represent significant differences among interaction treatments.

Applying biochar at 12.5 ton ha^{-1} increased herb fresh and dry weights per plant compared with the control. Averaged over the three cuts, biochar increased herb fresh weight by 58.48% and 57.77% and herb dry weight by 94.93% and 88.90% during the first and second seasons, respectively.

Foliar application of NPK, especially with seaweed extract, further enhanced herb yield. Plants treated with 5 g L^{-1} NPK + 4 mL L^{-1} SW had the highest herb fresh and dry weights per plant in all cuts of both seasons. Compared with the control, this treatment increased mean herb fresh weight per plant by 13.47% and 24.34% and mean herb dry weight by 51.42% and 43.27% during the first and second seasons, respectively.

The interaction between biochar and foliar treatments was significant. The highest herb fresh and dry weights per plant were consistently from plants receiving 12.5 ton ha^{-1} biochar combined with 5 g L^{-1} NPK + 4 mL L^{-1} SW across all cuts in both seasons. The lowest yields were in untreated plants.

3.3. Essential Oil Percentage and Yield per Plant

Essential oil percentage and essential oil yield per plant were significantly affected by biochar, growth stimulants, and their interaction (Table 7).

Table 7. Essential oil percentage (EO %) and essential oil yield per plant (mL) of spearmint (*Mentha spicata* L.) plants as affected by biochar and mineral NPK fertilizer with seaweed extract during the 2024 and 2025 seasons. The values represent the mean value of three cuts.

	Essential Oil Percentage (%)		**Essential Oil Yield per Plant (mL)**	
	Control	**Biochar at 12.5 ton ha^{-1}**	**Control**	**Biochar at 12.5 ton ha^{-1}**
	1st season			
Control	0.159 a	0.289 e	0.077 a	0.193 d
5 g L^{-1} NPK	0.172 b	0.336 f	0.087 a	0.263 e
5 g L^{-1} NPK + 2 mL L^{-1} SW	0.183 c	0.363 g	0.090 b	0.302 f
5 g L^{-1} NPK + 4 mL L^{-1} SW	0.198 d	0.387 h	0.107 c	0.353 g
	2nd season			
Control	0.224 a	0.318 e	0.108 a	0.190 e
5 g L^{-1} NPK	0.239 b	0.400 f	0.120 b	0.290 f
5 g L^{-1} NPK + 2 mL L^{-1} SW	0.252 c	0.430 g	0.133 c	0.350 g
5 g L^{-1} NPK + 4 mL L^{-1} SW	0.263 d	0.448 h	0.143 d	0.400 h

Different letters represent significant differences among interaction treatments.

Biochar application significantly increased essential oil percentage compared with the control in all cuts and both seasons. Plants grown in soil with 12.5 ton ha^{-1} biochar had the highest essential oil percentages in the first season (0.281, 0.320, and 0.430%) and the second season (0.333, 0.393, and 0.522%) during the first, second, and third cuts. Essential oil yield per plant was also highest with biochar, reaching 0.175, 0.256, and 0.403 mL $plant^{-1}$ in the first season and 0.208, 0.315, and 0.490 mL $plant^{-1}$ in the second season.

Foliar application of growth stimulants significantly enhanced essential oil percentage and yield per plant compared with the control. The highest essential oil percentages were achieved with 5 g L^{-1} NPK + 4 mL L^{-1} SW, reaching 0.231, 0.274, and 0.374% in the first season and 0.282, 0.347, and 0.439% in the second season across the three cuts. This treatment also produced the highest essential oil yield per plant in both seasons.

The interaction between biochar and foliar treatments was significant. The combination of 12.5 ton ha^{-1} biochar and 5 g L^{-1} NPK + 4 mL L^{-1} SW produced the highest essential oil percentage and yield per plant across all cuts and seasons. The lowest values were consistently observed in untreated plants.

3.4. Photosynthetic Pigments

Table 8 shows that chlorophyll a, chlorophyll b, and carotenoid contents were significantly influenced by biochar application, growth stimulants, and their interaction in both seasons.

Table 8. Chlorophyll a, chlorophyll b and carotenoids (mg/100 g FW) of spearmint (*Mentha spicata* L.) plants as affected by biochar and mineral NPK fertilizer with seaweed extract during the 2024 and 2025 seasons.

	Chlorophyll a (mg/100 g FW)		Chlorophyll b (mg/100 g FW)		Carotenoids (mg/100 g FW)	
	Control	Biochar at 12.5 ton ha^{-1}	Control	Biochar at 12.5 ton ha^{-1}	Control	Biochar at 12.5 ton ha^{-1}
			1st season			
Control	2.513 a	2.770 b	0.646 a	0.735 b	1.122 a	1.276 ab
5 g L^{-1} NPK	2.673 ab	2.844 b	0.766 b	0.832 d	1.127 a	1.336 b
5 g L^{-1} NPK + 2 mL L^{-1} SW	2.710 ab	2.895 b	0.821 c	0.917 e	1.150 a	1.355 b
5 g L^{-1} NPK + 4 mL L^{-1} SW	2.763 b	3.250 c	0.846 d	0.937 f	1.233 a	1.420 b
			2nd season			
Control	2.553 a	2.810 bc	0.625 a	0.783 c	1.350 a	1.250 bc
5 g L^{-1} NPK	2.603 ab	2.850 c	0.729 b	0.847 d	1.100 ab	1.262 bc
5 g L^{-1} NPK + 2 mL L^{-1} SW	2.730 abc	2.930 cd	0.765 bc	0.900 e	1.153 abc	1.328 c
5 g L^{-1} NPK + 4 mL L^{-1} SW	2.771 abc	3.110 d	0.803 c	0.919 e	1.180 abc	1.346 c

Different letters represent significant differences among interaction treatments.

Biochar application at 12.5 ton ha^{-1} significantly increased chlorophyll a, chlorophyll b, and carotenoid contents compared with the control. The highest mean values of chlorophyll a (2.940 and 2.925 mg 100 g^{-1} FW), chlorophyll b (0.862 and 0.855 mg 100 g^{-1} FW), and carotenoids (1.347 and 1.345 mg 100 g^{-1} FW) were recorded in the first and second seasons, respectively.

Foliar application of NPK combined with seaweed extract further enhanced photosynthetic pigment concentrations. The highest pigment contents were obtained with 5 g L^{-1} NPK + 4 mL L^{-1} SW. The interaction between biochar and foliar treatments was significant, with the highest values of chlorophyll a, chlorophyll b, and carotenoids recorded under the combined application of biochar and 5 g L^{-1} NPK + 4 mL L^{-1} SW in both seasons.

3.5. Nitrogen, Phosphorus, and Potassium Content

The effects of biochar, growth stimulants, and their interaction on leaf nitrogen (N), phosphorus (P), and potassium (K) percentages are presented in Table 9. All treatments significantly increased N, P, and K contents compared with the control in both seasons.

Table 9. Nitrogen, phosphorus and potassium (%) of spearmint (*Mentha spicata* L.) plants as affected by biochar and mineral NPK fertilizer with seaweed extract during the 2024 and 2025 seasons.

	N%		P%		K%	
	Control	Biochar at 12.5 ton ha^{-1}	Control	Biochar at 12.5 ton ha^{-1}	Control	Biochar at 12.5 ton ha^{-1}
			1st season			
Control	1.250 a	1.600 bc	0.116 a	0.223 de	1.205 a	1.549 d
5 g L^{-1} NPK	1.270 a	1.830 c	0.139 ab	0.247 ef	1.220 a	1.674 e
5 g L^{-1} NPK + 2 mL L^{-1} SW	1.350 a	2.100 d	0.167 bc	0.270 f	1.270 b	1.894 f
5 g L^{-1} NPK + 4 mL L^{-1} SW	1.447 ab	2.200 d	0.192 cd	0.249 ef	1.430 c	2.100 g
			2nd season			
Control	1.230 a	1.650 bc	0.106 a	0.195 e	1.200 a	1.450 b
5 g L^{-1} NPK	1.290 a	1.870 c	0.126 b	0.232 f	1.253 a	1.601 c
5 g L^{-1} NPK + 2 mL L^{-1} SW	1.380 a	2.150 d	0.161 c	0.248 g	1.260 a	1.740 d
5 g L^{-1} NPK + 4 mL L^{-1} SW	1.490 b	2.250 d	0.176 d	0.217 f	1.290 a	1.930 e

Different letters represent significant differences among interaction treatments.

Biochar application increased N, P, and K percentages compered to untreated soil. Foliar NPK, especially with seaweed extract, further enhanced nutrient accumulation. The highest mean N and K percentages were recorded with 5 g L^{-1} NPK + 4 mL L^{-1} SW in both seasons. The highest P percentage was recorded in the first season with 5 g L^{-1} NPK + 4 mL L^{-1} SW, and in the second season with 5 g L^{-1} NPK + 2 mL L^{-1} SW.

The interaction between biochar and foliar treatments was significant. The combined application of 5 ton ha^{-1} biochar and 5 g L^{-1} NPK + 4 mL L^{-1} SW produced the highest N and K percentages in both seasons. Phosphorus percentage was maximized with the same combination in the first season and with biochar plus 5 g L^{-1} NPK + 2 mL L^{-1} SW in the second season.

4. Discussion

This study showed that integrating biochar with mineral NPK fertilization and seaweed extract significantly enhances growth, biomass, nutrient status, photosynthetic capacity, and essential oil yield of *Mentha spicata* in sandy soil. Improvements across two seasons highlight the robustness and reproducibility of this management strategy.

4.1. Effect of Biochar Application

Applying biochar to soil is an effective way to improve environmental quality, increase fertility, support plant growth, and reduce soil pollution [47]. Biochar enhances soil nutrient dynamics and decreases dependence on chemical fertilizers. Its stable carbon structure and resistance to microbial decomposition help raise soil organic carbon and support long-term organic matter accumulation. Zhou et al. [48] found that biochar significantly increases the availability of soil nutrients, including organic carbon, nitrogen, phosphorus, and potassium. These benefits stem from biochar's origin in agricultural and forestry residues, which provide organic matter and accessible nutrients. Once incorporated, biochar boosts soil organic matter and microbial activity, especially for nutrient cycling. This process improves nutrient solubilization and raises nutrient concentrations in the soil solution. Biochar also strengthens soil particle stability through ongoing organic–mineral interactions [49], thereby improving aggregate stability and stabilizing soil organic carbon [50].

Biochar application consistently improved vegetative growth, herbage yield, essential oil content, photosynthetic pigments, and leaf mineral levels. These benefits are mainly due to biochar's unique physicochemical properties of biochar, such as high porosity, large surface area, and cation exchange capacity, which collectively enhance soil water retention, nutrient availability, and microbial activity. These improvements are especially important in sandy soils, which typically have low organic matter content, poor nutrient-holding capacity, and weak aggregation.

These results align with previous studies showing that biochar increases plant height, leaf area, biomass, and nutrient uptake in aromatic and medicinal plants [51,52]. Based on previous studies, biochar application has been reported to moderate soil pH toward neutrality, enhance microbial activity, and improve nutrient solubility; these mechanisms may partly explain the observed growth and yield responses in sandy soils [53,54]. However, since soil pH, dissolved organic carbon and nitrogen, and microbial biomass were not directly measured in the present study, these interpretations should be considered inferential and warrant further investigation.

4.2. Role of NPK Fertilization and Seaweed Extract

Foliar application of NPK fertilizer, alone or combined with seaweed extract, significantly improved vegetative growth, herb yield, essential oil accumulation, and photosynthetic pigment content. These results underscore the essential roles of macronutrients in plant growth and secondary metabolism. Nitrogen is fundamental for proteins, enzymes, and chlorophyll, supporting photosynthetic carbon assimilation and biomass production [55]. Phosphorus is crucial for energy transfer, metabolic regulation, and nucleic acid synthesis, while potassium supports enzymatic activation, osmotic regulation, and stomatal function. Together, these nutrients are key to productivity and essential oil biosynthesis in mint and other aromatic crops [38,56].

Potassium positively affects photosynthetic pigment concentration by activating enzymes and protecting cellular membranes, thereby reducing chlorophyll degradation and preserving chloroplast integrity [57]. Potassium also helps maintain chlorophyll structure, supporting photosynthetic efficiency and metabolite accumulation. Additionally, nitrogen can stimulate essential oil production in some aromatic species, such as basil, ginger, and sage [58–60], though its effects may vary depending on species, soil organic matter, and nitrogen availability.

Seaweed extract supplies bioactive compounds such as cytokinins, auxins, gibberellins, amino acids, and micronutrients that stimulate photosynthesis, enzymatic activity, and secondary metabolite biosynthesis. The improved nutritional status and photosynthetic efficiency collectively promote greater carbon allocation toward essential oil biosynthesis pathways, resulting in higher oil percentage and yield per plant [34,61,62]. The increase in photosynthetic pigments after seaweed extract application is likely due to its free amino acids and organic and mineral compounds that promote chlorophyll synthesis [61,63]. Higher leaf chlorophyll may also result from reduced degradation, possibly because betaines in seaweed extracts protect chloroplasts under various conditions [64]. Unlike nitrogen, both potassium fertilization and seaweed extract application consistently increased essential oil content, likely by enhancing photosynthetic capacity and directing carbon toward secondary metabolite production [65,66]. Similar positive effects of seaweed extracts on growth, yield, and essential oil production in mint and related species are well documented [33,67,68]. Combining seaweed extract with nutrient inputs has also been shown to improve nutrient use efficiency, reduce nutrient losses, and boost crop yields, even under nutrient-limited conditions [69,70].

Consistent with these findings, previous studies have demonstrated the beneficial role of potassium nutrition in enhancing essential oil percentage and key constituents, such as thymol and *p*-cymene, particularly in thyme [71], further supporting the role of potassium and biostimulants in modulating secondary metabolism in aromatic plants.

4.3. Synergistic Interaction Between Biochar, NPK, and Seaweed Extract

The most pronounced improvements in all measured parameters were consistently obtained when biochar was combined with NPK fertilizer and the higher rate of seaweed extract. This synergistic interaction suggests that biochar improved soil conditions and nutrient retention, while NPK ensured adequate mineral supply and seaweed extract enhanced physiological and metabolic processes at the plant level. Together, these inputs created an optimal rhizosphere environment and physiological balance conducive to vigorous growth and enhanced secondary metabolite production.

The observed increases in chlorophyll a, chlorophyll b, and carotenoids under the combined treatments further support this interpretation, as improved photosynthetic capacity is closely linked to higher biomass accumulation and essential oil biosynthesis. Enhanced nutrient content (N, P, and K) in plant tissues under integrated treatments also indicates improved nutrient acquisition and utilization efficiency, which is essential for sustaining high productivity under low-fertility sandy soils.

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4.4. Sustainable Efficiency of Integrating Biochar and Biostimulants with NPK Fertilization

With respect to the economic yield of mint, represented by dry herb biomass, the application of mineral NPK fertilizer alone resulted in a modest increase in dry weight in both growing seasons (8.5–9.8%) compared with the control treatment. In contrast, soil amendment with biochar led to a substantial enhancement in dry herb yield, with increases ranging from 56.2 to 64.6%. When mineral fertilizer was combined with biochar, dry biomass further increased to 94.2–118.1%, reflecting an additional gain of approximately 38–53.5% attributable to NPK fertilization in the presence of biochar. This indicates that plant responsiveness to mineral fertilizer increased markedly—from only 8.5–9.8% under NPK alone to 38–53.5% when NPK was integrated with biochar. These findings clearly demonstrate the pivotal role of biochar in improving mineral fertilizer use efficiency by enhancing nutrient availability, increasing plant uptake capacity, and reducing nutrient losses from the soil system.

A similar synergistic trend was observed for foliar application of seaweed extract. When applied at rates of 2 and 4 mL in combination with mineral fertilizer but without biochar, dry herb yield increased by 20–21.1% and 26–28.6%, respectively. These increases correspond to net gains of 10.2–12.6% and 16.2–20.1% attributable to seaweed extract compared with mineral fertilizer alone. However, when biochar was incorporated into the soil, the combined application of mineral fertilizer and seaweed extract resulted in markedly higher increases in dry biomass, reaching 130.1–138.8% at 2 mL and 158.6–171.8% at 4 mL. These values represent additional increases of 20.7–35.9% and 53.8–64.5%, respectively, compared with the biochar–mineral fertilizer treatment alone. This synergistic response further confirms that biochar not only enhances mineral fertilizer efficiency but also amplifies the effectiveness of biostimulants by improving plant physiological responsiveness and nutrient assimilation.

Regarding essential oil percentage and oil yield, mineral fertilizer application alone resulted in relatively limited increases across the two seasons, amounting to 6.7–8.2% in oil percentage and 11.1–13% in oil yield compared with the control. In contrast, biochar application significantly improved oil-related traits, increasing oil percentage by 42–81.8% and oil yield by 75.9–150.6%. When mineral fertilizer was integrated with biochar, these increases rose further to 78.6–111.3% for oil percentage and 168.5–241.6% for oil yield, reflecting additional gains of approximately 29.6–36.6% attributable to mineral fertilizer in the presence of biochar. This clearly indicates that biochar substantially enhances the plant's ability to utilize mineral nutrients, thereby improving both yield quality and the accumulation of bioactive compounds.

Foliar application of seaweed extract also positively influenced oil traits. When applied at 2 and 4 mL in combination with mineral fertilizer alone, oil percentage increased by 12.5–15.1% and 17.4–24.5%, respectively, representing net gains of 5.8–6.9% and 10.7–16.4% compared with mineral fertilizer alone. Correspondingly, oil yield increased by 16.9–23.1% at 2 mL and 32.4–39% at 4 mL, reflecting additional gains of 3.9–12% and 21.3–26%, respectively. Notably, when biochar was incorporated, the combined application of mineral fertilizer and seaweed extract resulted in much greater improvements, with oil percentage increasing to 92–128.3% and 100–143.4% at 2 and 4 mL, respectively, while oil yield increased to 224.1–292.2% and 270.4–358.4%. These enhancements correspond to additional increases of 13.4–17% and 21.4–32.1% in oil percentage, and 50.6–55.6% and 101.9–116.9% in oil yield, compared with the biochar–mineral fertilizer treatment alone.

The observed enhancements in dry herb productivity and essential oil traits were strongly and positively correlated with improvements in photosynthetic pigment content and increased uptake and accumulation of key macronutrients, especially nitrogen, phosphorus, and potassium, in plant tissues, reflecting improved physiological performance and nutrient-use efficiency.

Overall, these results provide strong evidence that biochar acts as a key sustainability-driven soil amendment that enhances nutrient-use efficiency and potentiates the effectiveness of both mineral fertilizers and biostimulants. The integrated use of biochar, NPK fertilizer, and seaweed extract represents a highly efficient and environmentally sustainable strategy for improving biomass production, essential oil yield, and quality attributes of mint, while potentially reducing reliance on excessive mineral fertilizer inputs.

In addition, the high organic carbon content of the applied biochar (42.5%) supports its role as a stable carbon pool, contributing to long-term soil quality improvement. Although soil carbon balance was not quantitatively assessed in this study, the consistent agronomic benefits across two seasons suggest persistent positive soil–plant interactions. Collectively, these findings support the classification of the proposed management approach as a sustainable intensification strategy rather than a conventional yield-focused fertilization regime.

5. Conclusions

The present study demonstrates that soil amendment with biochar combined with foliar application of mineral NPK fertilizer and seaweed extract markedly enhances growth, biomass yield, nutrient status, photosynthetic efficiency, and essential oil production of *Mentha spicata* under sandy soil conditions. Biochar played a pivotal role in improving soil fertility and nutrient retention, while NPK fertilization ensured adequate mineral supply and seaweed extract stimulated physiological and metabolic activities in the plants. The synergistic interaction among these inputs was particularly evident, as the combined application of biochar (12.5 ton ha^{-1}) with NPK (5 g L^{-1}) and seaweed extract (4 mL L^{-1}) consistently produced superior results compared with individual treatments or untreated control plants. This integrated approach not only maximized herbage yield and essential oil productivity but also improved photosynthetic pigment concentration and leaf nutrient accumulation, reflecting enhanced plant health and metabolic efficiency.

Overall, integrating biochar with balanced mineral fertilization and seaweed extract represents a sustainable agronomic strategy that enhances spearmint productivity, improves nutrient utilization, and contributes to long-term soil quality improvement in sandy soils, thereby reducing reliance on intensive chemical fertilization. Therefore, the combined use of biochar, NPK fertilizer, and seaweed extract is strongly recommended for sustainable spearmint cultivation under similar agro-ecological conditions. Consequently, while the observed improvements highlight the potential of biochar-based integrated nutrient management, further research is required to validate these outcomes across different soil types, climates, and management systems. Future studies should focus on long-term field trials to assess residual and cumulative biochar effects, optimization of biochar application rates under reduced fertilization regimes, and comprehensive economic analyses to evaluate the feasibility and scalability of biochar use in commercial production systems.

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Institutional Review Board Statement: The spearmint seedlings used in the experiment were obtained from a certified private nursery located in Qena Governorate, Egypt (26°09′85″ N 32°47′34″ E). The plant material was propagated vegetative by stem cuttings, which is the standard commercial propagation method for this species. At the time of transplanting to the experimental site, the seedlings were uniform and healthy, with an average height of approximately 10 cm. The plant material represents a commonly cultivated, non-rare, and non-endangered species that is widely used in commercial production. Therefore, the material was not collected from wild populations, and no natural populations were sampled.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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