Interdisciplinary Research in Medical Sciences Specialty
ISSN: 3062-4401
2022, Volume 2, Issue 2, Page No: 126-140

Available online at: www.galaxypub.co/page/journals

Galaxy Publication

Impact of Enriched Soil Amendments on Soil Fertility, Forage Yield, and Bioactive Compounds of Cassia angustifolia Vahl. Cultivated in Two Distinct Soil Types

Peter Novák[1], Jan Svoboda[1], Martin Dvořák[1]*

[1]Department of Clinical Informatics, Faculty of Medicine, Charles University, Prague, Czech Republic.

***E-mail** ✉ martin.dvorak.med@gmail.com

Received: 04 August 2022; **Revised:** 08 November 2022; **Accepted:** 14 November 2022

ABSTRACT

The high cost of chemical fertilizers and the limited nutrient content of conventional organic sources, such as manure, compost, and charcoal, highlight the need for enriched organic amendments as an alternative. This study aimed to develop and evaluate enriched organic amendments by combining distillation waste biomass (DWB) from aromatic plants with naturally available low-grade rock phosphate (RP) and waste mica (WM). Two types of enriched products were prepared: enriched compost (ENC), produced through natural composting of DWB and blended with mineral powder, and biochar-fortified mineral (BFM), generated by hydrothermal conversion of DWB into biochar followed by mixing with mineral powder. The study assessed the effects of ENC and BFM at two application rates (2.5 and 5 t ha^{-1}) on soil properties, herbage yield, and quality of the medicinal herb Senna (Cassia angustifolia Vahl.), comparing them with conventional farmyard manure (FYM, 5 t ha^{-1}) and chemical fertilizers (CF, NPK 60-40-20 kg ha^{-1}) in two different soils under pot conditions. Both ENC and BFM enhanced soil fertility by increasing organic carbon, available nutrients, microbial biomass, and enzymatic activity. Total herbage yields increased by 21% and 16.3% with ENC and BFM, respectively, compared to FYM, while CF produced the highest dry herbage yield (32.7–37.4 g pot^{-1}) but was comparable to ENC (31.9–33.7 g pot^{-1}) and BFM (30.7–35.1 g pot^{-1}). Importantly, bioactive compound (sennoside) content in senna was significantly higher with ENC and BFM than with CF. These findings suggest that ENC and BFM not only overcome limitations of conventional FYM but also serve as cost-effective alternatives to chemical fertilizers in medicinal plant cultivation.

Keywords: Mineral enrichment, Distillation waste biomass, Compost, Biochar, Medicinal herb

How to Cite This Article: Novák P, Svoboda J, Dvořák M. Impact of Enriched Soil Amendments on Soil Fertility, Forage Yield, and Bioactive Compounds of Cassia angustifolia Vahl. Cultivated in Two Distinct Soil Types. Interdiscip Res Med Sci Spec. 2022;2(2):126-40. https://doi.org/10.51847/MaKuMDiSLi

Introduction

In developing countries, commercial fertilizers, particularly phosphorus (P) and potassium (K), are costly due to the scarcity of suitable raw materials and steadily rising prices [1, 2]. This financial burden limits accessibility for smallholder and marginal farmers, while indiscriminate chemical fertilizer use contributes to environmental degradation [3]. Therefore, exploring efficient fertilizer strategies using locally available nutrient sources, such as plant biomass and waste minerals, has become essential [4–6]. Production and application of compost and biochar from these sources can reduce reliance on expensive chemical fertilizers [6].

Organic amendments, including manure, compost, and biochar, have demonstrated potential in organic and ecological farming to improve crop yields and soil fertility by enhancing carbon retention and nutrient availability [7–11]. However, these amendments often fall short in meeting crop nutrient demands, particularly for major nutrients [5]. One approach to enhance their nutrient content involves blending low-grade minerals with waste biomass during co-composting or co-pyrolysis [11, 12].

India possesses around 200 million tonnes of low-grade rock phosphate (RP) and silicate mineral powder (SMP), byproducts of mining rich in P and K, respectively [13, 14]. However, their poor solubility, especially in neutral and alkaline soils, limits direct agricultural use [15]. Co-composting or co-pyrolysis with biomass improves the

bioavailability of these nutrients [15–17]. For example, composting RP with plant residues enhances water-soluble and Olsen P content, while biochar-mineral complexes formed via hydrothermal treatment exhibit increased surface area, functional groups, and slow-release properties, making them efficient soil amendments [5, 17–19].
Medicinal plants such as Senna require a consistent but moderate nutrient supply for optimal growth and bioactive compound synthesis [20, 21]. Aromatic plant distillation generates large amounts of solid waste biomass (DWB), which can be effectively utilized to produce enriched compost (ENC) and biochar-fortified mineral (BFM) amendments [14, 22, 23]. Senna (Cassia angustifolia Vahl.) is a prominent medicinal herb valued for its sennosides, the active compounds responsible for its laxative effect, and represents a significant portion of India's medicinal herb exports [21, 24]. The plant thrives in marginal, semi-arid soils with pH 7.0–8.5 and tolerates salinity [25–26]. Senna responds well to nutrient management, though the benefits of enriched amendments may vary with soil texture, being more pronounced in coarse soils [27]. Organic amendments are commonly added to saline soils to improve fertility and productivity [20, 28]. However, the use of cost-effective enriched amendments for medicinal herb cultivation under different soil conditions remains underexplored.
Evidence on how enriched amendments influence soil properties, nutrient dynamics, and medicinal plant yield is limited. Therefore, it is hypothesized that ENC and BFM **(Figure 1)** may outperform conventional FYM and serve as viable substitutes for chemical fertilizers in improving soil quality, plant growth, yield, and bioactive compound production in Senna. This study aimed to (1) evaluate soil property changes following ENC and BFM application in two contrasting soils compared to FYM and CF, and (2) assess the potential of ENC and BFM to enhance Senna yield and sennoside content.

a) b)

Figure 1. Photograph showing the application of (a) enriched compost and (b) biochar-fortified mineral, prepared from distillation waste biomass and mineral powders.

Materials and Methods

Preparation and characterization of enriched compost and biochar

Distillation residues from Palmarosa (Cymbopogon martini (Roxb.) Wats.), collected from the hydro-distillation facility at ICAR-Directorate of Medicinal and Aromatic Plants Research, Anand, were dried and chopped into pieces no larger than 5 cm. Low-grade rock phosphate (RP) and silicate mineral powder (SMP) were sourced from Udaipur, Rajasthan, and Nellore district, Andhra Pradesh, respectively, and pulverized to 150 μm using a Wiley mill. The RP contained 0.02 g kg^{-1} water-soluble P, 17 g kg^{-1} citrate-soluble P, and 94.1 g kg^{-1} total P [13], while the SMP had 0.11, 0.21, 1.56, and 80.7 g kg^{-1} of water-soluble, exchangeable, non-exchangeable, and total K, respectively [14].
Enriched compost (ENC) was prepared by combining the distillation waste biomass with RP and SMP in equal proportions (2% of total biomass), along with cow dung slurry as a natural compost inoculant. The slurry was prepared by mixing fresh cow dung and water in a 1:1 ratio and fermenting it for 24 hours. For each 100 kg of biomass, 10 kg of cow dung slurry and 4 kg of mineral mixture were incorporated. The mixture was placed into composting bins and regularly turned and watered to maintain moisture and aeration. After approximately 120 days, compost maturity was confirmed by a C:N ratio below 20:1 **(Figure 1a)**.
For biochar preparation, the chopped biomass was ground to ≤2 mm and pyrolyzed at 350 °C under limited oxygen conditions in a muffle furnace [23]. Biochar-fortified mineral (BFM) was then produced using a hydrothermal method, blending biochar with clay, minerals, and organic matter, adapting previously reported protocols [18, 19,

29]. In this formulation, farmyard manure (FYM) replaced chicken manure, and RP and SMP substituted commercial calcium carbonate, magnesium sulfate, and ilmenite. To increase surface area and functional groups, biochar was pre-treated with 10% (v/v) phosphoric acid. In a batch hydrothermal reactor, 35 g biochar, 30 g kaolinite clay, 7.5 g RP, 7.5 g WM, and 20 g FYM were combined to produce BFM, which was then stored in sealed containers for further use **(Figure 1b)**. All three amendments—FYM, ENC, and BFM—were ground to ≤2 mm prior to analysis.

The pH of each amendment was measured in a 1:5 (w/v) suspension with deionized water using a digital pH meter. Cation exchange capacity (CEC) was determined according to Sumner and Miller [30]. Total carbon and nitrogen were analyzed using a CNH analyzer. For total P and K, samples were digested in a 9:4 v/v HNO_3/$HClO_4$ mixture [31], with P quantified spectrophotometrically via a yellow-colored complex [32] and K measured using a flame photometer. Water-soluble and available P were extracted using ultra-pure water and 0.5 M $NaHCO_3$, respectively [33], while exchangeable and water-soluble K were extracted with 1 N NH_4OAc and ultra-pure water, respectively [34], followed by flame photometric quantification.

The physicochemical characteristics of ENC and BFM, in comparison with FYM, are presented in **Table 1**. BFM had the lowest total carbon content among the amendments, whereas ENC contained higher carbon. BFM was mildly acidic (pH 6.8), contrasting with the alkaline biochar (pH 8.13) [23]. CEC was highest in BFM (63.8 cmol p^+ kg^{-1}), significantly exceeding that of ENC and FYM. Although BFM had relatively low total carbon (8.9%), it exhibited higher nutrient levels than both pristine biochar [23] and FYM. ENC showed the highest nitrogen and phosphorus contents, while BFM was richest in potassium. Overall, nutrient concentration and availability were superior in ENC and BFM relative to FYM.

Table 1. Physicochemical properties of farmyard manure (FYM), enriched compost (ENC), and biochar-fortified mineral (BFM)

Property	FYM	ENC	BFM
pH	6.51 ± 0.09[a]	7.40 ± 0.11	6.82 ± 0.07
Cation Exchange Capacity (cmol p^+ kg^{-1})	43.2 ± 1.2	47.9 ± 2.2	63.8 ± 2.3
Total Carbon (g kg^{-1})	316.2 ± 3.1	246.7 ± 3.4	89.0 ± 7.9
Total Nitrogen (mg kg^{-1})	5143 ± 73	13127 ± 486	4557 ± 694
Phosphorus			
Total P (mg kg^{-1})	2312 ± 43	24128 ± 907	13709 ± 721
Olsen P (mg kg^{-1})	–	609 ± 8.4	911 ± 11.7
Water-soluble P (mg kg^{-1})	89.7 ± 2.1	206.8 ± 2.8	187.5 ± 2.6
Potassium			
Total K (mg kg^{-1})	4719 ± 109	19223 ± 878	27243 ± 628
Exchangeable K (mg kg^{-1})	–	9329 ± 351	12706 ± 447
Water-soluble K (mg kg^{-1})	91.3 ± 1.7	209.3 ± 2.7	141.7 ± 2.1

[a]Values represent mean ± standard error (n = 3).

Experimental site and soils

Senna (Cassia angustifolia Vahl.) was cultivated in pots under a net house at ICAR-DMAPR, Boriavi, Anand, situated at 22° 35′ 57″–22° 36′ 06″ N latitude and 73° 27′ 57″–73° 27′ 16″ E longitude, with an elevation of 45.11 m above sea level. The site experiences a semi-arid subtropical climate characterized by hot summers (maximum temperature reaching 41.5 °C) and cool winters (minimum temperature around 9 °C). The region receives an average annual rainfall of 860 mm, primarily during August and September.

For the pot experiment, bulk soil samples were collected from two locations: a fallow site at ICAR-DMAPR, Anand (Fluvic Cambisol) and Bharuch, Gujarat (Haplic Vertisol) [35]. The Anand soil exhibited a sandy loam texture, whereas the Bharuch soil was clayey. Soil samples were taken from a 0–15 cm depth and analyzed for their physicochemical properties. Soil pH and electrical conductivity (EC) were measured using a digital pH-EC meter in a 1:2.5 soil-to-deionized water suspension [36]. Soil texture was determined by the hydrometer method [37], and organic carbon content was estimated using the oxidation-titration technique [38]. Mineral nitrogen (NH_4^+ + NO_3^-) was extracted with 2 M KCl and quantified via micro-Kjeldahl distillation followed by titration [39]. Available phosphorus was extracted using 0.5 M $NaHCO_3$ (pH 8.5) and determined spectrophotometrically based on blue color development [32, 33]. Available potassium was obtained using neutral 1 N NH_4OAc and measured with a flame photometer [34]. Detailed physicochemical properties of the experimental soils are summarized in **Table 2**.

Table 2. Physicochemical characteristics of the experimental soils

Soil Parameter	Soil 2 (Non-saline)	Soil 1 (Slightly Saline)
Particle Size Distribution		
Sand (%)	69.1 ± 0.87	15.5 ± 0.23[a]
Silt (%)	14.2 ± 0.33	28.2 ± 0.57
Clay (%)	16.7 ± 0.72	56.3 ± 1.28
Soil Texture	Sandy Loam	Clay
pH	7.8 ± 0.09	8.1 ± 0.11
Electrical Conductivity (dS m⁻¹)	0.28 ± 0.03	2.62 ± 0.07
Organic Carbon (g kg⁻¹)	2.92 ± 0.13	4.45 ± 0.17
Mineral Nitrogen (mg kg⁻¹)	39.6 ± 1.29	51.7 ± 1.78
Available Phosphorus (mg kg⁻¹)	16.3 ± 1.23	10.5 ± 0.92
Available Potassium (mg kg⁻¹)	89.7 ± 2.52	201.7 ± 4.28

[a]Values are mean ± standard error (n = 3).

Plant growth experiment

The senna cultivar ALFT 2 was grown in pots under a net house at ICAR-DMAPR during the rainy season (June–September). The study was conducted as a factorial experiment using a completely randomized design (CRD). Two application rates (2.5 and 5 t ha^{-1}) of enriched compost (ENC) and biochar-fortified mineral (BFM) were evaluated alongside conventional farmyard manure (FYM) and the recommended dose of chemical fertilizer (CF). A total of seven treatments were established:

- T1: Control (no amendment)
- T2: FYM (5 t ha^{-1})
- T3: ENC (2.5 t ha^{-1})
- T4: ENC (5 t ha^{-1})
- T5: BFM (2.5 t ha^{-1})
- T6: BFM (5 t ha^{-1})
- T7: CF (NPK 60-40-20 kg ha^{-1})

These treatments were tested in two soil types: slightly saline soil (S1) and non-saline soil (S2), with three replicates per treatment, resulting in a total of 42 pots.

Soil samples (<5 mm) were spread on a clean polythene sheet, and calculated amounts of FYM, ENC, and BFM were incorporated according to the treatment plan (T2–T6) and mixed thoroughly **(Table 3)**. For CF treatment (T7), nutrients were supplied using urea, diammonium phosphate (DAP), and muriate of potash (MOP) to deliver 26.67 mg N, 17.77 mg P, and 8.89 mg K per kg soil, respectively, and mixed evenly with the soil. Each treated soil portion (20 kg) was placed in earthen pots.

Senna seeds were pre-treated by soaking in 0.4% Trichoderma harzianum solution for 2 hours, followed by drying in shade for 1 hour. Five seeds were sown per pot, and after germination, thinning was performed to maintain a single seedling in each pot. Throughout the 120-day growth period, pots were irrigated regularly to maintain field capacity soil moisture. Weeding was performed once, 30 days after sowing.

Table 3. Nutrient input levels corresponding to different treatments in the pot experiment (mg kg⁻¹ soil)

Nutrient	T1: Control	T2: FYM (5 t ha⁻¹)	T3: ENC (2.5 t ha⁻¹)	T4: ENC (5 t ha⁻¹)	T5: BFM (2.5 t ha⁻¹)	T6: BFM (5 t ha⁻¹)	T7: CF
Nitrogen	0	11.42	14.58	29.16	5.07	10.13	26.67
Phosphorus	0	5.15	26.80	53.60	15.24	30.44	17.78
Potassium	0	10.49	21.33	42.71	30.27	60.53	8.89

Abbreviations: FYM – Farmyard manure; ENC – Enriched compost; BFM – Biochar-fortified mineral; CF – Chemical fertilizer.

Plant growth measurements

Plant height was recorded at the flowering stage, measuring from the soil surface up to the base of the uppermost fully expanded leaf. The count of primary branches per plant was noted at harvest, 120 days post-sowing. Fresh leaf and pod weights were determined immediately after uprooting each plant using an electronic balance. Subsequently, the samples were oven-dried at 40 °C to obtain dry weights of leaves and pods. Total fresh and dry herbage yields per plant were calculated by summing the respective weights of leaves and pods.

Analysis of bioactive compounds

At 120 days after sowing, mature leaves (up to the third from the top) and green pods were harvested. Samples were initially air-dried in the shade and then oven-dried at 60 ± 0.5 °C for 48 hours. The dried material was finely powdered using a Wiley mill for sennoside determination. Approximately 100 mg of powder was extracted in 20 mL of 70% aqueous methanol using a sonication bath for 10 minutes. After centrifugation, the extracts were filtered through a 0.45 µm membrane and analyzed with HPLC (LC-20A, Shimadzu Corporation, Kyoto, Japan). Sennoside-A and sennoside-B (Sigma-Aldrich, Bangalore, India) served as reference standards. Total sennoside content was calculated following the methodology of Srivastava *et al*. [40].

Soil collection and examination

After harvesting, representative soil samples were taken from each pot. A portion of the soil was stored at 4 °C for microbial analyses, while the remaining portion was air-dried, pulverized, and used for physicochemical evaluation. Parameters measured included pH, electrical conductivity, organic carbon, mineral nitrogen (NH_4^+ + NO_3^-), and available phosphorus and potassium, following standard methods described earlier. Refrigerated samples were equilibrated to room temperature prior to measuring microbial biomass carbon (MBC) via fumigation-extraction [41] and dehydrogenase enzyme activity by estimating the formation of triphenyl formazan (TPF), expressed as TPF g^{-1} soil h^{-1} [42].

Statistical procedures

All experimental data were expressed as mean values of three replicates. A completely randomized design (CRD) was used for the analysis of variance (ANOVA). Treatment differences were evaluated using Duncan's multiple range test at a 5% significance level. Correlation analyses and multiple comparisons were conducted using SPSS version 24 (SPSS Inc., Chicago, USA), while Microsoft Excel (Microsoft Corporation, USA) was used for data management, tabulation, and graphical presentation.

Results and Discussion

Soil quality

Soil pH, electrical conductivity, and soil organic carbon

The influence of various treatments on soil physicochemical properties is summarized in **Table 4**. After senna harvest, notable variations in soil pH, electrical conductivity (EC, dS m^{-1}), and soil organic carbon (SOC, g kg^{-1}) were observed due to the application of enriched compost (ENC) and biochar-fortified mineral (BFM). Slightly saline soil exhibited higher pH (7.85) and EC (1.23 dS m^{-1}) compared to the non-saline soil (7.67 and 0.36 dS m^{-1}, respectively). Treatments with BFM and ENC at 5 t ha^{-1} increased soil pH more than FYM and chemical fertilizer (CF), whereas CF consistently produced the lowest pH values across both soils, likely owing to its acidic nature. BFM applications led to the highest EC readings, followed by ENC, while EC under CF was comparable to ENC. The increase in EC for non-saline soil under BFM was attributed to the inherently higher EC of the amendment itself **(Table 1)**. Slightly saline soil naturally showed elevated pH and EC relative to the non-saline soil.

FYM-treated soils consistently had the highest SOC (3.41–4.58 g kg^{-1}), while CF treatments had the lowest SOC across both soils **(Figure 2)**. Both ENC and BFM significantly ($p \leq 0.05$) enhanced SOC compared to control and CF, with higher application rates (5 t ha^{-1}) outperforming the lower rates (2.5 t ha^{-1}) in both soil types.

Application of FYM and enriched amendments (ENC and BFM) generally decreased soil pH while increasing EC and SOC, indicating a buffering effect on soil acidity. The reduction in pH and EC may be attributed to adsorption of Na, chelation of Ca and Mg by organic anions, and the production of organic acids during the decomposition of FYM and ENC [43]. In contrast, soluble cations (Ca, Mg, K) and resistant carbon compounds in BFM likely contributed to higher EC values. Similar trends have been reported in previous studies, where biochar and biochar-based products increased both soil pH and EC [23, 44].

The enriched amendments also contributed to a significant accumulation of SOC relative to chemical fertilizers, likely due to their higher carbon content **(Table 1)** compared to the native soils. Organic manures and composts play a synergistic role in enhancing SOC pools in cultivated soils over time. However, the duration of this study was insufficient to determine the long-term stability of SOC. Conversely, rapid mineralization of native soil carbon under CF likely caused the observed SOC decline [45]. These findings align with prior research showing that FYM and enriched amendments improve soil pH, EC, and SOC across different soil types [17, 20, 46, 47]. For instance, earlier studies reported that SOC increased by 17.3% with FYM and 10.2% with enriched compost compared to CF application [6].

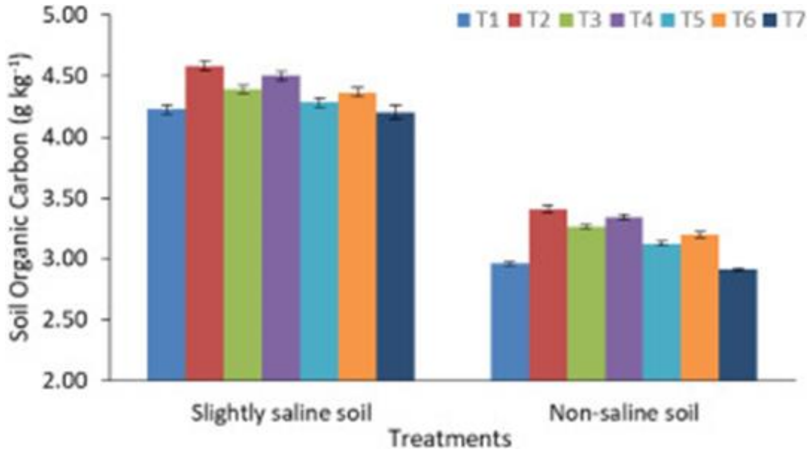


Figure 2. Soil organic carbon (SOC) levels following the application of enriched amendments (ENC and BFM) and chemical fertilizer (CF). Error bars represent standard error of the mean (n = 3).

Table 4. Effect of enriched amendments and chemical fertilizer on soil physicochemical properties and nutrient availability

Soil Parameter	**Soil Type**	**T1: Control**	**T2: FYM (5 t ha⁻¹)**	**T3: ENC (2.5 t ha⁻¹)**	**T4: ENC (5 t ha⁻¹)**	**T5: BFM (2.5 t ha⁻¹)**	**T6: BFM (5 t ha⁻¹)**	**T7: CF**	**ANOVA: Treatment**	**ANOVA: Soil**	**ANOVA: Interaction**
pH	S1 (Slightly saline)	7.96 ± 0.04 ab	7.70 ± 0.04 efg	7.91 ± 0.03 b	8.01 ± 0.05 a	7.79 ± 0.02 cd	7.82 ± 0.04 c	7.77 ± 0.03 cde	***	***	***
	S2 (Non-saline)	7.63 ± 0.01 gh	7.57 ± 0.01 hi	7.67 ± 0.01 fg	7.75 ± 0.01 cdef	7.71 ± 0.03 defg	7.81 ± 0.01 c	7.53 ± 0.01 i			
EC (dS m⁻¹)	S1	1.17 ± 0.02 de	1.13 ± 0.02 e	1.22 ± 0.02 cd	1.24 ± 0.02 bc	1.28 ± 0.02 b	1.37 ± 0.02 a	1.23 ± 0.03 bc	***	***	**
	S2	0.30 ± 0.01 h	0.34 ± 0.01 gh	0.36 ± 0.01 fgh	0.37 ± 0.01 fg	0.39 ± 0.01 fg	0.41 ± 0.01 f	0.35 ± 0.01 gh			
SOC (g kg⁻¹)	S1	4.23 ± 0.03 e	4.58 ± 0.02 a	4.39 ± 0.02 c	4.50 ± 0.02 b	4.28 ± 0.02 d	4.37 ± 0.02 c	4.20 ± 0.02 e	***	***	***
	S2	2.96 ± 0.01 j	3.41 ± 0.01 e	3.26 ± 0.01 g	3.34 ± 0.02 f	3.12 ± 0.01 i	3.20 ± 0.01 h	2.91 ± 0.01 j			
Mineral Na (mg kg⁻¹)	S1	48.47 ± 1.64 cd	51.47 ± 1.82 bc	51.53 ± 1.17 bc	54.60 ± 1.62 ab	48.17 ± 2.20 cd	54.87 ± 1.28 ab	57.17 ± 1.56 a	***	***	NS
	S2	37.37 ± 1.13 f	41.37 ± 0.98 ef	43.03 ± 0.83 e	45.10 ± 0.79 de	41.23 ± 0.84 ef	43.73 ± 0.75 e	48.50 ± 0.51 cd			
Available P (mg kg⁻¹)	S1	11.23 ± 0.55 g	13.53 ± 0.69 g	16.00 ± 0.93 f	17.77 ± 0.97 def	11.53 ± 0.69 g	13.57 ± 1.18 g	18.43 ± 1.04 de	***	***	NS
	S2	16.57 ± 0.55 ef	19.87 ± 0.78 cd	21.57 ± 0.63 bc	23.70 ± 0.52 ab	16.87 ± 0.38 ef	18.80 ± 0.85 de	24.77 ± 0.29 a			

Available K (mg kg⁻¹)	S1	188.57 ± 2.60 c	202.93 ± 2.88 b	208.33 ± 2.58 b	216.27 ± 3.78 a	218.13 ± 2.98 a	222.50 ± 2.82 a	223.30 ± 3.32 a	***	***	NS
	S2	91.57 ± 1.10 h	105.27 ± 1.15 g	110.67 ± 0.90 fg	115.93 ± 1.47 ef	115.80 ± 1.16 ef	121.50 ± 1.69 de	124.97 ± 1.14 d			

Abbreviations: FYM = Farmyard manure; ENC = Enriched compost; BFM = Biochar-fortified mineral; CF = Chemical fertilizer; S1 = Slightly saline soil; S2 = Non-saline soil; SOC = Soil organic carbon; EC = Electrical conductivity; NS = Not significant.
All values are expressed as mean ± standard error from three independent experiments (n = 3).
Significance levels are indicated as P < 0.05 (*), P < 0.01 (**), and P < 0.001 (***). Different letters within the same row denote statistically significant differences among treatments according to Duncan's multiple range test at 5% significance.
[a] Mineral nitrogen (NH_4^+-N + NO_3^--N).

Nutrient availability

Both conventional farmyard manure (FYM) and enriched amendments (ENC and BFM) positively affected mineral nitrogen (N), available phosphorus (P), and potassium (K) levels in the soil **(Table 4)**. The enriched amendments (ENC and BFM), along with chemical fertilizers (CF), significantly ($p \leq 0.05$) enhanced the availability of these nutrients. Available K was markedly higher with ENC and BFM than with FYM in both soil types. Across both soils, chemical fertilizer (CF) treatments recorded the highest values: mineral N (48.5–57.2 mg kg⁻¹), available P (18.4–24.8 mg kg⁻¹), and available K (125–223 mg kg⁻¹). Increasing the application rate of ENC and BFM from 2.5 to 5 t ha⁻¹ did not result in statistically significant further improvements in nutrient availability. However, available P under ENC at 5 t ha⁻¹ (17.8–23.7 mg kg⁻¹) and available K under BFM at 5 t ha⁻¹ (121.5–222.5 mg kg⁻¹) were comparable to those achieved with CF.

In slightly saline soil, mineral N (NH_4^+ + NO_3^-) and available K were higher than in non-saline soil, whereas available P showed the opposite trend. No significant interaction ($p \leq 0.05$) was observed between treatments and soil types. Overall, the enriched amendments (ENC and BFM) performed comparably to, or nearly as effectively as, chemical fertilizers in sustaining nutrient availability in both soils. The incorporation of P- and K-bearing minerals during the preparation of ENC and BFM **(Table 1)** likely enhanced nutrient retention and release. BFM, being nutrient-rich with improved physicochemical characteristics, probably benefited from organo-mineral complex formation, as confirmed by SEM and FTIR analyses [29]. These amendments appear to have increased the mineral N pool through better retention and gradual release [44], aligning with findings in medicinal crops where vermicompost [48] and enriched compost [6] outperformed FYM.

The organic matter in ENC and BFM likely reduced P fixation by blocking adsorption sites [6, 21] and promoting rapid incorporation of soluble P into microbial biomass [49], thereby maintaining higher available P levels. The substantial K input from both ENC and BFM **(Table 3)**, combined with organic-matter-driven bio-activation of native mineral K, contributed to elevated available K, consistent with earlier reports on silicate-enriched compost [14]. Thus, ENC and BFM, produced from natural minerals and biomass waste, can effectively enhance nutrient-use efficiency and soil nutrient status [6, 17, 46, 50].

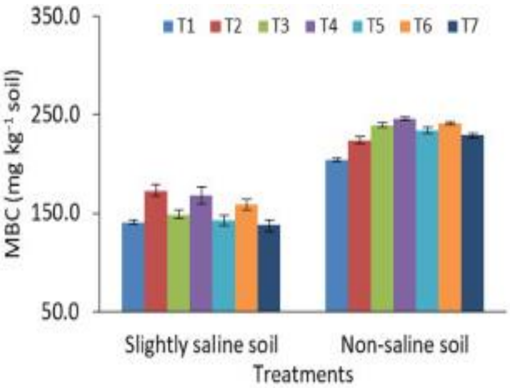
Soil biological properties

Compared to chemical fertilizers (CF), the enriched amendments (ENC and BFM) significantly ($p \leq 0.05$) increased microbial biomass carbon (MBC) and dehydrogenase activity (DHA) in both slightly saline and non-saline soils **(Figure 3)**. The highest MBC (245.4 mg kg⁻¹) was recorded with ENC at 5 t ha⁻¹, closely followed by BFM at the same rate (240.6 mg kg⁻¹). In slightly saline soil, however, FYM outperformed ENC (5 t ha⁻¹) for MBC (173.1 mg kg⁻¹) **(Figure 3a)**. A similar pattern emerged for DHA, with ENC (5 t ha⁻¹) achieving the highest value (37.23 µg TPF g⁻¹ h⁻¹) in slightly saline soil and FYM performing best (27.07 µg TPF g⁻¹ h⁻¹) in non-saline soil **(Figure 3b)**.

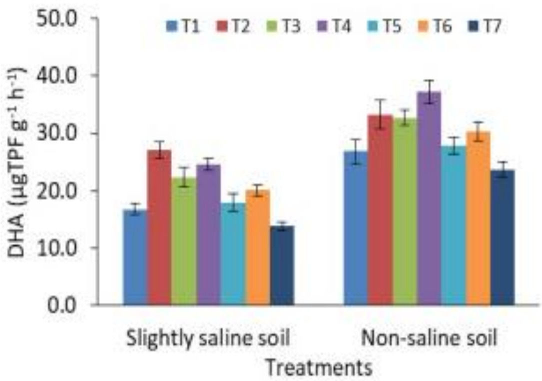
Higher application rates (5 t ha⁻¹) of ENC and BFM consistently produced greater improvements in MBC and DHA than the lower rate (2.5 t ha⁻¹). FYM also markedly boosted DHA, particularly in slightly saline soil, whereas CF reduced enzyme activity in both soil types. ENC generally induced higher DHA than BFM across soils.

Organic amendments improve the soil's physicochemical conditions, nutrient supply, and substrate availability, creating a favorable habitat for microbial proliferation [51], unlike chemical fertilizers, which often suppress microbial and enzymatic activity [45, 52]. MBC, as the most dynamic fraction of soil organic carbon, responds rapidly to organic inputs [53]. Both ENC and BFM, by providing balanced carbon and nutrient supplies, served as superior substrates for microbial growth compared with CF [6, 50]. Dehydrogenase activity reflects the size and metabolic activity of the microbial community [54]; the enriched amendments likely enhanced DHA by supplying organic carbon and essential nutrients while fostering beneficial microorganisms [55].

Non-saline soil exhibited superior biological properties (higher MBC and DHA) than slightly saline soil, probably due to a more favorable soil environment. A significant treatment × soil-type interaction was detected for MBC but not for DHA. These results concur with previous studies showing enhanced MBC and DHA following applications of enriched composts [6, 20] and biochar-based amendments [11, 50, 53]. Therefore, ENC and BFM represent promising alternative nutrient sources capable of substantially improving soil biological health.



a)



b)

Figure 3. Influence of enriched amendments and chemical fertilizer on soil microbial biomass carbon (a) and dehydrogenase activity (b). Error bars represent standard errors (n = 3).

Plant growth and yield

The effects of different organic amendments on the growth and yield of senna are presented in **Table 5**. Both enriched amendments (ENC and BFM) and chemical fertilizer (CF) significantly improved plant growth parameters in both soil types compared to the unfertilized control. The greatest plant height and number of branches were achieved with CF, followed closely by ENC (5 t ha^{-1}) in slightly saline soil and BFM (5 t ha^{-1}) in non-saline soil. Statistically, however, CF, ENC (5 t ha^{-1}), and BFM (5 t ha^{-1}) performed at par with one another ($p > 0.05$). Relative to FYM, ENC (5 t ha^{-1}) increased plant height by 30.0% in slightly saline soil and 18.8% in non-saline soil, while BFM (5 t ha^{-1}) improved it by 25.4% and 22.7%, respectively. Although CF produced the highest branch number, it was statistically comparable to the higher doses of ENC and BFM. Across both soils and application rates (2.5 and 5 t ha^{-1}), ENC and BFM consistently outperformed FYM in plant height and branching. The higher rate of BFM (5 t ha^{-1}) significantly outyielded the lower rate of ENC (2.5 t ha^{-1}) in plant height. Non-saline soil supported superior plant growth regardless of treatment, with no significant treatment × soil-type interaction ($p > 0.05$).

The beneficial effects of ENC, BFM, and CF were also evident in total dry herbage (leaf + pod) yield **(Figure 4)**. When averaged across soils, CF produced the highest total dry herbage yield ($p \leq 0.05$). However, in slightly saline soil, ENC at 5 t ha^{-1} delivered a yield nearly identical to CF. Dry leaf yield was highest under CF (28.4–31.8 g $plant^{-1}$), followed by ENC (5 t ha^{-1}) and BFM (5 t ha^{-1}), both of which significantly surpassed FYM in the two soils. For dry pod yield, CF was statistically equivalent to ENC (5 t ha^{-1}) and BFM (5 t ha^{-1}) in slightly saline soil. Higher application rates (5 t ha^{-1}) of ENC and BFM consistently produced greater fresh and dry herbage yields than the lower rates (2.5 t ha^{-1}). Overall, ENC and BFM significantly outyielded FYM in leaf, pod, and total dry herbage production. A significant treatment × soil-type interaction was observed for dry pod yield but not for dry leaf yield. Non-saline soil recorded higher herbage yields than slightly saline soil across all treatments.

Improved plant growth and economic yield of senna resulted from the balanced nutrient supply and organic matter provided by ENC and BFM **(Table 3)**. Incorporation of low-grade rock phosphate (RP) and soluble potassium minerals (SMP) during hydrothermal processing and composting substantially raised the nutrient content of ENC and BFM compared to conventional FYM **(Table 1)**. The superior nutrient-delivery capacity, combined with enhanced nutrient retention and elevated soil biological activity **(Tables 3 and 4)**, created a more favorable rhizosphere environment [46]. The slow-release characteristics of these enriched amendments ensured prolonged nutrient availability [12, 44], supporting sustained cellular metabolism and greater biomass accumulation.

These findings align with previous research demonstrating that enriched biochar-based formulations and mineral-enriched composts significantly enhance growth and yield of lettuce [56], wheat [50], ginger [17], and several medicinal plants, including isabgol (Plantago ovata Forsk.) [6], senna (Cassia angustifolia Vahl.) [21], Centella asiatica (L.) [57], and ashwagandha (Withania somnifera (L.) Dunal) [20] **(Figure 4)**.

Table 5. Plant biometric parameters as influenced by application of enriched amendments and chemical fertilizer.

Plant biometric parameters		T1: Control	T2: FYM (5 t ha^{-1})	T3: ENC (2.5 t ha^{-1})	T4: ENC (5 t ha^{-1})	T5: BFM (2.5 t ha^{-1})	T6: BFM (5 t ha^{-1})	T7: CF	ANOVA: Treatment	ANOVA: Soil	ANOVA: Interaction	ANOVA: T1: Control
Plant height (cm)	S1	31.33 ± 0.74^{i}	34.67 ± 0.99^{hi}	42.43 ± 0.38^{ef}	45.07 ± 0.63^{cde}	39.03 ± 1.05^{fg}	43.47 ± 0.41^{de}	47.37 ± 0.98^{cd}	***	***	NS	
	S2	36.43 ± 0.75^{gh}	43.67 ± 1.60^{de}	48.37 ± 3.43^{bc}	51.90 ± 0.71^{ab}	47.03 ± 1.91^{cd}	53.60 ± 0.46^{a}	54.63 ± 0.44^{a}				
Number of branches (plant^{-1})	S1	9.67 ± 0.88^{e}	11.00 ± 0.58^{de}	13.00 ± 0.58^{abcd}	13.33 ± 0.88^{abcd}	12.33 ± 0.33^{bcde}	12.67 ± 0.88^{abcd}	14.67 ± 0.88^{ab}	***	**	NS	
	S2	11.00 ± 1.15^{de}	11.67 ± 0.88^{cde}	14.33 ± 0.88^{abc}	14.67 ± 0.88^{ab}	13.67 ± 0.88^{abcd}	15.33 ± 0.88^{a}	15.33 ± 0.88^{a}				
Dry leaf yield (g plant^{-1})	S1	20.07 ± 0.92^{i}	23.07 ± 0.75^{gh}	25.30 ± 1.21^{efg}	27.80 ± 0.59^{bcd}	23.80 ± 0.95^{fgh}	26.70 ± 1.21^{cde}	28.40 ± 0.36^{bcd}	***	***	NS	
	S2	22.83 ± 0.85^{h}	26.07 ± 0.73^{def}	27.80 ± 0.59^{bcd}	28.43 ± 0.41^{bcd}	29.10 ± 0.47^{bc}	29.80 ± 0.38^{ab}	31.80 ± 0.55^{a}				
Dry pod yield (g plant^{-1})	S1	2.38 ± 0.13^{h}	3.33 ± 0.05^{g}	3.82 ± 0.06^{ef}	4.15 ± 0.14^{d}	3.71 ± 0.05^{f}	4.01 ± 0.11^{de}	4.28 ± 0.08^{d}	***	***	*	
	S2	3.54 ± 0.17^{fg}	4.09 ± 0.11^{de}	4.83 ± 0.06^{c}	5.27 ± 0.06^{b}	5.15 ± 0.04^{b}	5.28 ± 0.04^{b}	5.63 ± 0.10^{a}				
Total dry herbage yield (g plant^{-1})	S1	22.44 ± 0.86^{i}	26.40 ± 0.79^{h}	29.12 ± 1.19^{fg}	31.95 ± 0.61^{cde}	27.51 ± 0.98^{gh}	30.71 ± 1.24^{def}	32.68 ± 0.33^{bcd}	***	***	NS	
	S2	26.38 ± 0.70^{h}	30.16 ± 0.84^{ef}	32.63 ± 0.62^{bcd}	33.71 ± 0.45^{bc}	34.25 ± 0.44^{bc}	35.08 ± 0.41^{b}	37.43 ± 0.64^{a}				

FYM: Farmyard manure; ENC: Enriched compost; BFM: Biochar fortified mineral; CF: Chemical fertilizer; S1: Slightly Saline soil and S2: Non-saline soil; ANOVA: Analysis of variance; NS: Non-significant.
All the data are presented as mean values ± standard error of three independent experiments (n = 3).
*, **, and *** indicate significance at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively. Within the same row, different letters denote statistically significant differences among treatments based on Duncan's multiple range test at 5% significance.

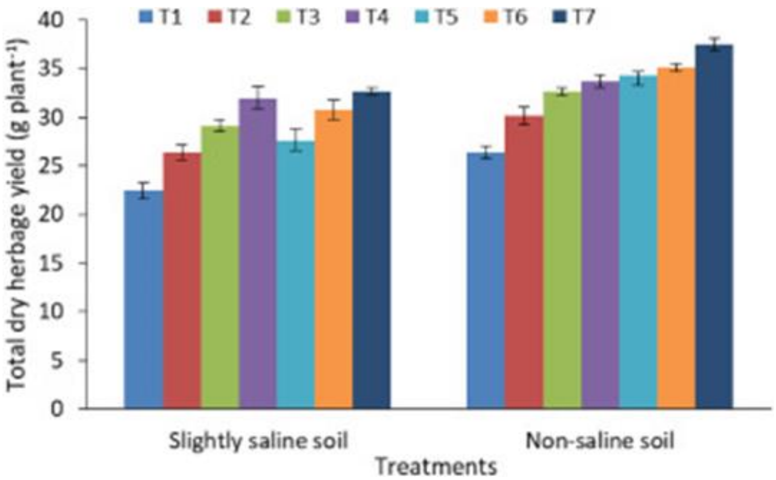


Figure 4. Total dry herbage yield of senna as affected by enriched amendments and chemical fertilizer. Error bars represent standard errors (n = 3).

Bioactive compound content and yield

The effects of different organic and enriched amendments, along with chemical fertilizer, on sennoside accumulation and yield in two soil types are shown in **Figure 5**. Leaf sennoside concentrations were enhanced by

FYM and the enriched treatments (ENC and BFM) relative to the control; however, pod sennoside content remained largely unchanged across treatments in both soils. In slightly saline soil, none of the fertilization strategies produced a significant difference in total sennoside levels. In contrast, in non-saline soil, ENC and BFM significantly ($p \leq 0.05$) increased total sennoside content compared to CF and FYM **(Figure 5a)**. The highest sennoside content (3.13 %) occurred under BFM at 5 t ha^{-1} in non-saline soil, corresponding to increases of 21.5 % and 29.2 % relative to FYM and CF, respectively.

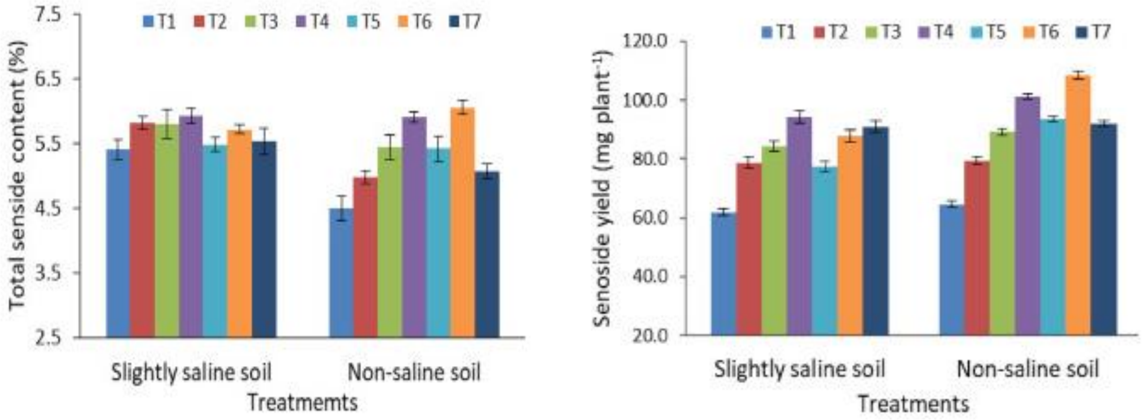
When considering total sennoside yield, distinct differences emerged among treatments in both soils **(Figure 5b)**. In non-saline soil, BFM (5 t ha^{-1}) produced the maximum total sennoside yield (108.46 mg $plant^{-1}$), followed closely by ENC (5 t ha^{-1}) at 101.23 mg $plant^{-1}$. Higher application rates of ENC and BFM (5 t ha^{-1}) consistently outperformed lower rates (2.5 t ha^{-1}) in terms of yield. In slightly saline soil, the highest yield was observed with ENC, followed by CF. Overall, non-saline soil supported higher sennoside yields than slightly saline soil.

Secondary metabolite synthesis, including alkaloids, is strongly influenced by nutrient availability [58], and organic amendments can markedly affect secondary metabolite production in medicinal species [59]. Organic fertilizers deliver essential nutrients throughout the growing season while enhancing soil quality, thereby promoting secondary metabolism [44]. In the present experiment, sennoside yield responded differently to fertilization because both biomass and sennoside concentration contribute to overall yield. Enriched amendments supplied higher levels of essential nutrients and organic carbon, improving nutrient availability and favoring secondary metabolite biosynthesis [20]. Continuous nutrient provision from ENC and BFM facilitated efficient nutrient uptake and assimilation, resulting in enhanced synthesis of both primary and secondary metabolites [60]. By contrast, conventional organic manures such as FYM primarily provide organic carbon but are relatively deficient in essential nutrients [6, 46]. The combined mineral-organic composition of ENC and BFM made them more effective than FYM for sennoside accumulation [12, 17].

The enriched amendments likely created a favorable rhizosphere environment for the biosynthesis of sennosides [21]. In non-saline soil, optimal pH, electrical conductivity, and soil biological activity contributed to higher sennoside production compared to slightly saline soil. Similar trends have been documented, where organic amendments enhanced sennoside yield more in non-saline than saline soils [45]. ENC's superior performance in slightly saline soil may be attributed to its higher organic carbon content, improving SOC and nutrient availability. Conversely, BFM promoted nutrient retention and efficiency in non-saline soil [44]. These findings align with prior reports indicating that enriched compost is more effective than biochar in saline soils [61], whereas enriched biochar performs better in non-saline soils [44].

Correlation analyses for each soil type **(Tables 6 and 7)** revealed strong positive associations between total herbage yield and plant height ($r = 0.80$, $p \leq 0.01$), soil EC (0.70, $p \leq 0.01$), mineral N (0.83, $p \leq 0.01$), available P (0.53, $p \leq 0.01$), available K (0.94, $p \leq 0.01$), and microbial biomass carbon (MBC) (0.71, $p \leq 0.01$) in non-saline soil **(Table 7)**. Sennoside content was positively correlated with soil pH (0.68) and organic carbon (0.49), with comparable patterns in slightly saline soil **(Table 6)**. Sennoside concentration, however, did not significantly correlate with other soil parameters. Soil microbial biomass carbon and dehydrogenase activity were strongly associated with organic carbon across both soils. These results highlight the contribution of nutrient availability and microbial activity to senna biomass yield, suggesting that enriched amendments improve both soil fertility and plant productivity. The outcomes are consistent with previous studies on the benefits of organic and enriched amendments for medicinal plants [6, 21].

In conclusion, the enriched amendments ENC and BFM outperformed conventional FYM and demonstrated potential as alternatives to chemical fertilizers for senna cultivation. However, this study was limited to a single-season pot experiment, and effects may differ under field conditions. Future research, including field trials, is necessary to fully assess the potential of these amendments for sustainable production of high-value medicinal crops. Additionally, the economic feasibility of using ENC and BFM compared to FYM and CF was not evaluated here, an important consideration for practical adoption by farmers.



a) b)

Figure 5. Effect of enriched amendments and chemical fertilizer on bioactive compound content (a) and total yield (b) of senna. Error bars represent standard errors (n = 3).

Table 6. Correlations among plant and soil parameters of senna pot experiment in slightly saline soil.

	Plant height	**Leaf dry weight**	**Pod dry weight**	**Total herbage yield**	**Total sennoside**	**Soil pH**	**EC**	**Organic carbon**	**Mineral N**	**Available P**	**Available K**	**MBC**	**DHA**
Plant height	1												
Leaf dry weight	.821**	1											
Pod dry weight	.922**	.848**	1										
Total herbage yield	.857**	.996**	.894**	1									
Total sennoside	.146	.056	.039	.054	1								
Soil pH	.009	−.064	−.163	−.083	.259	1							
EC	.485*	.480*	.471*	.489*	.012	.056	1						
Organic carbon	.131	.152	.284	.178	.055	.091	.129	1					
Mineral N	.569**	.686**	.587**	.684**	.048	.011	.316	.075	1				
Available P	.740**	.658**	.704**	.680**	.057	.146	.043	.128	.604**	1			
Available K	.751**	.798**	.814**	.818**	−.140	−.231	.623**	.176	.570**	.391	1		
MBC	−.027	.088	.112	.094	−.027	−.076	−.096	.877**	.077	.051	.023	1	
DHA	−.182	.023	.039	.027	−.046	−.012	−.259	.798**	−.034	.014	−.117	.848**	1

Table 7. Correlations among plant and soil parameters of senna pot experiment in non-saline soil.

Plant height	**Plant height**	**Leaf dry weight**	**Pod dry weight**	**Total herbage yield**	**Total sennoside**	**Soil pH**	**EC**	**Organic carbon**	**Mineral N**	**Available P**	**Available K**	**MBC**	**DHA**
Plant height	1												

Leaf dry weight	.773**	1											
Pod dry weight	.857**	.910**	1										
Total herbage yield	.801**	.996**	.941**	1									
Total sennoside	.239	.101	.353	.153	1								
Soil pH	.259	.126	.307	.163	.677**	1							
EC	.599**	.688**	.704**	.700**	.280	.633**	1						
Organic carbon	.369	.186	.362	.223	.468*	.821**	.650**	1					
Mineral N	.799**	.819**	.813**	.830**	.041	−.029	.411	.114	1				
Available P	.620**	.517*	.567**	.535*	−.099	−.209	.032	.059	.828**	1			
Available K	.907**	.925**	.934**	.940**	.209	.233	.733**	.303	.829**	.526*	1		
MBC	.776**	.679**	.797**	.711**	.309	.555**	.771**	.781**	.588**	.464*	.753**	1	
DHA	.074	−.168	−.032	−.144	.043	.423	.184	.741**	−.055	.176	−.036	.460*	1

*$p \leq 0.05$, **$p \leq 0.01$ significant correlation co-efficient n = 21.
EC: Electrical conductivity; MBC: Microbial biomass carbon; DHA: Dehydrogenase activity.

Conclusion

The present study revealed that integrating waste biomass with mineral powders through hydrothermal treatment and composting substantially enhanced the nutrient content of biochar-fortified mineral (BFM) and enriched compost (ENC). Both ENC and BFM applications improved soil fertility and quality by increasing available nutrients, microbial biomass, and enzymatic activity, thereby confirming our hypothesis that enriched amendments can enhance soil properties. Compared to traditional organic manure (FYM), these enriched amendments markedly promoted plant growth and herbage yield in the medicinal plant Senna, with ENC showing superior performance in slightly saline soil and BFM in non-saline soil. Higher application rates (5 t ha−1) of both ENC and BFM consistently outperformed the lower rates (2.5 t ha−1) across soils. While chemical fertilizer generated the highest overall herbage yield, ENC and BFM were more effective than CF in slightly saline soil in terms of sennoside content and yield, supporting their potential as alternatives to chemical fertilizers. In conclusion, the application of enriched amendments (ENC and BFM) offers a more effective approach than conventional FYM for enhancing both total herbage and sennoside production in Senna, and they hold promise as cost-efficient substitutes for chemical fertilizers in medicinal herb cultivation.

Acknowledgments: Authors gratefully acknowledge ICAR-Directorate of Medicinal and Aromatic Plants Research, Anand for providing the required facilities to undertake this work. The senior author gratefully acknowledges National Talent Scholarship (NTS) scheme of Indian Council of Agricultural Research for financial support during his research work.

Conflict of Interest: None

Financial Support: None

Ethics Statement: None

References

1. World Bank, Commodity Prices, 2018. www.worldbank.org/en/research/commodity-markets. (Accessed 6 May 2018).

2. FAO, World Fertilizer Trends and Outlook to 2022, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 2019.
3. Y. Chen, S. Hu, Z. Guo, T. Cui, L. Zhang, C. Lu, Y. Yu, Z. Luo, Y. Jin, Effect of balanced nutrient fertilizer: a case study in Pinggu District, Beijing, China, Sci. Total Environ. 754 (2021) 142069.
4. A.I. Abou-Sreea, M.M. Rady, M.H. Roby, S.M. Ahmed, A. Majrashi, E.F. Ali, Cattle manure and bio-nourishing royal jelly as alternatives to chemical fertilizers: potential for sustainable production of organic Hibiscus sabdariffa L, J. Appl. Res. Med. Aromat. Plants. 25 (2021) 100334.
5. W. Buss, C. Wurzer, D.A. Manning, E.J. Rohling, J. Borevitz, O. Masek, Mineral-enriched biochar delivers enhanced nutrient recovery and carbon dioxide removal, Commun. Earth Environ. 3 (2022) 1–11.
6. B.B. Basak, A. Saha, Recycling of isabgol (Plantago ovata Forsk.) straw biomass and mineral powder with bio-inoculants as an effective soil amendment for isabgol cultivation, Pedosphere 32 (2022) 686–697.
7. M. Ayaz, U. Stulpinaite, D. Feiziene, V. Tilvikiene, K. Akthar, E. Baltre˙naite˙-Gediene˙, N. Striugas, U. Rehmani, S. Alam, R. Iqbal, M. Toleikiene, Pig manure digestate-derived biochar for soil management and crop cultivation in heavy metals contaminated soil, Soil Use Manag. 38 (2022) 1307–1321.
8. A. Saha, B.B. Basak, A. Banerjee, In-vitro antioxidant evaluation and production of biochar from distillation waste biomass of Mentha arvensis, J. Appl. Res. Med. Aromat. Plants. 31 (2022) 100428.
9. H.E. Zhongqi, P.H. Pagliari, H.M. Waldrip, Applied and environmental chemistry of animal manure: a review, Pedosphere 26 (2016) 779–816.
10. M. Ilyas, M. Arif, K. Akhtar, M. Riaz, H. Wang, Diverse feedstock's biochars as supplementary K fertilizer improves maize productivity, soil organic C and KUE under semiarid climate, Soil Tillage Res. 211 (2021) 105015.
11. B.B. Basak, B. Sarkar, A. Saha, A. Sarkar, S. Mandal, J.K. Biswas, H. Wang, N.S. Bolan, Revamping highly weathered soils in the tropics with biochar application: what we know and what is needed, Sci. Total Environ. 822 (2022) 153461.
12. S. Kizito, H. Luo, J. Lu, H. Bah, R. Dong, S. Wu, Role of nutrient-enriched biochar as a soil amendment during maize growth: exploring practical alternatives to recycle agricultural residuals and to reduce chemical fertilizer demand, Sustainability 11 (2019) 3211.
13. B.B. Basak, Evaluation of Indian rock phosphates for predicting agronomic potential through chemical and biological methods, Arch. Agron Soil Sci. 65 (2019) 1599–1609.
14. B.B. Basak, Recycling of waste biomass and mineral powder for preparation of potassium-enriched compost, J. Mater. Cycles Waste Manag. 20 (2018) 1409–1415.
15. D.R. Biswas, G. Narayanasamy, S.C. Datta, G. Singh, M. Begum, D. Maiti, A. Mishra, B.B. Basak, Changes in nutrient status during preparation of enriched organomineral fertilizers using rice straw, low-grade rock phosphate, waste mica, and phosphate solubilizing microorganism, Commun. Soil Sci. Plant Anal. 40 (2009) 2285–2307.
16. J.A. Kim, K. Vijayaraghavan, D.H.A. Reddy, Y.S. Yun, A phosphorus-enriched biochar fertilizer from bio-fermentation waste: a potential alternative source for phosphorus fertilizers, J. Clean. Prod. 196 (2018) 163–171.
17. M.B. Farrar, H.M. Wallace, C.Y. Xu, T.T.N. Nguyen, E. Tavakkoli, S. Joseph, S.H. Bai, Short-term effects of organo-mineral enriched biochar fertiliser on ginger yield and nutrient cycling, J. Soils Sediments 19 (2019) 668–682.
18. C.H. Chia, B.P. Singh, S. Joseph, E.R. Graber, P. Munroe, Characterization of an enriched biochar, J. Anal. Appl. Pyrolysis 108 (2014) 26–34.
19. P. Blackwell, S. Joseph, P. Munroe, H.M. Anawar, P. Storer, R.J. Gilkes, Z.M. Solaiman, Influences of biochar and biochar-mineral complex on mycorrhizal colonisation and nutrition of wheat and sorghum, Pedosphere 25 (2015) 686–695.
20. M. Gupta, P.K. Srivastava, A. Niranjan, S.K. Tewari, Use of a bioaugmented organic soil amendment in combination with gypsum for Withania somnifera growth on sodic soil, Pedosphere 26 (2016) 299–309.
21. B.B. Basak, N.A. Gajbhiye, Phosphorus enriched organic fertilizer, an effective P source for improving yield and bioactive principle of Senna (Cassia angustifolia Vahl.), Ind. Crop. Prod. 115 (2018) 208–213.
22. A. Saha, B.B. Basak, Scope of value addition and utilization of residual biomass from medicinal and aromatic plants, Ind. Crop. Prod. 145 (2020) 111979.

23. A. Saha, B.B. Basak, N.A. Gajbhiye, K.A. Kalariya, P. Manivel, Sustainable fertilization through co-application of biochar and chemical fertilizers improves yield, quality of Andrographis paniculata and soil health, Ind. Crop. Prod. 140 (2019) 111607.
24. K.P. Sastry, B.R.R. Rao, D.K. Rajput, C.P. Singh, K. Singh, Cultivation and Processing of Cassia Angustifolia Vahl. Tamil Nadu, Advances in Medicinal Plants, first ed., Hyderabad., 2015, pp. 123–129.
25. Y.C. Tripathi, Cassia angustifolia, a versatile medicinal crop, Int. Tree Crops J. 10 (1999) 121–129.
26. R.S. Jat, N.R. Reddy, R. Bansal, P. Manivel, Good Agricultural Practices for Senna, ICAR-Directorate of Medicinal and Aromatic Plants Research, Anand, Gujarat, 2015.
27. S. Butnan, J.L. Deenik, B. Toomsan, M.J. Antal, P. Vityakon, Biochar characteristics and application rates affecting corn growth and properties of soils contrasting in texture and mineralogy, Geoderma 237 (2015) 105–116.
28. M.S. Lashari, Y. Liu, L. Li, W. Pan, J. Fu, G. Pan, X. Yu, Effects of amendment of biochar-manure compost in conjunction with pyroligneous solution on soil quality and wheat yield of a salt-stressed cropland from Central China Great Plain, Field Crops Res. 144 (2013) 113–118.
29. Y. Lin, P. Munroe, S. Joseph, A. Ziolkowski, L. Van Zwieten, S. Kimber, J. Rust, Chemical and structural analysis of enhanced biochars: thermally treated mixtures of biochar, chicken litter, clay and minerals, Chemosphere 91 (2013) 35–40.
30. M.E. Sumner, W.P. Miller, Cation exchange capacity and exchange coefficients, Methods of Soil Analysis: Part 3 Chemical methods 5 (1996) 1201–1229.
31. M.L. Jackson, Soil Chemical Analysis, Prentice Hall of India Pvt. Ltd., New Delhi, 1973.
32. F.S. Watanabe, S.R. Olsen, Test of ascorbic acid method for determining phosphorus in water and sodium bicarbonate extracts of soils, Soil Sci. Soc. Am. Proc. 29 (1965) 677–678.
33. S.R. Olsen, C.W. Cole, F.S. Watanabe, L.A. Dean, Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate, US Department of Agriculture, Circular, 1954, p. 939.
34. J.J. Hanway, H. Heidel, Soil analysis methods as used in Iowa state college soil testing laboratory, Iowa Agric 57 (1952) 1–13.
35. IUSS Working Group WRB, World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps, fourth ed., International Union of Soil Sciences (IUSS), Vienna, Austria, 2022, p. 234.
36. L.A. Richards, Diagnosis and Improvement of Saline and Alkali Soils USDA Handbook, 1954, p. 60.
37. G.J. Bouyoucos, Hydrometer method improved for making particle size analyses of soils, Agron. J. 54 (1962) 464–465.
38. D.W. Nelson, L.E. Sommers, Total carbon, organic carbon, and organic matter, in: D. Sparks, A.L. Page, P.A. Helmke, R.A. Leoppert, P.N. Soltanpour, M.
39. A. Tabatabai, C.T. Johnston, M.E. Sumner (Eds.), Method of Soil Analysis, Part 3: Chemical Methods, Soil Science Society of America, Madison, USA, 1996,pp. 995–996.
40. D.R. Keeney, D.W. Nelson, Nitrogen-inorganic forms, in: A.L. Page, R.H. Miller, D.R. Keeney (Eds.), Methods of Soil Analysis. Part 2: Chemical and Microbiological Properties, second ed., American Society of Agronomy and Soil Science Society, Madison Wisconsin, 1982, pp. 643–698.
41. V.K. Srivastava, M.L. Maheshwari, S. Mandal, Investigation of chemical assay of sennoside in Senna (Cassia angustifolia Vahl.), Int. J. Trop. Agric. 1 (1983) 231–238.
42. D.S. Jenkinson, D.S. Powlson, The effects of biocidal treatment on metabolism in soil. I. Fumigation with chloroform, Soil Biol. Biochem. 8 (1976) 167–177.
43. D.A. Klein, T.C. Loh, R.L. Goulding, A rapid procedure to evaluate the dehydrogenase activity of soils low in organic matter, Soil Biol. Biochem. 3 (1971) 385–387.
44. M. Tejada, C. Garcia, J.L. Gonzalez, M.T. Hernandez, Use of organic amendment as a strategy for saline soil remediation: influence on the physical, chemical and biological properties of soil, Soil Biol. Biochem. 38 (2006) 1413–1421.
45. B.B. Basak, A. Saha, B. Sarkar, B.P. Kumar, N.A. Gajbhiye, A. Banerjee, Repurposing distillation waste biomass and low-value mineral resources through biochar- mineral-complex for sustainable production of high-value medicinal plants and soil quality improvement, Sci. Total Environ. 760 (2021) 143319.

46. B.B. Basak, A.R. Chinchmalatpure, A. Saha, D.H. Lodaya, P. Patel, N.A. Gajbhiye, Integrated nutrient management fostered economic yield and bioactive principle of medicinal herb (Cassia angustifolia Vahl.) in saline soil of semi-arid region of Western India, Commun. Soil Sci. Plant Anal. 54 (2023) 611–626.
47. J. Ye, R. Zhang, S. Nielsen, S.D. Joseph, D. Huang, T. Thomas, A combination of biochar–mineral complexes and compost improves soil bacterial processes, soil quality, and plant properties, Front. Microbiol. 7 (2016) 372.
48. M.D. Meena, B. Narjary, P. Sheoran, H.S. Jat, P.K. Joshi, A.R. Chinchmalatpure, Changes in physical and chemical properties of saline soil amended with municipal solid waste compost and chemical fertilizers in a mustard–pearl millet cropping system, Land Degrad. Dev. 33 (2022) 1177–1688.
49. B.B. Basak, A. Saha, N.A. Gajbhiye, P. Manivel, Potential of organic nutrient sources for improving yield and bioactive principle of ashwagandha (Withania somnifera) through enhanced soil fertility and biological functions, Commun. Soil Sci. Plant Anal. 51 (2020) 779–793.
50. B.B. Basak, Soil phosphorus dynamics and P uptake by medicinal crops as influenced by locally available organic amendments in light-textured soil of semi-arid western India, J. Soil Sci. Plant Nutr. 23 (2023) 2190–2201.
51. S. Joseph, H.M. Anawar, P. Storer, P. Blackwell, C. Chia, Y. Lin, P. Munroe, S. Donne, J. Horvat, J. Wang, Z.M. Solaiman, Effects of enriched biochars containing magnetic iron nanoparticles on mycorrhizal colonisation, plant growth, nutrient uptake and soil quality improvement, Pedosphere 25 (2015) 749–760.
52. Z. Zang, Q. Yang, J. Liang, Y. Yang, N. Li, H. Wang, J. Guo, L. Yang, Alternate micro-sprinkler irrigation and organic fertilization decreases root rot and promotes root growth of Panax notoginseng by improving soil environment and microbial structure in rhizosphere soil, Ind. Crop. Prod. 202 (2023) 117091.
53. X. Yue, Q. Yang, J. Liang, J. Tang, Y. Yang, Alternate micro-sprinkler irrigation synergized with organic fertilizer: a sustainable water-fertilizer management technology of improving quality and increasing efficiency in Panax notoginseng production, Ind. Crop. Prod. 194 (2023) 116335.
54. S. Nielsen, T. Minchin, S. Kimber, L. van Zwieten, J. Gilbert, P. Munroe, S. Joseph, T. Thomas, Comparative analysis of the microbial communities in agricultural soil amended with enhanced biochars or traditional fertilisers, Agric. Ecosyst. Environ. 191 (2014) 73–82.
55. P. Nannipieri, C. Trasar-Cepeda, R.P. Dick, Soil enzyme activity: a brief history and biochemistry as a basis for appropriate interpretations and meta-analysis, Biol. Fertil. Soils 54 (2018) 11–19.
56. X. Liu, Y. Zhang, Z. Jiang, X. Yue, J. Liang, Q. Yang, J. Li, N. Li, Micro-moistening irrigation combined with bio-organic fertilizer: an adaptive irrigation and fertilization strategy to improve soil environment, edible Rose yield, and nutritional quality, Ind. Crop. Prod. 196 (2023) 116487.
57. A. Gunes, A. Inal, M.B. Taskin, O. Sahin, E.C. Kaya, A.R.D. A Atakol, Effect of phosphorus enriched biochar and poultry manure on growth and mineral composition of lettuce (Lactuca sativa L. cv.) grown in alkaline soil, Soil Use Manag. 30 (2014) 182–188.
58. O. Trisilawati, B. Hartoyo, N. Bermawie, E.R. Pribadi, Application of AMF (Arbuscular Mycorrhizal Fungi) and organic fertilizer to increase the growth, biomass and bioactive content of centella, in: IOP Conference Series, Earth Environ. Sci., 2019 012067, 292.
59. S.M. Mohammadi, F. Sefidkon, S. Asadi-Sanam, S. Kalatejari, The changes of carvacrol content and essential oil yield of Satureja khuzestanica Jamzad in response to different fertilizer sources, Flavour Fragrance J. 38 (2023) 37–48.
60. C. Díaz-Guti´errez, A. Hurtado, A. Ortíz, C. Poschenrieder, C. Arroyave, C. Pel´aez, Increase in steviol glycosides production from Stevia rebaudiana Bertoni under organo-mineral fertilization, Ind. Crop. Prod. 147 (2020) 112220.
61. Z. Zhu, Z. Liang, R. Han, X. Wang, Impact of fertilization on drought response in the medicinal herb Bupleurum chinense DC.: growth and saikosaponin production, Ind. Crop. Prod. 29 (2009) 629–633.
62. M. Dashti, M. Kafi, M. Mirza, Chemical variation in the essential oil of salvia leriifolia benth. In response to organic and biological fertilizers, J. Med. plants By- prod 11 (2022) 93–101.