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Evaluation of Vermicompost, Seaweed, and Algal Fertilizers on Soil Fertility and Plant Production of Sunn Hemp

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Abstract: Regenerative agriculture increasingly relies on organic soil amendments to improve soil fertility and crop productivity. This study evaluates the effects of dried algae (DA), vermicompost (VC), liquid hydrolyzed fish and seaweed fertilizer (LA), and a control (S0, untreated soil without amendments) on the soil fertility, growth, nutrient uptake, and physiology of sunn hemp (*Crotalaria juncea* L.), a key cover crop for soil improvement. Treatments were applied at 1 ton/ha (DA), 3 ton/ha (VC), and 8 mL/L (LA). Plants were grown for 10 weeks, during which plant growth, chlorophyll content, and biomass were measured. Soil and plant samples were analyzed for macro- and micronutrients. S0 and DA treatments produced the highest biomass, with S0 showing the highest total carbon and organic matter content. LA-treated soils exhibited elevated phosphorus, potassium, and sodium levels, while DA and S0 shoots had significantly higher sulfur and zinc concentrations. LA treatment notably increased chlorophyll content by the study's end. Overall, DA demonstrated strong potential as a nutrient-rich organic amendment, while S0 provided a robust baseline for biomass production. VC enriched phosphorus and potassium but resulted in the lowest total biomass. LA promoted shoot growth and chlorophyll content but required root development and sodium management optimization. These findings highlight the need to align the amendment choice with soil characteristics and environmental conditions to optimize crop productivity and soil health in sustainable farming systems.

Keywords: harmful algal blooms; chlorophyll; cover crop; regenerative agriculture; biofertilizer

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1. Introduction

The growing demand for sustainable agricultural practices has spurred the adoption of organic soil amendments that enhance soil fertility, improve crop productivity, and promote ecological balance [1,2]. Among these practices, algal-based fertilizers, vermicompost (VC), and other natural inputs have gained popularity for enhancing soil health parameters, such as aggregate stability, nutrient cycling, and microbial activity, which are critical for long-term agricultural sustainability [3–5].

Harmful algal blooms (HABs) are a significant environmental challenge caused by nutrient pollution in water bodies, resulting in the proliferation of cyanobacteria and algae that release toxins harmful to marine life, ecosystems, and human health. Although HABs are often viewed as an environmental hazard, recent studies have explored their potential to be repurposed into biofertilizers [6,7]. These studies highlight the nutrient richness of HAB-derived fertilizers, including nitrogen, phosphorus, and potassium, as well as bioactive compounds like phytohormones that can improve soil microbial activity and nutrient availability. However, comparative research on HAB-derived fertilizers versus other organic amendments, such as VC, remains scarce, particularly regarding their effectiveness in enhancing soil health and crop productivity.

Sunn hemp (*Crotalaria juncea* L.), a warm-season leguminous cover crop, is valued for improving soil characteristics, reducing soil erosion, conserving soil moisture, and suppressing nematodes [8]. It is used in Florida, particularly in organic farming systems, where it enhances soil fertility and provides green manure [9]. While previous research has investigated individual organic amendments, this study is novel in its systematic comparison of HAB-derived fertilizers, liquid algae fertilizers, and vermicompost on sunn hemp, providing evidence of their relative efficacy. By integrating sunn hemp with these amendments, this research contributes to understanding how nutrient cycling and soil carbon sequestration can be optimized for sustainable farming practices.

The objectives of this study were to (1) assess the specific effects of dried algae (DA) derived from HABs, VC, and liquid algae fertilizer (LA) on crucial soil health indicators, such as total carbon, organic matter, and nutrient availability; (2) evaluate their impact on the growth parameters and nutrient uptake of sunn hemp; and (3) compare the effectiveness of these treatments in improving soil fertility and plant performance. By focusing on these objectives, this research hypothesizes that each amendment will have distinct impacts on soil fertility and crop performance, with algal-based fertilizers (DA and LA) providing unique benefits due to their high nutrient content and bioactive compounds. Specifically, DA is expected to enhance nitrogen and organic matter levels, while VC will promote phosphorus and micronutrient availability. The control treatment (S0) serves as a baseline to evaluate the relative effects of these amendments. This research aims to provide actionable knowledge into using bio-based amendments for sustainable agricultural systems by addressing these hypotheses. Ultimately, this study seeks to advance organic farming by offering practical recommendations on selecting and managing organic amendments for diverse environmental and crop conditions.

2. Methodology

2.1. Experimental Design

In mid-July 2023, four raised beds, each measuring 15 feet (4.57 m) in length, 3 feet (0.91 m) in width, and 1 foot (0.30 m) in height, were prepared for planting sunn hemp (*Crotalaria juncea* L.) in the Organic Garden of the Agroecology Program at Florida International University using potting mix (RGS Nursery, Miami, FL, USA), which also served as the background soil [10]. Each raised bed was divided into three equal sections measuring 5 feet (1.52 m) in length by 3 feet (0.91 m) in width, allowing three replicates of each treatment to be distributed evenly across the beds. The seeds were sourced from Whitetail Institute (Pintlala, AL, USA). The experiment was designed with four different treatments in triplicate as follows: S0, control with no inorganic or biofertilizer amendments; DA, 1 ton/ha rate of dried algae (*Microcystis aeruginosa*) collected from Lake Okeechobee and applied during planting; VC, 3 ton/ha (3.36 metric tons/ha) rate of vermicompost (based on dry mass, prepared from mushroom residues from a mushroom-growing facility at Lions Fruit Farm, Miami, FL, USA) and applied during planting; LA, commercially available liquid hydrolyzed fish and seaweed algae fertilizer (Neptune's Harvest 2-3-1. 8 mL/L of water) (Gloucester, MA, USA) applied weekly from week 3 until week 6. The DA, VC, and LA application rates were determined based on preliminary assessments conducted during the study design phase to simulate practical farming scenarios and ensure sufficient nutrient input for comparative analysis. The specific composition of each amendment is described in Section 3.1.

The amendments were applied by spreading them evenly over the top of the soil and mixing them within a 2–7 cm depth using a hand rake to ensure even distribution. Liquid algae fertilizer was diluted with water and applied directly to the soil surface weekly from week 3 to week 6. Irrigation was performed once every morning using a sprinkler system, except when rainfall occurred, as the experiment was conducted during the summer. Daily rainfall was monitored using a rain gauge placed in the experimental area, and irrigation was adjusted accordingly.

2.2. Plant Growth Measurements

Plant growth for all replicates was measured weekly for 7 weeks from week 4 to week 10 after sowing by measuring plant height, and leaf chlorophyll content was measured for 5 weeks. The chlorophyll content was measured using a Soil-Plant Analysis Development (SPAD 502 plus) Chlorophyll meter (Spectrum Technologies Inc., Aurora, IL, USA).

2.3. Plant and Soil Sampling and Chemical Analysis

At the end of 10 weeks, the sunn hemp plants (including shoots and roots) were harvested and determined for plant biomass, and the samples were processed for chemical analysis. Soil samples from the beds were collected before and after planting to establish baseline soil characteristics. Post-harvest, soil samples were collected at surface depth (0–10 cm) and subsurface depth (10–20 cm), air-dried, ground, sieved through a 2-mm sieve, and stored at room temperature (18–20 °C) until analysis. These soil samples were analyzed for pH, N, P, K, Ca, Mg, Zn, Na, C, organic matter content, and cation exchange capacity (CEC). The pH was determined in 0.01 M $CaCl_2$ with a soil-to-water ratio of 1:2 after 30 min of equilibration. Organic matter content was assessed using the loss on ignition method by measuring the weight loss after ignition between the oven-dry soil mass and the post-combustion soil mass, divided by the oven-dry soil mass. Carbon and nitrogen contents were analyzed using a C/N Analyzer (Truspec, LECO Corporation, St. Joseph, MI, USA). Elemental concentrations of P, K, Ca, Mg, Zn, and Na were determined using inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7900, Santa Clara, CA, USA). Exchangeable cations were extracted using an unbuffered 1 M NH_4Cl solution, with the cation exchange capacity calculated as the sum of charge equivalents of exchangeable K, Ca, Mg, Zn, Na, and H.

Chemical analysis of plant shoots and roots included a broader range of elements, including N P, K, Ca, Mg, Zn, Na, S, B, Fe, Mn, and Cu, using ICP-MS.

2.4. Statistical Analysis

The data collected were statistically analyzed using Minitab software (version 21). One-way analysis of variance (ANOVA) [11] was conducted on all parameters at a 95% confidence level. Tukey's post hoc test [12] was employed to perform multiple comparisons when the ANOVA results indicated significant differences between treatment groups. The statistical analysis was based on triplicate experimental units (n = 12 in total). Assumptions of normality and homoscedasticity were tested before conducting ANOVA using the Shapiro–Wilk test [13] and Levene's test [14], respectively. If the assumptions were violated, appropriate transformations or nonparametric tests were applied to the data.

3. Results

3.1. Nutrient Content of the Biofertilizers and Background Soil

There was significant variation in the chemical composition of DA, VC, initial background soil [10], and the soil used before the experiment (Table 1). DA exhibited the highest concentrations for all the macro- and micronutrient concentrations except for P and K and had the lowest C/N ratio compared to the rest of the nutrients (Table 1). Furthermore, DA has notably high Na content, which is over 10 times higher than that of VC and over 25 times that of BS, and VC stood out for its relatively high Zn content, which exceeded that of DA and BS. LA, a commercial product, had a percentage nutrient content of 2-3-1 for N-P-K, respectively, which is significantly higher than the rest of the organic amendments.

Table 1. The elemental concentration of dry algae (DA), vermicompost (VC), and background soil [10] was based on the dry mass used in the experiment before planting sunn hemp.

Treatment	C/N (±SD)	TC (%) (±SD)	TN (%) (±SD)	P (%) (±SD)	K (%) (±SD)	Ca (ppm) (±SD)	Mg (ppm) (±SD)	Zn (ppm) (±SD)	Na (ppm) (±SD)	OM (%) (±SD)	CEC (meq/100 g) (±SD)
BS	20.1 ± 1.87 a	14.2 ± 3.13 c	0.7 ± 0.25 c	0.020 ± 0.014 b	0.06 ± 0.018 c	2636 ± 1.22 b	677 ± 4.77 c	12.23 ± 0.96 b	112 ± 2.48 c	25.21 ± 0.88 c	20.45 ± 0.42 c
DA	9.6 ± 0.52 c	25.2 ± 2.93 a	2.6 ± 0.13 a	0.004 ± 0.0012 b	0.15 ± 0.031 b	8156 ± 3.81 a	2650 ± 0.96 a	8.24 ± 1.07 b	2938 ± 3.42 a	44.80 ± 0.99 a	77.40 ± 1.04 a
VC	15.1 ± 2.12 b	23.0 ± 4.42 b	1.5 ± 0.36 b	0.015 ± 0.013 a	0.24 ± 0.051 a	1203 ± 4.84 c	1276 ± 2.77 b	35.84 ± 0.83 a	267 ± 0.92 b	40.94 ± 1.15 b	59.20 ± 0.93 b

Note: TC: Total Carbon, TN: Total Nitrogen, OM: Organic Matter, CEC: Cation Exchange Capacity. Means followed by a different letter are significantly different at the 0.05 probability level, grouped into classes a, b, and c.

3.2. Soil Chemical Analysis

The soil chemical analysis showed significant differences in the nutrient content among the four treatments in the surface layer (0–10 cm), while no significant differences were observed in the subsurface layer (10–20 cm) (Table 2). TC, Na, and organic matter showed marked variability across treatments in the surface soils. The S0 treatment exhibited the highest TC in the surface soils, significantly surpassing LA. At the same time, LA had significantly higher Na content than S0, and OM content was significantly higher in S0 than LA. Comparing nutrient content between surface and subsurface soils, the results showed that the nutrient content in surface soils was not statistically different from that in subsurface soils.

Table 2. The macro and micronutrient concentrations and physicochemical characteristics of surface (0–10 cm) and sub-surface (10–20 cm) soils.

Treatment	pH (±SD)	C/N (±SD)	TC (%) (±SD)	TN (%) (±SD)	P (ppm) (±SD)	K (ppm) (±SD)	Ca (ppm) (±SD)	Mg (ppm) (±SD)	Zn (ppm) (±SD)	Na (ppm) (±SD)	OM (%) (±SD)	CEC (meq/100 g) (±SD)
Surface soils (0–10 cm)												
S0	7.8 ± 0.20	18.9 ± 4.50	19.3 ± 0.67 a	1.02 ± 0.11	206 ± 2.38	81.4 ± 4.63	2820 ± 3.55	592 ± 4.09	12.0 ± 2.53	31.6 ± 4.87 b	34.4 ± 0.50 a	38.0 ± 1.20
DA	7.7 ± 0.30	19.0 ± 3.80	19.1 ± 2.45 ab	1.01 ± 0.19	207 ± 3.29	82.6 ± 3.89	7978 ± 4.10	606 ± 4.75	12.3 ± 3.12	32.8 ± 2.91 ab	34.1 ± 2.32 ab	45.2 ± 0.95
VC	7.8 ± 0.15	18.6 ± 4.02	18.9 ± 0.88 ab	1.02 ± 0.22	221 ± 4.00	72.6 ± 3.44	2860 ± 4.87	545 ± 3.66	11.8 ± 2.25	42.6 ± 4.55 ab	33.6 ± 1.44 ab	19.0 ± 2.64
LA	7.8 ± 0.12	17.8 ± 1.45	15.2 ± 1.89 b	0.86 ± 0.26	244 ± 3.87	88.5 ± 3.71	3176 ± 3.21	720 ± 4.99	14.1 ± 4.87	53.8 ± 3.99 a	27.1 ± 0.76 b	41.4 ± 3.11
SubsurfaceSoils(10–20 cm)												
S0	7.8 ± 0.1	19.6 ± 3.85	15.8 ± 2.45	0.82 ± 0.13	185 ± 4.55	65.0 ± 4.40	2696 ± 4.23	651 ± 4.01	11.0 ± 3.78	36.3 ± 2.67	28.1 ± 2.89	37.9 ± 1.20
DA	7.4 ± 0.3	20.9 ± 2.88	16.5 ± 1.44	0.79 ± 0.25	143 ± 3.78	50.8 ± 3.99	2853 ± 4.44	550 ± 4.00	9.3 ± 3.45	39.9 ± 4.33	29.4 ± 0.78	39.3 ± 1.33
VC	7.8 ± 0.2	22.8 ± 3.32	14.7 ± 3.29	0.66 ± 0.20	127 ± 4.34	57.5 ± 4.22	2556 ± 3.12	489 ± 2.75	8.7 ± 3.87	55.2 ± 4.88	26.3 ± 3.11	17.0 ± 2.88
LA	7.8 ± 0.2	18.4 ± 2.67	16.6 ± 2.18	0.91 ± 0.27	179 ± 3.55	69.2 ± 3.45	2801 ± 3.99	575 ± 4.67	11.3 ± 4.33	49.7 ± 2.89	29.5 ± 0.98	59.1 ± 3.44

Note: TC: Total Carbon, TN: Total Nitrogen, OM: Organic Matter, CEC: Cation Exchange Capacity. Means followed by a different letter are significantly different at the 0.05 probability level, grouped into classes a, ab, and b.

The ratio of the nutrient content of the four treatments and background soil was compared in Table 3 to understand which of the treatments resulted in increased nutrients in the soil since the purpose of the sunn hemp and the applied treatments was to understand which of the treatments increased nutrient content of the background soil. Although insignificant, the results show that all four treatments increased the soil's N, P, Ca, OM, and CEC concentrations except for P content in S0 and DA. However, the LA-treated soils had noticeably lower TC (1.07) and OM (1.07) ratios compared to the other treatments, along with slightly reduced TN (1.23). The Zn concentrations were higher in DA and LA treatments than in BS, showing an increase in the Zn content compared to other treatments (Table 3).

Table 3. Ratio comparison of the nutrient content in the four treatments with the background soil.

Ratio	C/N	TC	TN	P	K	Ca	Mg	Zn	Na	OM	CEC
S0/BS	0.94	1.36	1.46	1.03	0.14	1.07	0.87	0.98	0.28	1.36	1.86
DA/BS	0.95	1.35	1.44	1.03	0.14	3.03	0.90	1.01	0.29	1.35	2.21
VC/BS	0.93	1.33	1.46	1.11	0.12	1.08	0.81	0.96	0.38	1.33	0.93
LA/BS	0.89	1.07	1.23	1.22	0.15	1.20	1.06	1.15	0.48	1.07	2.02

Note: TC: Total Carbon, TN: Total Nitrogen, OM: Organic Matter, CEC: Cation Exchange Capacity.

3.3. Shoot and Root Chemical Analysis

The chemical analysis of sunn hemp shoot samples revealed significant differences in S, Na, and Zn contents, while only the Cu content was significantly different in the roots. In the leaf samples, the LA treatment exhibited significantly lower S concentrations than S0, DA, and VC, while Na levels were notably lower in DA than S0 (Table 4). Similarly, the Zn content was significantly lower in LA compared to S0 and DA. DA and S0 treatments generally promoted higher accumulation of most nutrients, while LA was associated with lower concentrations of key elements like S, Na, and Zn. The Cu content was significantly lower in VC compared to LA (Table 4).

Table 4. Plant tissue nutrient contents.

Treatment	N (%) (±SD)	P (%) (±SD)	K (%) (±SD)	Ca (%) (±SD)	Mg (%) (±SD)	S (%) (±SD)	Na (%) (±SD)	B (ppm) (±SD)	Fe (ppm) (±SD)	Mn (ppm) (±SD)	Zn (ppm) (±SD)	Cu (ppm) (±SD)
Shoots												
S0	3.68 ± 1.52	0.36 ± 0.19	0.96 ± 0.55	4.47 ± 0.88	0.84 ± 0.29	0.25 ± 0.06 a	0.02 ± 0.02 a	49.75 ± 2.77	148 ± 4.55	29.8 ± 3.87	43.0 ± 0.99 a	10.9 ± 3.45
DA	3.78 ± 2.45	0.34 ± 0.12	1.00 ± 0.22	5.33 ± 1.15	0.72 ± 0.29	0.22 ± 0.04 a	0.01 ± 0.008 b	55.66 ± 1.09	132 ± 3.98	26.1 ± 2.56	41.3 ± 1.44 a	9.7 ± 2.11
VC	1.58 ± 1.89	0.35 ± 0.12	1.08 ± 0.48	4.92 ± 0.99	0.78 ± 0.17	0.22 ± 0.08 a	0.01 ± 0.007 ab	47.66 ± 4.32	142 ± 2.15	32.1 ± 2.99	38.8 ± 2.03 ab	11.1 ± 3.67
LA	3.63 ± 0.78	0.30 ± 0.11	0.78 ± 0.35	5.10 ± 0.33	0.85 ± 0.21	0.18 ± 0.07 b	0.01 ± 0.006 ab	50.35 ± 3.18	120 ± 3.33	27.8 ± 3.55	34.4 ± 3.87 b	8.1 ± 2.33
Roots												
S0	1.01 ± 0.77	0.10 ± 0.03	0.97 ± 0.41	0.63 ± 0.12	0.24 ± 0.17	0.09 ± 0.005	0.42 ± 0.15	12.59 ± 2.44	252 ± 3.45	14.86 ± 1.78	28.94 ± 2.55	6.0 ± 3.11 ab
DA	1.13 ± 0.99	0.12 ± 0.09	1.22 ± 0.55	0.78 ± 0.21	0.25 ± 0.13	0.10 ± 0.04	0.37 ± 0.09	12.15 ± 1.98	289 ± 2.55	15.91 ± 2.11	29.78 ± 2.33	6.8 ± 3.77 ab
VC	1.13 ± 0.21	0.10 ± 0.02	0.87 ± 0.27	0.72 ± 0.18	0.23 ± 0.05	0.09 ± 0.03	0.42 ± 0.18	11.08 ± 3.33	227 ± 2.77	14.62 ± 3.33	25.20 ± 3.15	5.2 ± 2.89 b
LA	1.18 ± 0.33	0.11 ± 0.05	1.29 ± 0.68	0.74 ± 0.34	0.21 ± 0.05	0.10 ± 0.03	0.26 ± 0.10	12.09 ± 1.55	288 ± 4.00	16.32 ± 2.55	28.56 ± 3.99	7.3 ± 3.55 a

Means followed by a different letter are significantly different at the 0.05 probability level, grouped into classes a, ab, and b.

When comparing the nutrient content in shoots and roots, the results show that the nutrient content is higher in the shoots than in the roots except for K, Na, and Fe (Table 4), which were higher in the roots than in the shoots. However, VC-treated plants had significantly higher K and Cu contents in shoots than roots. In addition, although nutrients were translocated from the soil to the roots, it is noticeable that the K and Na contents in the roots (Table 4) are more than 120 and 48 times the concentrations in the surface soils (Table 2), respectively.

3.4. Plant Height Measurements

Plant height consistently increased across all treatments from week 4 to week 9 (Figure 1). VC-treated plants generally exhibited the lowest height among all the treatments during the middle weeks (5 through 8). The weekly height measurements did not reveal significant differences between treatments. However, the height measurements for all treatments between weeks were significantly different except between weeks 8 and 9 (Figure 1), where only VC showed substantial differences. All the treatments influence sunn hemp height at the same rate each week.

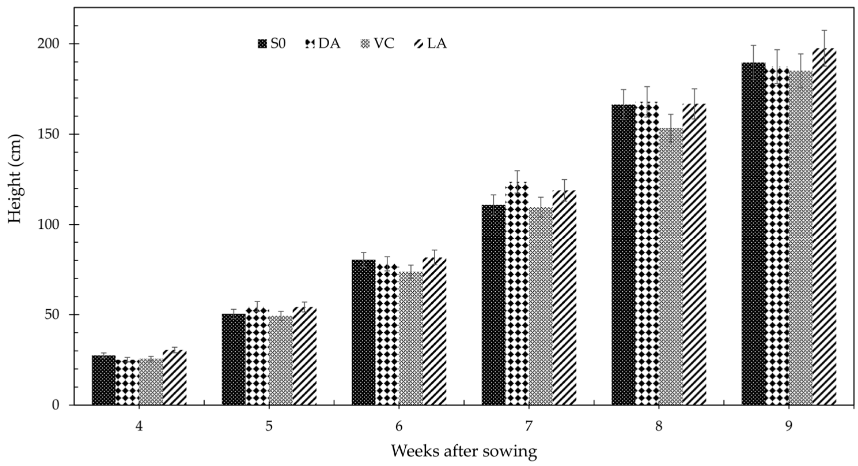

Figure 1. The effect of the various treatments on plant height during the growth period after sowing. Error bars indicate standard error; no statistically significant differences were observed between treatments.

3.5. Leaf Relative Chlorophyll Content

The SPAD chlorophyll meter readings showed a general increase across all treatments over the study period, with DA-treated plants reaching a plateau after week 8. Among the treatments, LA-treated plants showed the most substantial SPAD readings by week 10, peaking at 53.9, while S0, DA, and VC also showed progressive increases, with maximum readings of 46.76, 48.52, and 47.49, respectively (Figure 2). LA-treated plants achieved the highest SPAD readings in the final weeks (9 and 10), whereas VC led in weeks 5 and 6 (Figure 2). Conversely, VC-treated plants recorded the lowest readings in weeks 4, 8, and 9, with LA-treated plants showing the lowest in weeks 5 and 6. Although no significant differences were observed between treatments each week, within-treatment comparisons revealed substantial trends. For S0, SPAD readings in weeks 4 to 6 were significantly lower compared to weeks 9 and 10 (Figure 2). Similarly, the DA-treated plant's SPAD readings in the earlier weeks (4 to 6) were significantly lower than in weeks 8 to 10 (Figure 2). VC-treated plants followed a similar pattern, with readings in weeks 4 to 6 significantly lower than in week 10. The LA-treated plants, while showing lower readings earlier in the study (weeks 4 to 9), experienced a significant increase by week 10 (Figure 2).

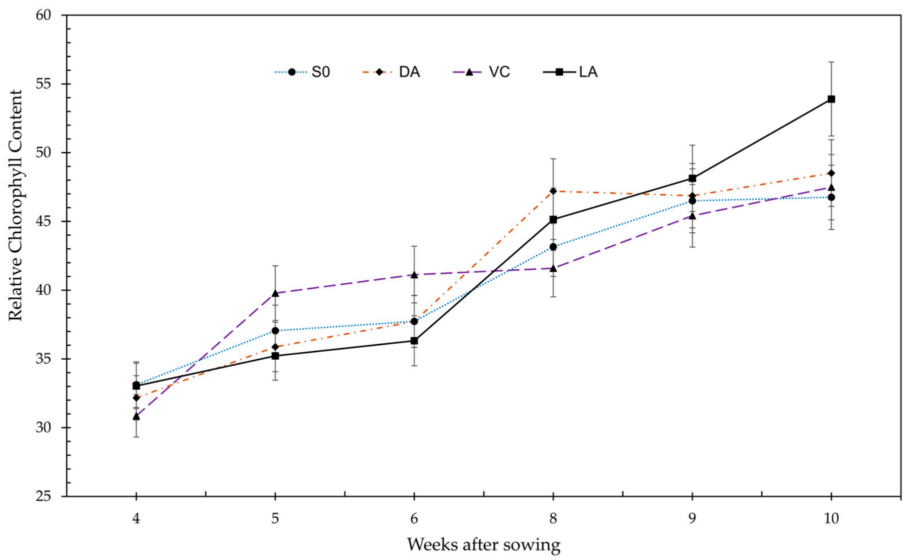

Figure 2. Variation in relative chlorophyll content with time after sowing across treatments. Error bars indicate standard error; no statistically significant differences were observed between treatments.

3.6. Plant Biomass

The dry biomass measurements showed significant differences among the various treatments. S0- and DA-treated plants produced the same and the highest biomass of 4.83 tons/acre (Table 5). While total biomass was similar, the distribution between shoots and roots differed across treatments, with S0 showing the highest root biomass and DA exhibiting slightly lower root biomass. Shoots biomass in S0 was comparable to VC and LA but significantly higher than in DA.

Table 5. Total biomass, shoots, and roots of sunn hemp under different treatments. Values represent mean ± standard deviation.

Treatment	Total Biomass (Ton/Acre)	Shoots (Ton/Acre)	Roots (Ton/Acre)	Shoot/Root
S0	4.83 ± 0.48 a	0.44 ± 0.03 ab	2.94 ± 0.03 a	0.15 c
DA	4.83 ± 0.40 a	0.36 ± 0.04 b	2.28 ± 0.04 b	0.16 c
VC	2.27 ± 0.19 b	0.48 ± 0.03 a	1.11 ± 0.04 d	0.25 b
LA	4.06 ± 0.35 b	0.42 ± 0.03 ab	1.68 ± 0.03 c	0.43 a

Means followed by different letters within each column are significantly different at a 95% confidence level.

LA-treated plants followed with a moderate biomass of 4.06 tons/acre, significantly lower than S0- and DA-treated plants but higher than VC-treated plants. VC-treated plants exhibited the lowest biomass at 2.27 tons/acre, considerably lower than all other treatments. The shoot-to-root ratio for LA-treated plants was notably higher at 0.43 (Table 5), reflecting a greater emphasis on shoot growth than root development.

4. Discussion

4.1. Nutrient Composition of the Biofertilizers and Background Soil

The DA exhibited the highest concentrations in most nutrient concentrations, indicating its potential as a rich nutrient source (Table 1). However, its low P and K contents compared to other treatments suggest it may not be the best option for boosting these specific nutrients in the soil. This is consistent with a similar study using freshwater algae [15]. The DA also had a notably high Na content, which was more than 10 times higher than that in VC and over 25 times higher than in BS. The high sodium content in DA is likely due to its origin from harmful algal blooms, as algae and cyanobacteria in these blooms can accumulate sodium from saline or brackish water environments [16,17]. While sodium can promote osmotic balance in small amounts, excessive levels may lead to soil salinization, potentially affecting soil structure and microbial activity [10,18,19]. Prolonged use of sodium-rich fertilizers like DA may necessitate leaching or crop rotation with salt-tolerant species to mitigate salinity risks.

The high sodium levels in the DA treatment present potential risks for soil salinization, particularly in arid or semi-arid regions where leaching is limited. Excessive sodium can disrupt soil structure by causing clay particle dispersion, thereby reducing water infiltration and root penetration [20]. In contrast, sodium may be leached from the root zone in regions with adequate rainfall, minimizing its impact [21,22]. Farmers could use DA in combination with low-sodium organic amendments, such as vermicompost, to mitigate salinity risks or apply it at reduced rates to avoid cumulative sodium buildup over multiple growing seasons. Integrating salt-tolerant crops into the rotation could alleviate salinity concerns [23].

The VC showed relatively high P, K, and Zn contents, exceeding both DA and BS. This suggests that vermicompost could be particularly beneficial for increasing these nutrients in the soil, supporting healthy plant growth [24]. The BS had a pH of 7.9, indicating a slightly alkaline soil environment. The C/N ratio was highest for BS, suggesting a relatively low nitrogen content relative to carbon, which could affect microbial activity and nutrient cycling.

4.2. Soil Chemical Analysis

The control treatment (S0) exhibited the highest total carbon content in the surface soil, significantly surpassing the LA treatment (Table 2). This result suggests that the higher TC in S0 may be attributed to below-ground carbon allocation through photosynthates, as plants in nutrient-deficient conditions often increase carbon allocation to the root zone for growth and nutrient acquisition. In contrast, the higher nutrient availability in the LA treatment may have reduced the need for below-ground carbon allocation, thereby contributing to the lower OM and TC observed in the LA-treated soil.

The absence of amendments may have preserved the existing soil carbon better than treatments involving additional inputs like liquid algae. The higher TC in S0 might be due to less disturbance and decomposition of organic material compared to other treatments. This agrees with other findings [9,15,25]. Additionally, the lack of amendments in S0 may have minimized microbial decomposition of organic material, allowing for greater organic matter retention.

The higher Na content in the LA treatment is likely a direct result of the high Na content in the liquid algae fertilizer (Neptune's Harvest 2-3-1), applied weekly from week 3 to week 6. The elevated Na levels in LA-treated soil could affect soil salinity, potentially affecting plant growth and soil structure if not appropriately managed. While LA provided a nutrient-rich environment, its liquid formulation might have favored rapid nutrient uptake by plants at the expense of carbon storage in the soil, explaining the lower OM and TC values compared to S0.

The significantly higher organic matter content in the S0 treatment compared to LA could be attributed to the fact that S0 did not receive any external amendments, thus preserving the existing organic matter [26]. The absence of amendments in the S0 treatment likely minimized microbial decomposition of organic material, which could explain its higher organic matter retention. In contrast, introducing liquid algae in the LA treatment might have altered microbial activity, leading to faster decomposition of organic matter and reduced total carbon levels [27]. The LA treatment's higher sodium content may have influenced soil chemical dynamics by altering cation exchange processes. In the subsurface soil, the lack of significant differences observed in nutrient content suggests that the impact of the treatments was primarily confined to the topsoil, with minimal effect on deeper soil layers.

To better understand the effects of the different treatments on soil nutrient content, the ratios of the nutrient contents of the four treatments to the baseline soil (background soil) were calculated (Table 3). This analysis revealed that while all treatments enhanced soil nutrient levels to some extent, the effects varied across nutrients and treatments. For example, the DA treatment demonstrated a notable increase in nitrogen content compared to the baseline soil, which can be attributed to its high nitrogen concentration. In contrast, the LA treatment contributed to elevated potassium levels, reflecting its nutrient composition. However, the improvements were not uniform across all nutrients, indicating that specific amendments have targeted nutrient benefits.

These findings suggest that the modest overall changes in nutrient levels may result from nutrient uptake by sunn hemp plants during the growth period, which likely reduced the residual soil nutrient concentrations. Additionally, nutrient leaching and microbial activity may have influenced nutrient availability and distribution [28]. This shows the dynamic interaction among soil amendments, plant nutrient uptake, and soil processes. Understanding these interactions is crucial for developing tailored amendment strategies to achieve more consistent and significant improvements in soil fertility.

While this study primarily focused on soil nutrient content and crop performance, understanding how these organic amendments influence microbial activity is critical for assessing long-term soil health. Microbial biomass and enzyme activity, which are vital indicators of microbial function, could give more insights into the effects of these amendments. For example, dried algae (DA), with its high organic matter content, may stimulate microbial populations, whereas its high sodium levels could inhibit specific microbial communities. Future studies should integrate microbial activity assessments to understand these dynamics better.

4.3. Shoot and Root Chemical Analysis

The LA-treated plants exhibited significantly lower S levels in the shoots compared to the other treatments. It suggests that the liquid algae fertilizer, despite its nutrient-rich composition, might not have effectively supplied or facilitated the uptake of sulfur by the plants. As seen in Table 5, the root biomass of LA-treated plants (1.68 ± 0.03 ton/acre) was lower than that of S0 (2.94 ± 0.03 ton/acre) and DA (2.28 ± 0.04 ton/acre). This reduction in root biomass aligns with the expectation that the higher nutrient supply in LA-treated soils, particularly NPK, reduced the plant's need to allocate carbon resources to root growth. Consequently, the smaller root system may have limited the plant's ability to take up other nutrients, such as S and Zn, which are less critical for immediate plant growth than macronutrients.

Sodium levels were notably lower in the shoots of all plants treated even when Na was high in the DA; VC treatments showed that much of Na remained in the soil and was not taken up by the plants, showing that sunn hemp has a high ability to regulate Na uptake [20,29]. The LA treatment was associated with significantly lower Zn content in the shoots than S0 and DA. This finding indicates that the bioavailability of Zn in the LA-treated soils was lower than in the soils treated with DA or in the untreated control. In contrast, the DA and S0 treatments supported higher Zn accumulation, possibly due to better nutrient availability or enhanced plant absorption mechanisms. The observed increase in Ca in the S0 treatment can be explained by the calcareous nature of the soils in the raised beds, to which the background soil (potting mix) was added [30]. Although no external Ca amendments were applied, blending the potting mix with the calcareous soils likely contributed to the observed increase in Ca content.

The analysis of sunn hemp roots also showed that the VC treatment resulted in significantly lower Cu content in the roots compared to the LA treatment. This could be due to the nature of the vermicompost, which might have led to a more balanced nutrient environment, reducing the excessive uptake of Cu by the plants [31,32]. In contrast, the LA treatment might have altered the soil chemistry to increase the availability or uptake of copper in the root zone.

When comparing nutrient content between the shoots and roots, the analysis revealed that most nutrients were more concentrated in the shoots than in the roots. However, the roots showed higher K concentrations than the shoots, indicating the accumulation of this essential macronutrient in roots. Notably, the VC treatment resulted in significantly higher K content in the shoots than in the roots, suggesting that vermicompost might have enhanced the translocation of K from roots to shoots. These findings agree with other studies [33,34].

The data in Table 5 indicate distinct patterns in shoot-to-root ratios across treatments. The LA treatment exhibited the highest shoot-to-root ratio (0.43), suggesting nutrient-rich conditions in LA-treated soils favored above-ground biomass production while suppressing root growth. Conversely, S0 and DA showed lower shoot-to-root ratios (0.15 and 0.16, respectively), suggesting more significant root investment in these treatments to support nutrient uptake under nutrient-limited conditions. These differences in biomass allocation patterns further explain the variability in nutrient uptake across treatments, particularly for secondary nutrients like S and Zn.

The lower TC and OM contents observed in LA-treated soils than in DA or VC-treated soils highlight the importance of amendment formulation and composition. While LA provides immediate nutrient availability through its liquid formulation, its lower contribution to soil carbon and organic matter underscores the need for complementary amendments to balance long-term soil health and nutrient cycling.

The Na and Fe contents were also more concentrated in the roots, highlighting the plant's ability to sequester these elements in the root zone, possibly as a protective mechanism against toxicity or as part of nutrient storage. The Na content in the roots was more than 48 times the concentration in the surface soils, demonstrating the plant's capacity to absorb and retain Na, even when soil levels are relatively low. The findings also indicated significant translocation of nutrients from the soil to the roots. The observed K and Na content in the roots were substantially higher at more than 120 and 48 times, respectively, than the concentrations found in the surface soils. This highlights the effectiveness of the sunn hemp plants in absorbing and concentrating these nutrients from the soil, even when the initial soil levels were relatively low.

4.4. Variation of Plant Height

The consistent increase in sunn hemp height from week 4 to week 9 across all treatments aligns with the experimental setup where different treatments were applied to assess their impact on plant growth. The VC treatment generally showed the lowest height during the middle weeks (weeks 5 through 8), which might be attributed to the slower nutrient release rate from vermicompost compared to the other treatments [24,31]. The lack of significant height differences between treatments suggests that all treatments, including the control, influenced sunn hemp height at a similar rate each week. This uniformity in growth could indicate that sunn hemp, a resilient legume, could utilize the nutrients provided by all treatments effectively. The significant difference observed only in VC-treated plants between weeks 8 and 9 suggests that VC might have delayed plant height, potentially due to the gradual nutrient release typical of organic amendments like vermicompost.

4.5. Leaf Relative Chlorophyll Content

The SPAD chlorophyll meter readings showed a general upward trend across all treatments, which is expected since treatments were applied to potentially enhance the growth and health of the plants, including chlorophyll production. The progressive increase in SPAD readings across all treatments suggests that the sunn hemp plants gradually accumulated more chlorophyll as they matured, typical as plants develop more photosynthetic tissue [35,36]. LA-treated plants stood out with the highest SPAD readings by week 10, indicating that the liquid hydrolyzed fish and seaweed fertilizer might have provided a more readily available source of nutrients that supported chlorophyll synthesis effectively, particularly in the later stages of the experiment. VC-treated plants recorded the highest SPAD readings in weeks 5 and 6, indicating an early boost in chlorophyll content, likely due to the slow-release nature of the nutrients in vermicompost [24,35].

4.6. Plant Biomass

The S0 and DA treatments produced the highest plant biomass (Table 5), indicating their effectiveness in supporting plant growth. The root biomass in S0 was the highest among all treatments, suggesting that the control provided sufficient baseline nutrients to support robust root development. This was likely due to stable organic matter content and the absence of sodium stress, which supported soil structure and nutrient cycling [37,38]. In contrast, DA-treated plants produced slightly reduced root biomass compared to S0, potentially due to sodium content in DA, which may have inhibited root elongation while promoting nutrient allocation to above-ground parts.

The performance of the LA treatment was moderate but showed a unique shoot-to-root ratio, suggesting that the liquid algae amendment primarily supported above-ground biomass production. This pattern may be attributed to the timing and frequency of application, which delivered nutrients during critical phases of shoot growth but was less consistent in supporting root development. Additionally, the sodium content in LA likely disrupted the ionic balance and water uptake, contributing to reduced overall growth [37,38]. Sodium at high concentrations can adversely affect plant water uptake and nutrient assimilation, leading to growth limitations.

The lowest biomass in the VC treatment was attributed to the slow release of nutrients from vermicompost, which may not have met the immediate nutrient demands of sunn hemp during critical growth stages [24,39]. Despite its relatively high phosphorus and zinc contents, the physical properties of vermicompost, such as compaction and altered soil moisture dynamics, may have limited root expansion and affected overall biomass accumulation. These findings are consistent with research suggesting that vermicompost benefits may be optimized when combined with faster-releasing amendments to support nutrient uptake during early growth phases.

The distinct shoot and root biomass patterns observed across treatments (Table 5) provide critical insights into sunn hemp nutrient allocation strategies under varying soil amendments. For instance, the low shoot-to-root ratios in S0 (0.15) and DA (0.16) highlight their role in promoting robust root systems essential for water and nutrient acquisition. By contrast, the higher shoot-to-root ratio in LA (0.43) suggests that it favored shoot growth over root development due to its nutrient timing and sodium effects. Similarly, VC's shoot-to-root ratio (0.25) indicates an insufficient balance to maximize overall biomass production.

Despite its high sodium content, the performance of DA suggests that its nutrient-rich composition, particularly nitrogen and organic matter, offset potential adverse effects. Recent studies on algal-based fertilizers have demonstrated that the high nutrient density and presence of bioactive compounds, such as phytohormones and amino acids, enhance plant productivity even under challenging conditions [6]. However, the long-term sustainability of DA as a fertilizer requires careful management of its sodium content to prevent soil salinity.

These findings align with previous research showing that algal-based fertilizers can enhance soil fertility and crop productivity under specific conditions. For instance, ref. [15] observed that algal biofertilizers improved lettuce yield, emphasizing the importance of managing nutrient imbalances such as sodium and potassium. Similarly, studies by [6,7] highlighted the role of bioactive compounds in algal amendments for improving plant health and microbial activity in soils.

However, the contrasting performances of DA and LA highlight the need to optimize application protocols, particularly for liquid formulations, to maximize their benefits. Factors such as nutrient composition, application timing, and interactions with soil microbiota likely play critical roles. Future research should focus on combining algal-based fertilizers with complementary amendments to balance nutrient delivery and reduce sodium accumulation. This approach could further enhance their role in sustainable organic farming systems.

5. Conclusions

This study evaluated the effects of dried algae (DA), vermicompost (VC), and liquid algae fertilizer (LA) on sunn hemp growth, nutrient uptake, and soil fertility. The findings indicate that DA and S0 (control) produced the highest biomass, with DA offering significant nutrient enrichment due to its high nitrogen and organic matter content. However, the elevated sodium levels in DA highlight the need for careful management to avoid long-term soil salinity issues, such as incorporating leaching practices or using low-sodium amendments in rotation. Notably, no clear difference was observed in the positive effects on soil organic matter and nutrient content between the use of these amendments and the cultivation of sunn hemp alone (S0). This finding underscores the need to carefully evaluate the cost-effectiveness of applying organic amendments when sunn hemp can provide substantial soil benefits through below-ground carbon inputs and nutrient cycling.

These findings provide practical insights into selecting organic amendments based on specific soil and crop requirements for farmers. For instance, DA is well-suited for nitrogen-deficient soils but should be paired with strategies to mitigate sodium accumulation, such as application in areas with sufficient rainfall or combining it with low-sodium amendments like vermicompost. Meanwhile, VC is ideal for soils lacking phosphorus and potassium, while LA may require adjusted application rates to optimize its impact on soil fertility. However, the type of amendment is crucial, as the nutrient-rich LA treatment demonstrated lower soil organic matter formation compared to S0, likely due to reduced below-ground carbon allocation and nodulation as more nitrogen was readily available in the substrate. These dynamics show the need to consider organic amendments' compositions and application methods.

This research provides practical guidance for organic and regenerative farming, demonstrating the potential of algal-based fertilizers as sustainable alternatives to synthetic inputs. Future studies should explore strategies for optimizing application rates and combinations of these amendments, particularly for diverse crop species and environmental contexts. Additionally, investigating the long-term impacts of amendments at higher application rates, especially for DA and LA, would offer valuable insights into their cumulative effects on soil fertility and microbial activity. Long-term trials are also needed to assess the cumulative impact of these amendments on soil microbial activity, nutrient cycling, and productivity over multiple growing seasons. By addressing these gaps, this research can strengthen the case for using organic amendments in sustainable agriculture and offer actionable strategies for improving farming practices globally.

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