

Article

The Influence of Black Soldier Fly Residue on Watermelon Growth and the Properties of a Coarse-Textured Ultisol

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Abstract: Improving the fertility status of nutrient-depleted soils is critical to achieving food security. The negative effects of chemical fertilizers on soils necessitate the global quest for eco-friendly, effective, and sustainable alternatives. This work assessed the effect of black soldier fly (BSF) residue application on soil properties and watermelon growth. The study was set up in a completely randomized design with six replications. The treatments were BSF1 (BSF applied at 10 t ha⁻¹), BSF2 (20 t ha⁻¹), BSF3 (30 t ha⁻¹), and control. The plant data collected in this study were vine length, leaf width, number of leaves, and stem girth, and the soil's physicochemical properties were determined. The results show that BSF residue-treated soils had 20.4–49.5% higher aggregate stability and 50–160% higher hydraulic conductivity than the control treatment. BSF residue-treated soils had significantly ($p \leq 0.05$) higher pH, total N, available P, exchangeable K, and organic carbon than the control treatment. BSF3 treatment had the highest effect on available P and soil pH relative to other amended treatments. High rates of BSF residue application did not significantly increase the total available N and P contents, which could suggest that BSF application at 30 t ha⁻¹ may not pose a risk of N and P pollution to water systems. BSF residue-treated soils improved ($p < 0.05$) watermelon growth parameters relative to the control. Watermelon leaf length was significantly ($p \leq 0.05$) longer for BSF residue-treated soils than the control treatment. A similar trend was observed for the number of leaves, leaf width, and stem girth. At 4, 6, and 10 weeks after sowing, BSF residue-treated plants had 38.2–104%, 22.7–118%, and 25.7–103% longer vine lengths than the control treatment, respectively. The study results suggest that BSF residue application can enhance the fertility status of a coarse-textured ultisol for watermelon production.

Keywords: residues; nutrients; yield; black soldier fly residue; soils; watermelon; food security



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1. Introduction

Soil fertility decline is a global concern that is among the key factors militating against global security [1] due to the global decline in crop yield [2]. A decrease in soil nutrient

status can be linked to continuous cropping on a piece of land due to land scarcity, crop residue removal, nutrient leaching, and soil erosion, among others. These factors dwindle global crop production and threaten global food security. Unless sustainable ways of replenishing soil nutrients are developed and adopted, it will be difficult to achieve the desired global food security.

Given the increase in the global population, which is projected to reach 8.5 billion by 2030 and 10.4 billion by 2100 [3], there will be increase in demand for food. Thus, meeting global demands for food will require a huge increase in agricultural production. To minimize the burden of agricultural inputs that increase the capital cost of production, rural farmers patronize organic nutrient sources due to their cost-effectiveness and particularly due to the scarcity and non-availability of chemical fertilizers [4]. The benefits of organic amendment application include the provision of macro- and micronutrients, soil organic matter enhancement, soil moisture retention, stimulation of microbial activities, and an increase in the mobility of phosphorous and potassium [5,6].

The quest for organic amendments in crop production has necessitated further research to provide alternatives to chemical fertilizers that help in overcoming soil fertility challenges. Among such studies is the study on the effectiveness of organic manure mixtures and their application suitability for vegetable crops' production [7]. A similar study on the use of animal manure to enhance ultisol performance for melon production further buttressed the need to enhance the fertility status of soils in Nigeria [8].

Conscious efforts are currently underway to find sustainable and eco-friendly ways of converting organic wastes to useful byproducts for agricultural use. The use of black soldier fly (BSF, *Hermetia illucens*) to manage organic wastes is generating more attention [9–11]. There are copious studies on the bioconversion of organic materials by BSF [11] and the suitability of frass as an alternative source of organic fertilizer [10]. Frass fertilizer is a byproduct of the bioconversion of organic wastes by BSF larvae into nutrient-rich and sanitary organic fertilizer [10,12]. Beesigamukama et al. [9] reported that BSF can convert organic wastes to organic fertilizer in about five weeks, as against 8–24 weeks that it takes a conventional composting process to occur. Other benefits of BSF include high bioconversion efficiency of organic wastes as well as increased crop yield [13], having a higher amount and diversity of microbial decomposers [14], and the ability to reduce the number of pathological pathogens present in the organic wastes [11,12].

Insect decomposition of solid waste produces a nutrient-dense material that can improve soil health through organic matter deposition and the mineralization of nutrients to support maize production [15]. Insect frass fertilizers are promising alternatives to existing commercial fertilizers, such as mineral and organic fertilizers, as they have higher nitrogen and potassium contents than other fertilizers [11].

Watermelon (*Citrullus lanatus*) is a warm-season vegetable crop grown in many parts of Nigeria [16]. Watermelon is a crop with lots of economic potential, due to its high returns on investment [17]. It is also rich in calories and vitamins such as C and A, and potassium, which help to prevent stroke through the control of blood pressure [18,19]. For optimum growth and yield, watermelon requires nutrient-rich soil with good characteristics as a growth medium [20].

To date, the cultivation of watermelon and its corresponding yields in Nsukka, Southeast Nigeria, is low, primarily due to low soil fertility status and partly due to the inadequate application of organic amendments among smallholder farmers. BSF residue is relatively new in the study location, and its use as a soil conditioner is uncommon. Unfortunately, there is scarce information on the effects of BSF residue, as an organic amendment, on the physiochemical characteristics of ultisol. Such information is essential to enhance easy adoption by smallholder farmers. Therefore, this work evaluated

the effects of black soldier fly residue on the properties of a coarse-textured ultisol and watermelon growth performance.

2. Materials and Methods

This study, a completely randomized design (CRD) experiment, was undertaken in 2022 at the greenhouse facility of the Department of Soil Science, University of Nigeria Nsukka (6°51'52" N, 7°24'29" E). The study soil was collected from a fallowed field beside the greenhouse. The organic amendment used in the study was black soldier fly (BSF) residue, which was collected from the Animal Science Research Farm, University of Nigeria Nsukka. The Animal Science Unit performed a pilot study on providing alternative protein sources for broiler feed production. BSF larvae were fed on different feedstocks like animal waste, household, and plant waste. After the study, the BSF residue (a byproduct generated after feeding the BSF) produced was in bulk and used in the present study. The treatments were BSF1, black soldier fly residue applied at a rate of 22.5 g/5 kg soil (equivalent to 10 t/ha); BSF2, black soldier fly residue applied at a rate of 44.5 g/5 kg soil (equivalent to 20 t/ha); BSF3, applied at a rate of 67.0 g/5 kg soil (equivalent to 30 t/ha); and control (unamended soil). As mentioned earlier, BSF residue is an uncommon soil amendment in the study area. Thus, to easily adopt the outcomes of this study, the quantity of the applied BSF residue is akin to the conventional quantity of organic amendments used by farmers in the study location.

The treatments were replicated six times, and that gave a total of 24 experimental units. Topsoil, 0–20 cm depth, was excavated, air-dried, and sieved through a 2 mm sieve. Then, 10 kg of the sieved soil sample was weighed into the experimental pots, measuring 20 cm long, 20 cm wide, and 20 cm deep. The experimental pots were perforated at the bottom to allow for drainage of excess water and prevent water logging. Each treatment was well mixed with the soil, and thereafter, 50 cm³ of water was applied at 2-day intervals during a 2-week incubation period, to keep the treatments moist and enhance the biological decomposition of the organic amendment applied.

After incubation, four watermelon seeds (Crimson sweet variety) were sown per pot. The watermelon seeds were purchased from Nsukka Main Market, a local market where the study was undertaken. After emergence, the seedlings were thinned down to one seedling per pot, to reduce competition for nutrients. The pots were watered intermittently until the end of the experiment to keep the pots moist and provide water to the plants. The pots were manually weeded on a weekly basis. The effects of treatment application on watermelon growth were monitored biweekly using the following plant parameters: number of leaves, leaf length, leaf width, vine length, and stem girth. The watermelon vine length was obtained using a flexible measuring tape, which is measured from the base of the plant above the soil surface to the tip of the plant. Data on stem girth were obtained using a micro-meter screw gauge.

2.1. Laboratory Analysis

Prior to amending the soil and at the end of the experiment, soil samples from the experimental pots were taken for some physical and chemical analyses. The soil bulk density was determined using the core method presented in [21]. The soil aggregate stability was determined using the wet sieving method in [22]. For hydraulic conductivity, the constant-head test method was employed, as stated in [23], and calculations were performed using Darcy's equation, $K_{\text{sat}} \text{ (cm/h)} = \frac{Q}{At} * \frac{L}{\Delta H}$, where Q is the steady-state volume of flow (cm³), L is the length of the core sample (cm), A is the cross-sectional area (cm²), t is the change in time interval (h), and ΔH is the hydraulic head change (cm).

The soil samples were also subjected to chemical analyses. The soil pH was obtained with a pH meter in a soil–liquid ratio of 1:2.5 suspensions of soil in 0.1 N KCl and distilled water. The Walkley–Black method was used to determine soil organic carbon [24]. Soil exchangeable potassium was extracted using 1 M ammonium acetate and then read on a flame photometer [25]. The cation exchange capacity (CEC) was determined using the ammonium acetate (NH₄OAc) method [26]. The Bray II method was used to determine the available phosphorus content [27], while the soil total nitrogen content was determined using the macro-Kjeldahl method [28]. The chemical compositions of the black soldier fly (BSF) residue were also analyzed following the above-mentioned procedures.

2.2. Percentage Changes in the Soil's Chemical Properties Relative to the Baseline Soil

The percentage change in the soil's chemical properties following BSF residue application relative to the baseline soil's chemical properties was calculated using $\% \text{ Change} = \frac{Y-X}{Y} * \frac{100}{1}$, where Y is the final soil value, and X is the initial soil value.

2.3. Statistical Analysis

All the obtained data were subjected to a one-way analysis of variance (ANOVA) and analyzed using GenStat Discovery Edition version 4.2 statistical software. The treatment means were separated using Fisher's least significant difference (F-LSD) at a 5% probability level.

3. Results and Discussion

3.1. Chemical Properties of BSF and Its Effect on the Physical Properties of the Soil

Regarding the initial physical properties of the test soil, in terms of texture, the soil was sandy loam (clay, <0.002 mm, 160 g kg^{−1}; silt, 0.02–0.002 mm, 90 g kg^{−1}; fine sand 0.20–0.02 mm, 240 g kg^{−1}; and coarse sand 0.02–2.00 mm, 510 g kg^{−1}) with 9.88% aggregate stability. The soil bulk density was 1.60 g cm^{−3} and had a hydraulic conductivity of 0.11 cm hr^{−1}. The initial chemical properties of the test soil prior to the application of BSF residue were as follows: the soil was acidic (pH 5.7) and had 0.15 g kg^{−1} total nitrogen, 12.0 mg kg^{−1} available P, 0.09 mg kg^{−1} exchangeable potassium, 0.78 mg kg^{−1} exchangeable magnesium, 9.55 cmol kg^{−1} cation exchange capacity (CEC), and 1.06% organic carbon. This indicated that the test soil had low fertility status, which will affect plant nutrient uptake and consequently affect watermelon growth and yield. The chemical composition of the organic amendment (BSF residue) used in this study was slightly acidic (pH 6.6) and high (29.8%) in organic matter content (Table 1). Unlike the test soil, the BSF residue had richer nutrient contents, an indication that BSF residue will impact soil properties as well as crop growth and development.

Table 1. Chemical properties of black soldier fly residue.

Amendments	pH (H ₂ O)	pH (KCl)	Total N (g kg ^{−1})	Total P (g kg ^{−1})	Total K (g kg ^{−1})	Total Ca (g kg ^{−1})	Total Mg (g kg ^{−1})	OM (g kg ^{−1})
BSF residue	6.6	5.3	3.80	1.86	4.60	42.7	48.8	298

BSF: black soldier fly; OM: organic matter; P: phosphorous; K: potassium; Ca: calcium; N: nitrogen; Mg: magnesium.

Treatment application had varying effects on the soil's physical properties (Table 2). The soil bulk density (BD) was not affected significantly across the applied treatments. Unlike BD, the soil aggregate stability was significantly ($p \leq 0.05$) higher in BSF residue-treated soils than in the control treatment. The BSF residue-amended soils had circa 20.4–49.5% higher aggregate stability than the control treatment. Also, a higher BSF residue application

rate resulted in a significantly ($p < 0.05$) higher aggregate stability than a lower BSF residue application rate. A similar trend in aggregate stability was observed for hydraulic conductivity (Table 2). BSF residue-amended soils had circa 50–160% higher hydraulic conductivity (HC) than the control treatment. An increase in soil HC is essential for enhanced crop performance because low HC can limit water and nutrient availability for plant uptake and consequently affect crop growth. The positive effects on the soil's physical properties following treatment application clearly demonstrate the capacity of BSF residue amendment to influence the soil's physical properties.

Table 2. Effect of treatment application on the soil's physical properties after watermelon harvest.

Treatment	Bulk Density (g cm ⁻³)	Aggregate Stability (%)	Hydraulic Conductivity (cm hr ⁻¹)
BSF1	1.68 (0.098)	12.4 (1.09)	0.15 (0.023)
BSF2	1.56 (0.087)	14.0 (1.18)	0.25 (0.051)
BSF3	1.66 (0.086)	15.4 (1.06)	0.26 (0.090)
Control	1.58 (0.069)	10.3 (1.11)	0.10 (0.008)
F-LSD	NS	1.02	0.03

BSF1: black soldier fly residue applied at a rate of 22.5 g/5 kg soil (equivalent to 10 t/ha); BSF2: applied at a rate of 44.5 g/5 kg soil 44.5 g (equivalent to 20 t/ha); BSF3: applied at a rate of 67.0 g/5 kg soil (equivalent to 30 t/ha); F-LSD: Fisher's least significant difference at 5% probability; values in bracket is the standard error of the mean.

Improvement in soil organic carbon with BSF residue application (Table 3) can enhance the soil structure and thus influence water movements through the soil and soil aeration [29]. Sushma et al. [29] reported significant ($p < 0.05$) decreases in soil BD following the application of BSF-digested poultry manure. According to the authors, higher treatment rates (7 tons/acre) led to lower soil BD than lower treatment rates (5 tons/acre and 2.5 tons/acre, respectively).

Table 3. Effect of treatment application on the soil's chemical properties after harvest.

Treatment	pH (H ₂ O)	pH (KCl)	Total N (g/kg)	Available P (mg/kg)	Ex. K (mg/kg)	Ex. Ca (cmol/kg)	Ex. Mg (cmol/kg)	CEC (cmol/kg)	OC (g/kg)
BSF1	6.30 (0.058)	5.25 (0.029)	0.24	3.26 (0.081)	0.93 (0.013)	1.20 (0.115)	1.90 (0.058)	12.40 (0.922)	1.39 (0.109)
BSF2	6.10 (0.058)	5.05 (0.144)	0.27	7.00 (0.018)	1.01 (0.017)	2.30 (0.172)	2.10 (0.520)	15.80 (0.808)	1.59 (0.111)
BSF3	6.30 (0.058)	5.45 (0.087)	0.28	10.05 (0.025)	1.27 (0.105)	2.40 (0.188)	1.90 (0.758)	16.80 (0.924)	1.63 (0.102)
Control	5.59 (0.062)	4.95 (0.059)	0.18	2.33 (0.068)	0.80 (0.006)	1.00 (0.005)	1.40 (0.061)	9.60 (0.428)	1.02 (0.098)
F-LSD	0.212	0.241	0.022	4.831	0.224	0.371	0.341	2.420	0.131

BSF1: black soldier fly residue applied at a rate of 22.5 g/5 kg soil (equivalent to 10 t/ha); BSF2: applied at a rate of 44.5 g/5 kg soil 44.5 g (equivalent to 20 t/ha); BSF3: applied at a rate of 67.0 g/5 kg soil (equivalent to 30 t/ha); Ex.: exchangeable; CEC: cation exchange capacity; OC: organic carbon; F-LSD: Fisher's least significant difference at 5% probability; values in bracket is the standard error of the mean.

3.2. Effect of Black Soldier Fly Residue Application on the Chemical Properties of the Soil

BSF residue application significantly affected the soil's chemical properties such as soil pH, available phosphorus, CEC, calcium, and organic carbon (Table 3). The soil pH was significantly lower in the control treatment than in the BSF residue-amended soils. The increase in soil pH was attributed to the high pH value in the BSF residue applied (Table 1). An increase in soil pH positively influenced soil nutrient availability and consequently enhanced watermelon growth. Authors have reported an increase in soil

pH following the application of organic amendments [8,30,31]. Wang et al. [32] reported significant improvement in soil pH with the application of 2–8% BSF frass fertilizer. In contrast, Sushma et al. [29] found decreases in soil pH with the application of BSF-digested poultry manure relative to the initial soil pH (8.6). The authors attributed the reduction in soil pH to the production of acids during the microbial decomposition of organic manure.

The soil total N content was significantly ($p \leq 0.05$) higher in BSF residue-amended soils than in the control treatment, by circa 33–56%. The higher ($p \leq 0.05$) total N in the BSF residue-amended soils is expected considering the total N content of BSF residue (38 g kg⁻¹; Table 1) relative to the initial soil total N content (0.15 g kg⁻¹). Although BSF3 had 16.7% higher total N than BSF2, neither rate had any significant ($p > 0.05$) effect on the total N content. Since the test soil had a low N content, the plant N uptake likely contributed to the non-significant ($p > 0.05$) effect on the total N content, which was associated with the rates of the BSF residue applied. A study by [15] recorded higher total N with BSF application than the unamended treatment. In their study, Beesigamukama et al. [33] noted that BSF treatment exceeded the performance of mineral N fertilizer when applied at the same rates. Similarly, Klammsteiner et al. [34] noted increases in the total N content with BSFF application. A study by Sushma et al. [29] showed higher ($p < 0.05$) total N with BSF application, which the authors attributed to the high mineral N concentration in BSF since BSF consisted of excretions, substrate residue, and shed exoskeletons. The high total N in BSF residue-amended soil can enhance crop growth and productivity [33,35].

For available P, BSF residue treatments recorded significantly ($p \leq 0.05$) higher available P compared with the control treatment (Table 3). Across the BSF residue treatments, an increase in treatment application rate increased the available P content. Phosphorus is an important macronutrient that is key for higher yield. In addition, since P plays an important role in energy transfer, the higher P concentrations as found in frass could facilitate N accumulation in watermelon by consequently improving N uptake [36]. Lalander et al. [12] suggested that the application of BSF residue can have significant effects on nutrients and consequently impact crop development.

Similarly, BSF residue treatments revealed a significant ($p \leq 0.05$) effect on exchangeable K relative to the control treatment. Potassium is an important macronutrient needed for plant biochemical and physiological processes that are critical in plant activities such as carbohydrate metabolism, protein synthesis, and the activation of enzymes [37,38]. Higher exchangeable K in BSF residue-treated soils can have a positive impact on watermelon performance. The soil exchangeable Ca varied significantly ($p \leq 0.05$) following treatment application. BSF2 and BSF3 treatments had a significantly ($p \leq 0.05$) higher exchangeable Ca when compared with the control treatment. The treatment effect on exchangeable Mg was similar to that of exchangeable Ca. The result obtained in this study corroborates similar findings. For instance, Dzepe et al. [31] reported an increase in exchangeable Ca with the application of BSFF, while a study by [11] reported higher potassium (K) concentrations with BSF frass fertilizer than other fertilizers. In this work, the soil CEC was higher for BSF-treated soils than the control treatment, by over 29% (Table 3). Higher rates of BSF residue yielded higher CEC content. Plant nutrient uptake also contributed to the non-significant effect in the soil CEC for BSF2 and BSF3 treatments. Dzepe et al. [31] found increases in the CEC content for BSF-treated soils in comparison with the control treatment.

Soil organic carbon (SOC) ranged from 1.02% (control treatment) to 1.63% (BSF3 treatment). SOC was significantly ($p \leq 0.05$) higher in BSF residue-treated soil compared with the control treatment. BSF1 treatment had the lowest ($p \leq 0.05$) SOC content, while BSF3 treatment had the highest ($p \leq 0.05$) SOC content. The significantly ($p \leq 0.05$) high SOC obtained is mainly due to the direct effect of BSF residue application. Further, the BSF

residue applied in this study may have likely stimulated microbial growth and activities, which potentially contributed to the higher SOC obtained [29]. Organic amendment application can enhance soil carbon sequestration [29]. Soil amended with 2–8% BSF frass fertilizer improved soil organic matter content [32].

3.3. Changes in Soil pH, SOC, CEC, and TN Relative to the Baseline Soil Properties Following BSF Application

BSF residue application had significant effects on the chemical properties of the soil relative to the initial soil's chemical properties (Figures 1 and 2). Regarding soil pH, soils amended with BSF residue exhibited a 6.6–9.5% increase in soil pH, while the control treatment decreased the soil pH by circa 2% (Figure 1A). Higher rates of treatment application did not result in a corresponding percentage increase in soil pH. Overall, this result demonstrates the significance of organic amendment application in enhancing soil pH. The increase in the percentage SOC for BSF residue treatments was circa 26–37% relative to the initial SOC (Figure 1B). The percentage increase and decrease in the SOC associated with BSF residue-treated soils and the control treatment, respectively, attest to the importance of organic amendment application in improving the SOC status.

There were percentage increases in CEC across the treatments. The BSF residue treatments led to a 23–43% percentage increase in CEC, while the control treatment yielded a 0.5% percentage increase in CEC relative to the initial soil's CEC status (Figure 1C). The percentage increase in CEC with BSF residue treatment application demonstrates the significance of organic amendment in enhancing the soil's CEC status. There was a percentage increase in the soil's total N content across the treatments (Figure 1D). An increase in the BSF residue application rate resulted in a corresponding percentage increase in the soil's total N content.

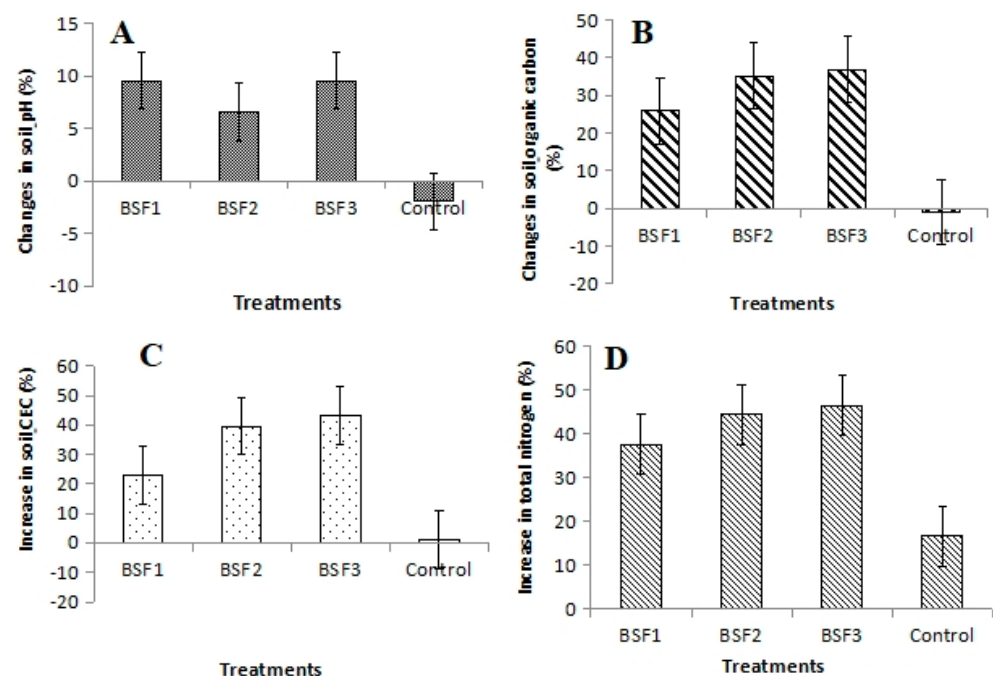


Figure 1. Percentage changes in soil pH, SOC, CEC, and TN with BSF application relative to the baseline soil. SOC: soil organic carbon; TN: total nitrogen; CEC: cation exchange capacity; BSF1: black soldier fly residue applied at a rate of 22.5 g/5 kg soil (equivalent to 10 t/ha); BSF2: applied at a rate of 44.5 g/5 kg soil (equivalent to 20 t/ha); BSF3: applied at a rate of 67.0 g/5 kg soil (equivalent to 30 t/ha); bars denote Fisher's least significant difference (F-LSD) at 5% probability. (A) Changes in soil pH; (B) Changes in soil organic carbon; (C) Increase in soil CEC; (D) Increase in total nitrogen.

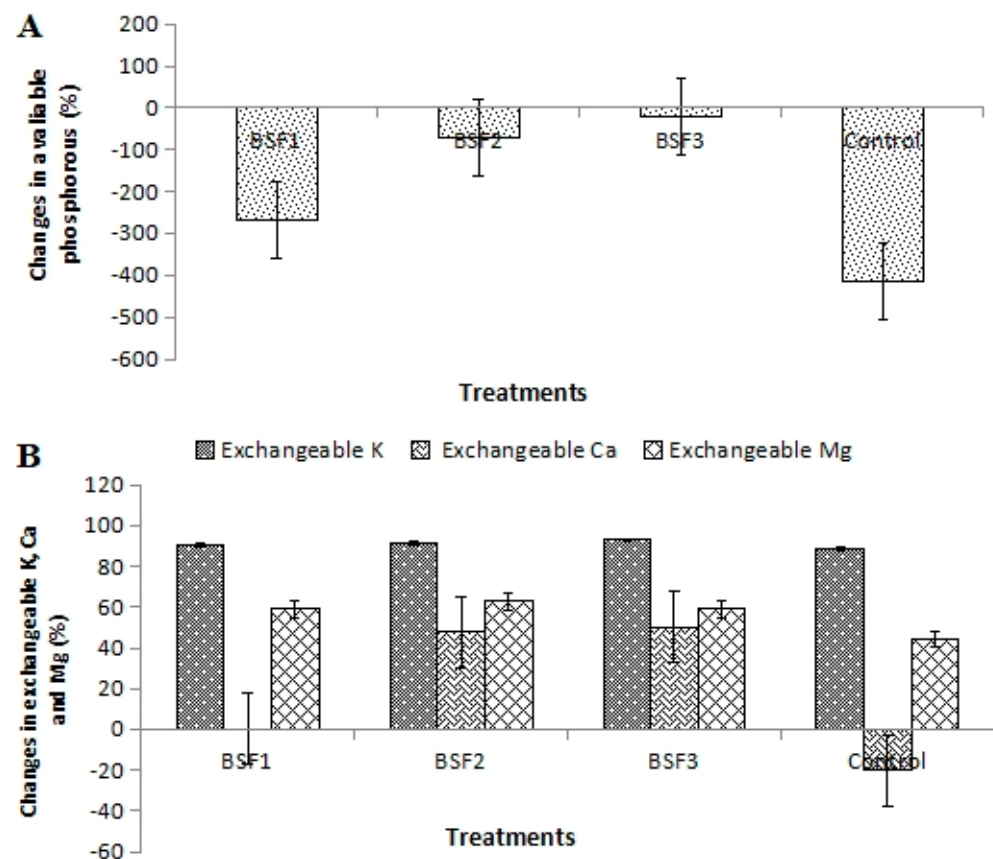


Figure 2. Percentage changes in soil P, exchangeable K, Ca, and Mg with BSF application relative to the baseline soil. BSF1: black soldier fly residue applied at a rate of 22.5 g/5 kg soil (equivalent to 10 t/ha); BSF2: applied at a rate of 44.5 g/5 kg soil 44.5 g (equivalent to 20 t/ha); BSF3: applied at a rate of 67.0 g/5 kg soil (equivalent to 30 t/ha); bars denote Fisher's least significant difference (F-LSD) at 5% probability; (A) changes in available available (%), (B) changes in exchangeable K, Ca and Mg (%).

3.4. Changes in Available P and Exchangeable Nutrients Relative to the Baseline Soil Properties Following BSF Application

There was a considerable change in the soil's available P across the treatments. The percentage decreased in available P ranged from −268% for BSF1 treatment to −19% for BSF3 treatment (Figure 2A). Higher rates of BSF residue led to low percentage decreases in available P. The control treatment exhibited the highest percentage decreases in available P. This result might suggest that the available P content in the BSF residue amendment, although not determined, may be insufficient to support watermelon production. This implies that higher rates of BSF residue may be needed for watermelon cultivation. The percentage decreases in available P with BSF residue treatments could also suggest that applying BSF at 30 t ha^{−1} may not pose a potential danger of P pollution, which is one of the risks associated with applying organic amendments at high rates. In a maize study, Beesigamukama et al. [15] noted significant increases in the total P content. The authors attributed the increased total P content to P-nutrient enrichment following BSF frass application, which provided phosphorus that is deficient in most typical soils [29]. The provisioning capacity of BSF residue to enhance soil P will support plant health and productivity.

As regards exchangeable K, there were 90–93% percentage increases in exchangeable K with BSF residue treatment relative to the initial exchangeable K (Figure 2B). Similarly, the control treatment exhibited 88% increases in exchangeable K. Although plant K uptake was not determined, this result may suggest that exchangeable K may not be a critical nutrient for watermelon cultivation. Higher BSF residue application rates led to corresponding

higher percentage increases in exchangeable Ca (Figure 2B). BSF1 treatment resulted in no zero (0%) percentage improvement in the exchangeable Ca, while with the control treatment, we recorded a 20% decrease in exchangeable Ca. Unlike exchangeable K, this result may suggest that Ca is an important nutrient element for watermelon production and that might account for the percentage decrease associated with the control treatment. Soil exchangeable Mg followed a similar trend to that of exchangeable K, although its percentage increases were not of the same magnitude (Figure 2B).

3.5. The Response of Watermelon Growth Indices to BSF Residue Amendment

The progressive development in watermelon leaf dimensions following BSF residue application attests to the effectiveness of this organic amendment in enhancing crop growth. Notably, the impact became pronounced eight weeks after sowing (WAS) (Table 4), suggesting that the benefits of BSF residue amendment may be more evident in later vegetative stages than during seedling establishment. This delayed but substantial effect could result from the gradual decomposition and mineralization of BSF residue, which releases nutrients in a sustained manner rather than in an immediate, highly soluble form. The long-term effectiveness of organic amendments is largely attributed to their slow decomposition and nutrient mineralization [39].

Table 4. Effect of black soldier fly residue on watermelon leaf and vine parameters.

Treatment	WAS 2	WAS 4	WAS 6	WAS 8	WAS 10
Leaf length (cm)					
BSF1	4.67	4.17	7.37	12.7	12.3
BSF2	3.67	4.83	6.00	11.3	12.7
BSF3	2.17	3.47	7.67	10.0	12.0
Control	2.10	4.33	5.00	9.00	9.33
F-LSD	0.99	NS	1.05	1.73	1.57
Leaf number					
BSF1	5.67	7.67	9.33	15.7	13.0
BSF2	5.00	7.67	9.67	18.7	23.0
BSF3	4.33	6.67	10.7	20.3	25.0
Control	4.33	7.67	8.67	12.0	11.0
F-LSD	0.761	NS	1.655	1.961	3.234
Leaf width (cm)					
BSF1	4.00	4.83	5.33	8.80	9.67
BSF2	3.13	4.33	5.33	10.0	10.7
BSF3	1.67	2.50	8.00	9.00	11.0
Control	1.60	3.97	5.30	7.00	7.67
F-LSD	0.98	0.72	1.22	1.10	1.05
Stem girth (cm)					
BSF1	1.27	1.30	1.43	2.17	2.33
BSF2	1.27	1.43	1.70	2.50	2.57
BSF3	1.20	1.30	1.67	2.57	2.47
Control	1.30	1.37	1.70	2.63	2.73
F-LSD	0.19	0.16	Ns	Ns	0.23
Vine Length (cm)					
BSF 1	8.67	17.0	30.0	54.7	70.0
BSF2	10.0	27.3	40.0	92.3	96.3
BSF3	7.00	16.3	44.3	83.7	113
Control	9.00	16.7	21.7	42.3	55.7
F-LSD	3.709	5.97	12.02	9.59	12.59

WAS: weeks after sowing; BSF1: black soldier fly residue applied at a rate of 22.5 g/5 kg soil (equivalent to 10 t/ha); BSF2: applied at a rate of 44.5 g/5 kg soil 44.5 g (equivalent to 20 t/ha); BSF3: applied at a rate of 67.0 g/5 kg soil (equivalent to 30 t/ha); F-LSD: Fisher's least significant difference at 5% probability.

At 10 WAS, the plants grown in BSF residue-amended soils exhibited significantly longer leaves compared to the control, with BSF2 treatment producing the longest leaves, at an average of 12.7 cm. BSF1 and BSF3 treatments followed closely, with leaf lengths of 12.3 cm and 12.0 cm, respectively (Table 4). In contrast, the control treatment had significantly shorter leaves, averaging 9.33 cm. The enhanced leaf elongation observed in BSF residue-amended plants is likely due to improvements in soil structure, water retention, soil pH status, and nutrient availability, facilitated by the organic matter and nutrients contained in BSF residue. Several studies have reported similar improvements in plant morphology when BSF residues were incorporated into the soil, attributing these effects to increased microbial activity and nutrient cycling [40,41]. Interestingly, the fact that BSF2 treatment resulted in the longest leaves, while BSF3 treatment had slightly shorter leaves, suggests that moderate BSF residue application may optimize nutrient availability, whereas excessive application could lead to nutrient imbalances or reduced efficiency in nutrient uptake. High organic matter inputs can sometimes cause microbial immobilization of nitrogen and phosphorus [39], which may explain why the BSF3 treatment did not produce significantly longer leaves than the BSF2 treatment.

Leaf width exhibited a similar trend to leaf length, with BSF residue-treated plants consistently outperforming the control treatment at all growth stages. By 10 WAS, the BSF3 treatment had the broadest leaves (11.0 cm), slightly exceeding the BSF2 and BSF1 treatments (Table 4). The control plants, however, had significantly narrower leaves (7.67 cm), reinforcing the role of BSF residue in promoting leaf expansion. Wider leaves provide a large surface area for light interception and enhance plant photosynthetic ability. The increased leaf expansion observed in BSF residue-treated plants could be attributed to better soil aeration and moisture retention, which improve nutrient uptake and support turgor pressure in expanding cells. This assertion is corroborated by the findings of Risman et al. [42], who reported that the soil's chemical properties, including pH, organic matter, electrical conductivity, total nitrogen, available phosphorus, exchangeable potassium, iron, arsenic, and lead, can be improved using vermicompost and BSF combined with inorganic fertilizers, leading to better plant growth outcomes. The trend in leaf width also suggests that BSF residue amendments provide structural benefits beyond mere nutrient supply. By improving soil aggregation and reducing bulk density, BSF residues likely facilitated better root penetration and water availability, creating optimal conditions for expansive leaf growth.

The number of leaves on watermelon vines exhibited the most significant response to BSF residue amendments, particularly at later growth stages. By 10 WAS, BSF3-treated plants had the highest leaf count (25.0), followed closely by BSF2-treated plants, while BSF1 treatment yielded a moderate increase (Table 4). In contrast, the control plants had significantly ($p \leq 0.05$) fewer leaves (11.0), suggesting that BSF residue amendments play a crucial role in canopy expansion. Leaf number is a key determinant of a plant's photosynthetic capacity, as more leaves equate to greater energy capture for growth and fruit development [43]. The substantial increase in leaf production under BSF residue treatments indicates that plants benefited from improved nutrient availability and soil health. Previous studies have shown that BSF compost enhances microbial-mediated nutrient cycling, particularly in releasing nitrogen, phosphorus, and potassium, which are essential for leaf development [41]. The highest leaf count in BSF3-treated plants suggests that higher application rates may further stimulate vegetative growth. However, the relatively minor difference between BSF3 treatment (25.0 leaves) and BSF2 treatment (23.0 leaves) implies that, beyond a certain threshold, additional BSF residue application may yield diminishing returns in terms of leaf proliferation.

Stem girth is a crucial parameter in plant growth, as it determines the structural stability of the plant and its ability to support foliage, flowers, and fruit development. In this study, the application of BSF residue did not lead to substantial differences in stem girth across treatments, with values ranging between 2.33 cm and 2.57 cm for BSF residue-treated plants at 10 WAS (Table 4). The control plants, which did not receive BSF residue amendments, had a slightly higher but statistically similar stem girth (2.73 cm). The lack of significant variation in stem girth suggests that while BSF residue amendments enhanced leaf and vine growth, their effect on stem thickening was less pronounced in watermelon. This could be because the nutrient release from BSF residue was more directed toward canopy expansion and vine elongation rather than secondary thickening of the stem. Contrary to the observations in this study, Silva-Junior et al. [44] found significant differences in watermelon stem diameter under varying organic soil amendments. Similarly, Anyega et al. [35] reported significant differences in the stem diameter of tomatoes grown in BSF-amended soil.

Unlike stem girth, vine length was significantly ($p \leq 0.05$) influenced by BSF residue treatments, with the most substantial differences observed at 10 WAS. The longest vines were recorded in BSF3-treated plants (113 cm), followed by those treated with BSF2 and BSF1 (Table 4). In contrast, control plants exhibited the shortest vine length (55.7 cm), highlighting the strong influence of BSF residue amendments on vegetative growth. The progressive increase in vine length with higher BSF residue application rates suggests that BSF residues contribute to enhanced biomass accumulation and elongation. According to Anyega et al. [35], the combined application of black soldier fly frass organic fertilizer with NPK resulted in 22–135%, 20–27%, and 38–50% higher yields compared to sole NPK for tomatoes, kales, and French beans, respectively, under both greenhouse and open-field conditions.

4. Conclusions

Black soldier fly (BSF) residue amendment presents a promising strategy for enhancing soil quality and supporting watermelon growth. BSF residue application increased the key physicochemical properties of the test soil and stimulated crop performance. Higher BSF residue application rates had greater effects on soil properties than the BSF residue applied at lower rates. Higher rates of BSF residue treatments did not increase total N and available P contents significantly. This may suggest that the application of BSF residue at 30 t ha⁻¹ may not pose an environmental risk of N and P pollution to water bodies. However, further investigation under field conditions can validate these findings and assess the long-term sustainability of BSF residue use for watermelon cultivation in a coarse-textured ultisol.

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