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EFFECTIVENESS OF BIOCHAR AND MICROBIAL APPLICATIONS IN SWEET SORGUM (SORGUM BICOLOR L.) CROPS ON SEAWATER-INTRUDED MEDIA

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Abstract

This study aims to determine the effect of biochar and microbial application on the growth and yield of sweet sorgum (Sorghum bicolor L.) in in seawater-intruded media. Biochar functions to improve soil structure and increase water retention and nutrient efficiency, while tobacco microbes have the potential to act as biological agents. The study employed a Split-Plot Design with two factors: biochar (0, 40, 80, 120 g/polybag) and microbes (0, 5, 10, 15 ml/polybag), each with three replications. Analysis results indicated that biochar application significantly influenced the parameters of seeds per panicle and seed weight per plot. The biochar treatment at a dose of 80 g/polybag produced the highest number of seeds per panicle at 74.54 seeds, while the treatment without biochar (B_0) yielded the highest seed weight per plot at 57.65 g. The application of microorganisms and the interaction between biochar and microorganisms did not show a significant effect on all observed parameters. Biochar was proven effective in increasing sorghum yield on salt-intruded land through improved generative growth when applied at the optimal dose.

Keywords: Soil Conditioner, Biological Agents, Saline Soil

INTRODUCTION

Sorghum plants (Sorghum bicolor L.) are one of the cereal crops that have an important role globally as a source of food, animal feed, and bioenergy. In addition, sorghum is known as a plant that is adaptive to extreme environmental conditions, such as drought and high temperatures, making it a strategic alternative to crops in tropical and subtropical regions. This plant thrives in soil with a pH between 6.0 - 7.5 and is able to survive in environments with varying levels of fertility, ranging from low to high (Tarigan and Ismuhadi, 2021). Sweet sorghum, in particular, has a high sugar content in its stems, which makes it a potential source of bioethanol and a promising agroindustrial commodity. Historically, sorghum originated in Africa and has spread to different parts of the world, including Asia and the Americas, thanks to its extensive adaptability and high economic value (Ameen et al., 2024). Indonesian sorghum production is still very low, even in general sorghum products are not yet available in the markets. Currently, throughout Indonesia there are around 853 thousand hectares of marginal land which, if managed properly, will produce around 6-10 million tons of sorghum seeds per year and 75-100 million tons of stems per year containing 40-60 million kl of sap per year. However, currently the average national sorghum production is only around 4000-6000 tons year-1. The average planting area and productivity of sorghum in several sorghum production centers in Indonesia are quite varied. These variations are caused by differences in agroecology and cultivation technology applied by farmers, especially varieties and fertilizers (Tarigan et al., 2024). In 2022, world sorghum production decreased by 2.8% compared to the previous year, reaching around 1,467 million tons, which is the lowest output since 2019. This decline was mainly due to declines in corn production in the European Union, Ukraine, and the United States, as well as a decline in sorghum production in the United States. Despite this, sorghum remains an important commodity in many developing countries, especially in Africa and Asia, accounting for about 70% of the world's total production. On the other hand, the average global sorghum productivity in 2022 was recorded at around 1,490.4 kg/ha, an increase of around 0.98% compared to 2017. However, this figure is still far below its maximum potential, which can reach 5–6 tons per hectare under optimal conditions with the use of superior varieties and modern agricultural technologies (Soare et al., 2024). Sorghum cultivation has a strategic role in supporting national food security and suboptimal land resource management. Its potential is very large to be developed in areas with marginal agroecosystem conditions such as dryland, nutrient-poor, and saline land, which has not been optimally utilized. Sorghum is known to have a high tolerance to drought and salinity, making it a great choice for food crop diversification in Indonesia. Based on national data, the area of dry land that has the potential to be developed in the agricultural sector reaches around 30.6 million hectares, with 6.5 million hectares spread across the Sumatra region. The development of sorghum on these lands can not only increase the productivity of marginal land, but also provide economic added value for farmers in disadvantaged and climate-vulnerable areas (Momongan et al., 2019). However, sorghum productivity in many regions still faces obstacles, especially related to the quality of planting media, especially saline soil. About 20% of the world's agricultural land and 33% of irrigated land are affected by salinity, which leads to a significant decline in crop yields being one of the major agronomic problems that limit the development of food crops, including sorghum (Hoque et al., 2022).

Saline soil is a soil that experiences an excessive accumulation of dissolved salts that negatively impact plant growth. According to (Barus et al., 2023) Salinity can inhibit plant growth through osmotic effects, as well as reduce the ability of plants to absorb water which in turn results in decreased growth. Soil salinity causes osmotic stress that interferes with water absorption by plant roots and causes toxicity of harmful ions such as sodium (Na+) and chloride (Cl−), thus negatively affecting plant growth and physiology. The impact of salinity stress on sorghum includes a decrease in plant height, leaf area, chlorophyll, and biomass yield and seed production which directly reduces productivity (Kusvuran et al., 2021). Research by Ibrahim et al., (2021) shows that soil salinity levels with a NaCl concentration of more than 6 dS/m drastically reduce sorghum tolerance, so that it can reduce crop yields by more than 50%. This shows that the handling of saline land is very crucial to ensure the success of sweet sorghum cultivation in areas prone to salinity. An agronomic approach based on improving planting media is a strategic choice. One of them is the use of biochar, which is activated charcoal obtained from the biomass pyrolysis process at low temperatures without oxygen. Biochar has the ability to improve the physical and chemical properties of the soil and increase soil fertility, especially in marginal lands such as saline soils (Patani et al., 2023). Biochar is known to be able to increase the capacity of the soil to hold water, improve soil porosity and aeration, and reduce the toxicity of Na+ and Cl− ions which are very detrimental to plants in high salinity conditions. In addition, biochar can also increase the cation exchange capacity (CEC) and pH of the soil, creating soil conditions that are more conducive to plant growth (Nehela et al., 2021).

In addition to the role of biochar, biofertilizers such as microbes also make an important contribution to increasing soil fertility and plant growth. Microorganisms such as phosphate solubilizing bacteria (PSB) and plant growth-promoting rhizobacteria (PGPR) are able to dissolve essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), which further increases the availability of nutrients for plants (Rizvi et al., 2021). Recent research shows that the combination of biochar and biofertilizer has a synergistic effect in increasing soil microbial activity, nutrient utilization efficiency, and more optimal plant biomass production, especially in land exposed to high salinity (Mashamaite et al., 2024). This synergy is an important basis in developing sustainable agricultural technology on marginal land. Based on the above statement, it is necessary to conduct research on the effectiveness of biochar and microbial applications in sweet sorghum plants in saline soil media. To determine the effect of biochar and microbial bacteria on plant growth (Sorghum bicolor L.).

METHOD

Location and Time of Research

This research was carried out from July 2024 to December 2024 on Tuar land, Tuar, Amplas Village, Medan Amplas District with an altitude of ± 27 meters above sea level.

Tools and Materials

The materials used in this study are Soper 6 variety sorghum, saline soil, biochar organic fertilizer, microbes, and other materials that support the research. The tools used are meters, hoes, machetes, buckets, gnats, plastic ropes, scissors, analytical scales, research signs, calculators, polybags measuring 40 x 50 cm with a soil volume of 10kg, cameras and stationery and other tools.

Research Methods

The research method used is a quantitative research method with a parameter observation approach that can be measured due to the influence of biochar and microbial treatment. The research was carried out using a Split plot

Design which consisted of 2 treatment factors with 3 replicates. The treatment factor is the administration of biochar (B), with 4 levels, namely: B0 (0 g/polybag), B1 (40 g/polybag), B2 (80 g/polybag), B3 (120 g/polybag). Microorganism administration factors (M), with 4 levels, namely: M0 (0 ml/polybag), M1 (5 ml/polybag), M2 (10 ml/polybag), M3 (15 ml/polybag).

Observations Parameters

Research parameters as a value or condition that is used as a benchmark in finding something that already exists, digging deeper into what already exists, developing, expanding and testing what has existed but is still doubtful of its truth. Therefore, the research was conducted to re-test several parameters that can indicate growth and development in sweet sorghum plants in saline soil media. The parameters observed were plant height (cm), number of leaves (strands), leaf area (cm2), stem diameter (cm), panicle length (cm), panicle weight (g), number of seeds per panicle, seed weight per panicle (g), seed weight per plot (g), weight of 100 seeds (g).

Data Analysis

The data from the research were analyzed using variance analysis (ANOVA), which was then followed by a real difference test between treatments using the Duncan's Multiple Range Test (DMRT) method. This analysis refers to the mathematical model of Split Plot Design, which is used to test the influence of the main treatment and the subplots and their interactions. The tabulated and calculated data is created in the form of graphs or tables for interpretation.

RESULTS AND DISCUSSION

Plant Height

Plant height is a key indicator for assessing the initial response of plants to the applied treatments, particularly during the vegetative phase. This parameter reflects the plant's ability to perform photosynthesis, nutrient uptake, and adaptation to environmental conditions, especially in saline soils.

Table 1. Sorghum Plant Height in Response to Biochar and Microbial Application at 2, 4, 6, and 8 MST.

Treatment	Plant Height			
	2 MST	4 MST	6 MST	8 MST
	....	.....cm......	....	....
Biochar				
B0	29.92	62.25	120.29	182.08
B1	24.04	45.13	99.38	167.96
B2	28.79	58.21	115.96	184.75
B3	27.98	60.46	107.75	166.17
Microbes				
M_0	26.85	58.92	112.33	176.75
M_1	29.23	58.08	116.54	185.83
M_2	29.73	55.88	111.75	176.08
M_3	24.92	53.17	102.75	162.29
Interaction				
B0 M0	30.25	64.00	129.67	183.83
B0 M1	31.50	67.50	131.17	192.83
B0 M2	31.67	60.67	117.67	182.00

B0 M3	26.25	56.83	102.67	169.67
B1 M0	24.50	47.33	98.33	173.33
B1 M1	25.83	43.83	102.83	181.50
B1 M2	23.25	39.33	88.50	154.00
B1 M3	22.58	50.00	107.83	163.00
B2 M0	27.50	55.67	113.33	179.33
B2 M1	30.83	62.50	123.83	197.50
B2 M2	31.33	63.50	124.17	193.17
B2 M3	25.50	51.17	102.50	169.00
B3 M0	25.17	68.67	108.00	170.50
B3 M1	28.75	58.50	108.33	171.50
B3 M2	32.67	60.00	116.67	175.17
B3 M3	25.33	54.67	98.00	147.50

Based on Table 1, the results indicate that the application of biochar and microbes, either individually or in combination, did not significantly affect sorghum plant height at 2, 4, 6, and 8 MST. A DMRT post-hoc test at the 5% level placed all treatments in the category of no significant difference. Nevertheless, descriptively, there was a trend of increased plant height in treatments B2(80 g/plant) and M1(5 mL/plant), with the B2M1combination showing a maximum height of 197.50 cm at 8 MST. This indicates that biochar can improve soil structure as well as enhance water retention capacity and nutrient availability. On the other hand, microorganisms such as *Plant Growth-Promoting Rhizobacteria* (PGPR) play a role in phytohormone synthesis and improve nutrient uptake efficiency. The study byand suggests that biochar can improve soil quality and support microbial activity, while by Ayumnuazmi *et al*.., (2025) reports that rhizosphere microbes contribute to stimulating root growth and crop yield. by *et al*.., (2016) also indicates that the interaction between biochar and microbes can create a positive synergy in the root zone. Although the effects in this study were not yet statistically significant, the agronomic potential of this combination is promising and warrants further investigation with a wider range of dosage variations and environmental conditions.

Stem Diameter

Stem diameter is an important morphological parameter that reflects a plant's structural strength in supporting vegetative and generative growth. Stem diameter increase is also closely related to the activity of secondary meristem tissues, particularly the cambium, as well as the availability of nutrients that support cell division and enlargement.

Table 2. Stem Diameter of Sorghum Plants in Response to Biochar and Microbial Application at 4, 6, and 8 MST.

Treatment	Stem Diameter		
	4 MST	6 MST	8 MST
	.....cm......	....	....
Biochar			
B_0	8.17	16.66	182.08
B_1	6.08	13.13	167.96
B_2	8.64	15.94	184.75
B_3	10.40	16.40	166.17
Microbes			
M_0	8.75	15.36	36.76
M_1	8.38	16.78	35.95
M_2	8.59	14.75	37.83
M_3	7.57	15.23	37.19
Interaction			
B_0M_0	9.58	17.72	36.78
B_0M_1	8.93	18.78	39.65
B_0M_2	7.18	14.83	31.58
B_0M_3	6.97	15.32	39.03
B_1M_0	5.23	12.15	37.53
B_1M_1	7.27	15.10	34.73
B_1M_2	4.98	11.62	29.52
B_1M_3	6.85	13.63	42.03
B_2M_0	7.97	15.63	38.22
B_2M_1	8.32	17.55	35.20
B_2M_2	11.03	16.38	39.02
B_2M_3	7.25	14.18	38.87
B_3M_0	12.23	15.95	36.90
B_3M_1	9.00	15.70	33.35
B_3M_2	11.15	16.15	41.55
B_3M_3	9.22	17.80	36.95

Based on Table 2, the results of the study indicate that the application of biochar, microbes, or a combination of both did not have a significant effect on sorghum stem diameter at 4, 6, and 8 weeks after sowing. A DMRT test at the 5% level placed all treatments in the category of not significantly different (NSD). However, descriptively, a positive trend was observed in treatments B2(80 g/plant) and B3(120 g/plant), which tended to increase stem diameter. The highest values were recorded in treatment B3at 10.40 cm at 4 MST, and B3M2at 41.55 cm at 8 MST. This indicates that higher biochar doses have the potential to improve soil physical properties, increase cation exchange capacity, and prolong nutrient release to the root zone.

The statistically insignificant response in stem diameter may be due to its slower and more complex growth nature compared to plant height, as it depends on cambium activity and secondary tissue growth. Additionally, the slow decomposition of biochar causes nutrient release to occur gradually and not yet be optimally absorbed during the early vegetative phase (Malik *et al.*, 2022) . Environmental factors such as plant density and low light intensity also trigger competition among individual plants, so growth is directed more toward stem elongation rather than thickening (*et al.*, 2022) . On the other hand, the synthesis of cytokinin, a hormone involved in stem cell division, is highly dependent on nutrient balance and supportive environmental conditions (Battong *et al.*, 2020). Thus, although not yet significantly effective, the combination of high-dose biochar and microbes, as in treatment B3M(2),shows potential in increasing sorghum stem diameter.

Number of Leaves

Leaf number is an important indicator for assessing a plant’s photosynthetic capacity, as leaves serve as the primary organs in light capture and energy synthesis. An increase in leaf number is directly related to vegetative growth potential and plant biomass accumulation.

Table 3. Number of Sorghum Leaves in Response to Biochar and Microbial Application at 2, 4, 6, and 8 MST

Treatment	Number of Leaves			
	2 MST	4 MST	6 MST	8 MST
	....	.....cm......	....	....
Biochar				
B_0	3.38	5.04	8.21	10.13
B_1	3.00	4.21	6.75	9.29
B_2	3.29	5.17	7.63	9.38
B_3	3.33	5.21	7.13	9.42
Microbes				
M_0	3.25	4.92	7.42	9.79
M_1	3.25	4.96	7.67	9.67
M_2	3.46	4.75	7.54	9.08
M_3	3.04	5.00	7.08	9.67
Interaction				
B0M0	3.67	5.17	8.67	10.50
B0M1	3.33	5.00	8.67	10.00
B0M2	3.50	4.67	8.17	9.83
B0M3	3.00	5.33	7.33	10.17
B1M0	2.83	4.17	6.50	8.67
B1M1	3.17	4.67	6.67	9.50
B1M2	3.17	3.50	6.17	9.17
B1M3	2.83	4.50	7.67	9.83
B2M0	3.17	4.67	7.67	10.00
B2M1	3.17	5.33	8.00	9.33
B2M2	3.67	5.67	8.17	8.83
B2M3	3.17	5.00	6.67	9.33
B3M0	3.33	5.67	6.83	10.00
B3M1	3.33	4.83	7.33	9.83
B3M2	3.50	5.17	7.67	8.50
B3M3	3.17	5.17	6.67	9.33

Based on Table 3, the application of biochar, microbes, or a combination of both did not have a significant effect on the number of sorghum leaves at 2, 4, 6, and 8 MST according to the DMRT test at the 5% level. However, descriptively, the B0 M0 interaction showed the highest result with an average of 10.50 leaves at 8 MST, indicating a positive response to the combination of stable soil conditions (without biochar) and the presence of natural microbes. Although B0is not a treatment involving biochar addition, the higher response is likely due to soil conditions that were already sufficiently supportive physically and chemically, allowing microorganisms to play an optimal role in enhancing nutrient availability. This aligns with the report by(2023) , which states that soil microorganisms contribute to improving soil structure and enhancing nutrient uptake efficiency through synergistic interactions with organic compounds such as biochar.

On the other hand, treatments B(2),M2,and B(0),M1also showed relatively high results during the late vegetative phase, reinforcing the assumption that the balance between carbon supply from biochar and the role of microbes in phytohormone production (e.g., auxin and cytokinin) also influences leaf growth dynamics.

Leaf Area

Leaf area is an important physiological parameter that plays a role in determining photosynthetic capacity and light absorption efficiency by plants. The larger the leaf surface area, the greater the plant's potential to produce energy to support growth and development. Leaf area is also frequently used as an indicator of plant response to fertilization treatments or environmental stress, such as salinity.

Tabel 4. Leaf Area of Sorghum Plants in Response to Biochar and Microbial Application at 4, 6, and 8 MST

Treatments	Leaf Area		
	4 MST	6 MST	8 MST
	.....cm......	....	....
Biochar			
B_0	122.08	260.45	383.09
B_1	74.18	198.04	354.11
B_2	118.81	236.83	384.18
B_3	137.75	218.68	344.05
Microbes			
M_0	123.54	213.67	354.20
M_1	120.46	262.19	383.96
M_2	111.79	215.56	368.04
M_3	97.03	222.59	359.23
Interaction			
B_0M_0	124.65	281.44	410.95
B_0M_1	158.42	308.61	391.15
B_0M_2	101.66	224.67	355.39
B_0M_3	103.60	227.10	374.88
B_1M_0	65.12	178.06	335.72
B_1M_1	91.91	225.09	375.05
B_1M_2	41.01	142.61	320.42
B_1M_3	98.66	246.41	385.24
B_2M_0	113.58	214.07	345.32
B_2M_1	126.84	269.38	420.08
B_2M_2	155.35	257.56	394.98
B_2M_3	79.47	206.33	376.35
B_3M_0	190.80	181.11	324.81
B_3M_1	104.68	245.68	349.54
B_3M_2	149.15	237.39	401.38
B_3M_3	106.39	210.53	300.44

The results in Table 4 show that the biochar, microbial, and their interaction treatments caused variations in sorghum leaf area at 4, 6, and 8 MST, although these differences were not statistically significant. Descriptively, the B3treatment showed the highest leaf area at 4 MST (137.75 cm²), while at 6 and 8 MST, the B0M1and B2M1combinations yielded the best responses at 308.61 cm² and 420.08 cm², respectively. This indicates that the interaction between biochar and microbes at certain doses can positively contribute to plant leaf area growth. The role of biochar in increasing leaf area is related to its ability to improve soil structure, enhance water and nutrient retention capacity, and support root development and microbial activity. Soil microbes, on the other hand, are capable of mobilizing nutrients and producing plant growth regulators such as auxins and cytokinins that stimulate leaf growth. This is supported by Alghamdi,(2018) , who states that biochar increases microbial activity and soil fertility, which impacts leaf area expansion. An-nafisa,(2023) , also indicates that applying biochar to marginal soils accelerates vegetative growth through increased soil biological activity. Meanwhile, Kartinaty *et al*., (2019) , confirm that the combination of biochar and microbes can enhance photosynthetic efficiency and nutrient uptake, thereby promoting the formation of larger leaves.

Panicle Length

Panicle length is a key yield component in cereal crops, including sorghum, as it is directly related to the potential number of seeds formed. Environmental factors and agronomic treatments such as the application of biochar and microbes can influence panicle development, particularly during the generative phase.

Table 5. Sorghum Panicle Length in Response
to Biochar and Microbial Application at 14 Days After Sowing.

Biochar	Microorganisms				Average
	M0	M1	M2	M3	
B0	30.83	21.83	24.67	24.83	25.54
B1	25.50	27.50	24.00	23.33	25.08
B2	22.67	21.00	21.83	20.17	21.42
B3	27.33	24.83	27.00	20.50	24.92
Average	26.58	23.79	24.38	22.21	

Based on Table 5, panicle length at 14 MST showed variations influenced by biochar and microbial treatments, both individually and in interaction. The highest panicle length was recorded in the B0 M0 combination (30.83 cm), i.e., without biochar or microbial treatment. Conversely, the B2M3combination treatment produced the shortest panicle, at 20.17 cm. In general, the highest average panicle lengths were found in the B0(25.54 cm) and M0(26.58 cm) treatments, indicating that the use of biochar and microbes does not always result in increased panicle length. This suggests that the application of biochar or microbes must consider dosage, microorganism type, and soil conditions to yield positive effects on the plant's generative phase. Inappropriate dosages or treatment combinations may cause physiological disturbances or nutrient competition within the rhizosphere. This aligns with the findings of*et al*.., (2022) , which state that biochar at certain doses can reduce the efficiency of nutrient uptake, such as phosphorus and potassium, if not adjusted to the plant's needs. Additionally, Lubis and Hidayat,(2019) add that microbes incompatible with soil conditions can disrupt rhizosphere symbiosis and reduce nutrient uptake efficiency, ultimately negatively impacting panicle formation and development.

Panicle Weight

Panicle weight is one of the primary indicators in determining yield potential in sorghum, as it reflects the accumulation of generative biomass that occurs during the flowering phase through seed maturation. Factors such as nutrient availability, soil conditions, and the interaction between biochar and microbes can influence panicle formation and filling.

Table 6. Sorghum Panicle Weight in Response
to Biochar and Microbial Application at 14 Days After Sowing.

Biochar	Microbes				Average
	M0	M1	M2	M3	
B0	18.93	14.07	17.65	24.83	18.87
B1	14.57	20.83	18.03	17.72	17.79
B2	18.98	24.93	18.02	14.67	19.15
B3	34.25	13.68	14.03	14.55	19.13
Average	21.68	18.38	16.93	17.94	

Based on Table 6, panicle weight at 14 MST varied in response to biochar and microbial treatments. Treatment B3M0produced the highest panicle weight of 34.25 g, indicating a positive effect of biochar without added microbes on generative yield. Conversely, the lowest panicle weight was recorded in the B3M1treatment (13.68 g), indicating that the combination of high-dose biochar and M1microbes may not be synergistic under the existing environmental conditions. The highest average panicle weight was generally obtained in the B2biochar treatment (19.15 g), indicating that a moderate dose of biochar exerts a stable effect on yield accumulation. Additionally, the average for the treatment without microbes (M0) yielded higher values compared to treatments with other microbes, indicating that microbial effectiveness is highly dependent on biological compatibility with soil conditions and the plant's growth stage.

The increase in panicle weight in some biochar treatments supports the findings of*et al*., (2022), which explain that biochar can improve soil structure and increase the availability of major nutrients such as nitrogen and potassium, which play a direct role in panicle formation and filling. Meanwhile, negative results in certain combinations with microbes, such as in B3M1, can be explained by Batista *et al*., (2021), which state that mismatches between microbial types and growing conditions can disrupt plant physiological processes, including reductions during the yield formation phase. Thus, the use of biochar has proven to be a potential method for increasing sorghum panicle weight; however, microbial application must be adapted to agroecosystem conditions to ensure that interactions do not have a counterproductive effect on crop yield.

Number of Seeds per Panicle

The number of seeds per panicle is a key yield component reflecting the success of flowering and seed formation in cereal crops. This parameter is significantly influenced by nutrient availability, plant physiological conditions, and agronomic treatments such as the application of biochar and microbes.

Table 7. Number of Seeds per Panicle of Sorghum in Response to Biochar and Microbial Application at 14 Days After Sowing.

Biochar	Microorganisms				Average
	M0	M1	M2	M3	
B0	56.50	68.33	60.83	66.17	62.96 b
B1	62.50	74.50	72.33	65.67	68.75 ab
B2	73.33	72.00	71.50	81.33	74.54 a
B3	66.17	64.50	81.67	63.67	69.00 ab
Average	64.63	69.83	71.58	69.21	

Note: Numbers followed by different letters in the same column are significantly different at the 5% significance level according to DMRT

The relationship between biochar application and the number of seeds per panicle at 14 MST is shown in Figure 1.

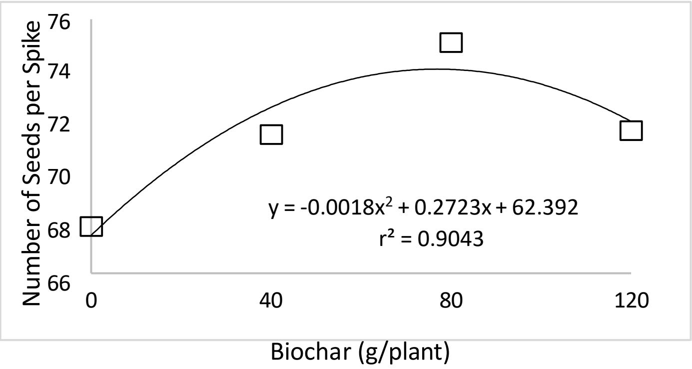

Figure 1. Graph of the Number of Seeds per Panicle of Sorghum Plants at 14 MST in Relation to Biochar Application

Based on the data in Table 7, the biochar and microbial treatments had a significant effect on this parameter. Treatment B2M3(80 g/plant biochar and 15 ml M3microbes) yielded the highest result at 81.33 seeds per panicle, while the lowest result was recorded for B0M0(56.50 seeds), i.e., the treatment without biochar or microbes. Statistically, the biochar treatment B2(80 g) yielded a significantly higher mean (74.54 a) compared to treatment B0(62.96 b), indicating that this dose is the most effective in enhancing generative yield. This trend aligns with Figure 1, which shows a positive quadratic relationship between biochar dose and the number of seeds per panicle, with the highest point at the 80 g/plant treatment. Beyond this point, there is a decrease in seed number, particularly at the highest dose (120 g/plant). The model yielded a coefficient of determination ($r^2 = 0.9043$), indicating that the variation in the number of seeds per panicle is largely explained by the variation in the applied biochar dose. These findings support the research results by Ginting,(2024) , which state that biochar can improve soil physical and chemical properties, such as aeration, water retention, and nutrient use efficiency, but only up to a certain dose. Excessive doses may reduce effectiveness due to the potential accumulation of compounds that interfere with nutrient availability or soil microbial activity. In addition to biochar, microbial effectiveness also contributes to increased seed yield, as evidenced by the high results in the B3M2combination (81.67 seeds). This indicates that the appropriate combination of biochar and microbes can synergistically enhance plant physiological efficiency. According toet al., (2021) , biochar improves soil conditions that support seed formation and filling, while Ullah et al., (2020) add that the success of the plant response is highly dependent on the compatibility between the type of microbes and soil conditions, as well as the soil amendment materials used, such as biochar. Thus, a dose of 80 g of biochar per plant can be recommended as the optimal dose to increase the number of seeds per sorghum panicle, especially when combined with suitable microbes.

Seed Weight per Panicle

Seed weight per panicle is a direct indicator of the final yield potential in sorghum plants, as it reflects the success of seed filling following the flowering and pollination processes. This parameter is influenced by nutrient uptake efficiency, photosynthetic activity, and the support provided by treatments during the generative phase.

Table 8. Grain Weight per Sorghum Panicle in Response
to Biochar and Microbial Application at 14 Days After Sowing (DAS).

Biochar	Microbes				Average
	M0	M1	M2	M3	
B0	19.13	14.03	11.48	17.53	3:55
B1	13:48	18:57	17:20	18:17	16:85
B2	18:37	25.18	20.30	6:23	20:52
B3	29:57	17:00	17:57	26.13	22.57
Average	20.14	18.70	16.64	20.02	

The result in table 8 show significant variation in seed weight among the biochar and microbial treatment combinations, reflecting the plants' physiological response to environmental conditions and agronomic treatments during the generative phase. The treatment combination B3M0(high-dose biochar without microbes) yielded the highest result with a seed weight of 29.57 g per panicle, while the lowest value was recorded for B0M2(11.48 g), i.e., the treatment without biochar and M2microbes. The highest average was found in the B3biochar treatment (22.57 g), indicating that a high dose of biochar (120 g/plant) is capable of supporting maximum seed filling. The effectiveness of B3in increasing seed weight per panicle indicates that high-dose biochar plays a role in improving soil characteristics, such as porosity, aeration, and cation exchange capacity (CEC). These improvements promote increased efficiency in the uptake of essential nutrients, particularly potassium and phosphorus, which are crucial during the seed formation and filling process (Agustina, 2018) . Potassium supports the transport of photosynthates to the panicle, while phosphorus is required for energy synthesis and cell division during the seed-filling phase. Meanwhile, the effects of microbes showed more varied results. The microbial treatment M2tended to produce lower seed weights, as seen in the combinations B0M2and B1M2, indicating that microbial inoculation does not always yield positive effects. This is likely due to a mismatch between the type of microbes used and the plant's growth stage, or the edaphic conditions of the experimental site. According to Suryantini,(2017) , the effectiveness of microbial inoculation depends heavily on the synchronization of the plant's physiological needs and soil environmental dynamics; thus, the selection of microbial types must consider the timing of application and the plant's developmental stage. In general, these results indicate that biochar plays a more consistent and significant role than microbes in increasing seed weight per sorghum panicle, particularly at high doses that significantly improve soil physical and chemical properties. However, the integration of biochar and microbes still has the potential to yield the best results if the suitability of microbial type, dose, and application timing can be optimized according to plant needs.

Seed Weight per Plant Plot

Seed weight per plot is one of the primary parameters for assessing total crop productivity per unit area. This parameter represents actual yield, which is influenced by the accumulation of individual yields per plant as well as the success rate of generative growth.

Table 9. Seed Weight per Plot of Sorghum Plants in Response to Biochar and Microbial Application at 14 Days After Sowing.

Biochar	Microbes				Average
	M0	M1	M2	M3	
B0	56.70	39.07	54.90	79.93	57.65a
B1	38.10	39.17	27.80	30.83	33.98b
B2	42.50	68.07	47.23	42.33	50.03ab
B3	82.47	65.07	37.80	44.23	57.39a
Average	54.94	52.84	41.93	49.33	

Note: Numbers followed by different letters in the same column are significantly different at the 5% significance level according to DMRT

The relationship between biochar application and the number of seeds per panicle at 14 MST is shown in Figure 2.

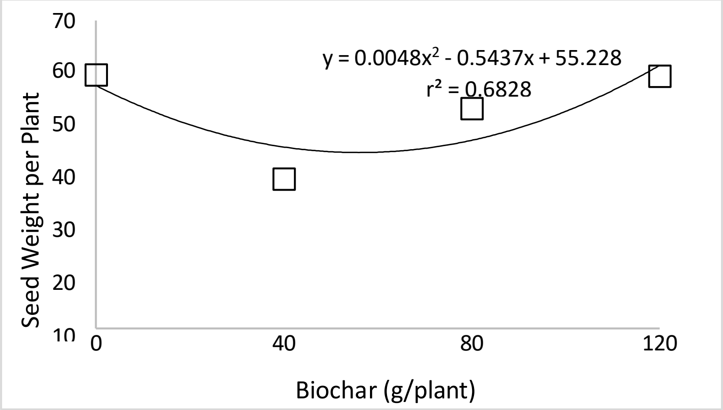

Figure 2. Seed Weight per Plot of Sorghum Plants at 14 MST in Relation to Biochar Application.

Based on Table 9, the biochar and microbial treatments showed a significant effect on seed weight per plot at 14 MST. Treatment B3M0(high-dose biochar without microbes) yielded the highest seed weight of 82.47 g, while treatment B1M2showed the lowest result of 27.80 g. Statistically, treatments B0(no biochar) and B3(120 g/plant) were not significantly different, but both were significantly higher than treatment B1(40 g/plant), which served as the critical point for yield decline. Interactions among treatments indicate that high-dose biochar has the potential to increase yield, particularly if not combined with microbes that could potentially disrupt soil biotic balance under certain conditions. The highest average yields were generally obtained in treatments B0and B3, at 57.65 g and 57.39 g, respectively, while B1yielded only an average of 33.98 g, representing a yield reduction of over 40%. This indicates that the application of biochar at low doses actually has a negative impact on seed yield, likely due to disruptions in nutrient availability, soil pH, or the activity of natural microbes that have not yet stabilized (Ilahi and Sefano, 2025). Figure 2 supports this analysis, as shown by the quadratic regression model $y = 0.0048x^2 - 0.5437x + 55.228$, with an r^2 of 0.6828. This pattern indicates that seed weight (y) exhibits a concave relationship with biochar dose (x), with a positive quadratic coefficient ( ) indicating an increase in seed weight after passing the minimum point. Based on the first derivative calculations, the lowest point is estimated to occur at a dose of ±56.6 g/plant, which aligns with empirical observations in the range of ±40 g/plant with the lowest weight around 34 g. After this dose, seed weight increases again until, at a dose of 120 g/plant, it approaches the initial weight (±58–60 g). This implies that biochar at high doses begins to demonstrate positive functions as a soil ameliorant, including improved porosity, increased water and cation retention capacity, and support for photosynthetic efficiency and the transport of assimilates to the seed (Wortel, 2023) . However, an R^2 value that has not yet reached 0.70 indicates that there are other variables beyond biochar dosage that also influence seed weight, such as variations in microbial types, soil fertility status, microclimate, or the plant's physiological adaptation to environmental conditions. Thus, an integrative approach that considers the interactions among these factors is crucial for optimizing sorghum crop yields. The application of biochar at the appropriate dose and in a context-specific manner will promote sustainable productivity, in line with the findings of "and Akbar,(2025) , which emphasizes the importance of synergy between organic inputs and agroecosystem management.

100-Grain Weight

The 100-seed weight is a key indicator for assessing the quality of cereal crop yields, as it reflects seed size, density, and filling efficiency, which are closely related to the plant's ability to allocate photosynthetic products during the seed-filling phase.

Table 10. 100-Seed Weight of Sorghum Plants in Response to Biochar and Microbial Application at 14 Days After Sowing.

Biochar	Microbes				Average
	M0	M1	M2	M3	
B0	33.33	20.37	20.12	26.07	24.97
B1	21.11	25.13	25.01	27.11	24.59
B2	24.44	35.75	27.31	22.45	27.49
B3	44.10	25.58	21.51	41.29	33.12
Average	30.74	26.71	23.49	29.23	

Based on Table 10, the biochar and microbial treatments showed variations in the weight of 100 sorghum seeds at 14 MST. The B3M0combination treatment yielded the highest weight of 44.10 g, while the lowest weight was obtained in the B0M2treatment at 20.12 g. The highest average was generally found in the B3biochar treatment (33.12 g), indicating that high-dose biochar application tends to support improved seed quality. However, no statistically significant differences were found among treatments, so the effects of biochar and microbes on the weight of 100 seeds cannot yet be categorized as significant. This lack of significance is likely due to the dominant role of genetic factors in determining seed size and weight. The 100-seed weight trait has high heritability and is generally more stable against environmental influences(Tarigan *et al.*, 2015) , so agronomic treatments such as biochar and microbes have a limited impact. Additionally, external environmental factors such as high rainfall, nutrient leaching, or water stress occurring during the reproductive phase can affect the seed-filling process, resulting in smaller and lighter final seeds.

Biochar is indeed known to improve the microenvironment in the root zone through increased water retention and gradual nutrient release, as reported by (Azeem et al., 2019) . However, its effectiveness on 100-seed weight will depend heavily on environmental stability and soil carrying capacity. On the other hand, the effect of microbes showed inconsistent responses, with treatment M2generally yielding lower values than the others. This confirms that the success of microbial inoculation is highly determined by the type of microbes used, soil conditions, and their compatibility with the organic carrier material (Ali et al., 2019) . Overall, although not statistically significant, the trend of increased 100-seed weight at high biochar doses still indicates potential that warrants further investigation.

Further studies considering application timing, biochar quality, and microbial formulations more adapted to local conditions could enhance the effectiveness of both treatments in supporting seed quality. These findings also support the report by Hasibuan et al.., (2022) that the weight of 100 seeds tends to show stability across environments, making the breeding of superior varieties the primary strategy for improving this trait.

CONCLUSION

Biochar application demonstrated a significant effect on several growth and yield parameters of sweet sorghum in saline soil. A dose of 80 g/polybag was shown to significantly increase the number of seeds per panicle and seed weight per plot. The response to biochar followed a quadratic regression curve, indicating the importance of determining the appropriate dose for its application. Although microbial application did not have a statistically significant effect, certain combinations showed a positive trend. Therefore, the use of biochar as a soil amendment on seawater-intruded land has the potential to support sustainable agricultural productivity, especially when combined with suitable microbes and tailored to edaphic conditions and plant growth stages.

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