



Synergistic Effects of Sewage Sludge and Carbon-Based Composite Fertilizer on Growth, Yield, and Soil Health in Rice (*Oryza sativa*)

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Abstract

*The management of sewage sludge (SS), a nutrient-rich byproduct of wastewater treatment, presents a significant challenge and opportunity for sustainable agriculture. Utilizing SS on cultivated land offers an environmentally friendly alternative to storage or incineration, supporting a circular economy. This study, conducted in a wire-house facility at the University of Agriculture Faisalabad's Institute of Soil and Environmental Sciences (ISES), investigated the effects of SS and carbon-based composite fertilizer (CBCF) on the growth and yield of rice (*Oryza sativa*). A pot experiment arranged in a Completely Randomized Design (CRD) with three replications evaluated two application rates of SS (1% and 2%) and CBCF (0.25% and 0.5%) under standard irrigation regimes. Data were collected on key agronomic parameters, including shoot length, fresh and dry biomass of shoots and roots, hundred-grain weight, and post-harvest soil properties like electrical conductivity (EC) and sodium adsorption ratio (SAR). Analysis of variance (ANOVA) revealed that while yield was affected by irrigation levels, the application of soil amendments significantly enhanced plant growth. Specifically, the 2% SS treatment was more effective than 1% in promoting shoot and root length. The combination of 2% SS and 0.5% CBCF, which provided a higher organic matter content, was particularly effective, suggesting that the addition of these organic amendments can be a promising strategy for mitigating the adverse effects of soil salinity and water stress, thereby improving crop productivity.*

1. Introduction

The escalating volume of ash and sewage sludge (SS) waste from energy production and wastewater treatment presents a significant environmental challenge, particularly in rapidly urbanizing nations like Pakistan. The expansion of wastewater treatment infrastructure, while crucial for public and environmental health, results in the continuous generation of SS—a complex mixture of water, organic matter, pathogens, and inorganic elements, including potential heavy metals (B. K. Singh et al., 2023). This creates a pressing waste management dilemma; if not managed properly, SS can contribute to soil degradation, water contamination, and greenhouse gas emissions from landfills. Concurrently, modern agriculture faces the dual pressures of depleted soil fertility and the inefficient use of conventional

mineral fertilizers, which often lead to nutrient runoff, ecosystem eutrophication, and the unsustainable depletion of finite resources such as phosphate rock (Kopittke et al., 2019). Within this context, a circular economy approach that views waste as a resource is imperative. The land application of SS aligns with this principle, offering a strategy for waste reduction while simultaneously recycling valuable nutrients and organic matter back into agricultural soils. This practice can enhance soil structure, water retention, and microbial diversity, thereby reducing the burden on landfills and the dependence on synthetic fertilizers (Sharma et al., 2022).

Rice (*Oryza sativa* L.) is a cornerstone of global food security, serving as a staple for over half the world's population and is of paramount importance in Pakistan's agrarian economy. However, stagnant yields and nutrient-deficient grains pose significant challenges to meeting the

demands of a growing population. Traditional rice cultivation systems are often characterized by low nutrient use efficiency, particularly for micronutrients like zinc and iron, which are crucial for both plant health and human nutrition (Bashir et al., 2023). This deficiency is exacerbated in intensively cultivated soils that are low in organic matter, a common feature in many regions of South Asia. Enhancing the organic carbon content of these soils is recognized as a fundamental strategy for improving soil fertility and crop productivity, creating a clear intersection between the need for sustainable soil management and the opportunity to utilize organic waste streams.

While the benefits of SS are notable, its direct application is not without risks, primarily concerning the potential accumulation of heavy metals, organic pollutants, and the introduction of pathogens into the food chain. These concerns necessitate treatment and strategic application methods to mitigate associated environmental and health risks. Recent research has focused on combining SS with other materials to enhance its safety and efficacy. Co-composting SS with carbon-rich biomass or its integration with adsorbent materials like biochar has shown promise in immobilizing heavy metals and reducing pathogen load, thereby transforming SS into a more stable and safer soil amendment (Hussain et al., 2021). This synergy forms the basis for developing advanced soil amendments that maximize benefits while minimizing potential hazards.

A promising advancement in this domain is the development of carbon-based composite fertilizers (CBCFs). These formulations are engineered to improve the efficiency of conventional fertilizers by controlling the release of nutrients, thereby minimizing environmental losses through leaching, volatilization, and runoff (Ran et al., 2025). CBCFs function by using carbon-rich materials, such as biochar, as carriers that can reduce the soil's strong binding affinity for certain nutrients, particularly phosphorus, making them more available to plants over an extended period (Ma et al., 2025). The integration of processed SS into such value-added products could synergistically address waste management and agricultural productivity challenges by creating a slow-release nutrient source that also builds soil organic carbon. This study therefore posits that the co-application of sewage sludge and a novel carbon-based micro-fertilizer composite will create a synergistic effect, enhancing soil health and nutrient use efficiency beyond what either amendment can achieve alone. We hypothesize that this combined application will significantly improve the growth, yield, and nutritional quality of rice by enhancing the bioavailability of essential micronutrients in the soil-plant system, modulating soil microbial activity, and ensuring the safe immobilization of any potential heavy metal contaminants.

The overarching goal of this research is to evaluate the agronomic efficacy and environmental feasibility of utilizing sewage sludge in conjunction with a carbon-based composite fertilizer for rice cultivation. The specific objectives are to quantify the effects of these amendments, both individually

and in combination, on the physicochemical and biological properties of soil, including nutrient availability, organic carbon content, and microbial biomass. Furthermore, the investigation aims to determine the subsequent impact on rice growth parameters, grain yield, and nutrient uptake efficiency, with a specific focus on micronutrient dynamics. A critical objective is to assess the safety of this approach by monitoring the bioavailability and translocation of heavy metals from the soil to the rice plant to ensure compliance with food safety standards. Ultimately, this work seeks to provide a scientific basis for a sustainable waste-to-resource strategy that can contribute to food security in Pakistan and similar regions.

2. Materials and Methods

The experimental soil was collected from the research fields of the Department of Soil and Environmental Sciences, University of Agriculture, Faisalabad. Samples were obtained from two distinct layers, specifically the topsoil from a depth of 0–15 cm and the subsoil from 15–30 cm, to ensure a representative profile. The collected soil was subsequently processed by air-drying, mechanically crushing, and sieving through a 2-mm mesh to homogenize the material and remove any coarse debris or plant matter. A comprehensive pre-experiment analysis was conducted to characterize the soil's fundamental physicochemical properties, which are detailed in Table 3.1. The soil was classified as sandy loam with a slightly alkaline pH of 7.45, an electrical conductivity of 1.98 dS m⁻¹, and an organic matter content of 0.55%.

A pot-based experiment was established using a Completely Randomized Design comprising a total of twenty-seven experimental units, with each of the nine treatments replicated three times. Each pot was uniformly filled with eight kilograms of the prepared soil. The treatment scheme was designed to evaluate the individual and combined effects of sewage sludge and a carbon-based composite fertilizer. The specific treatments included a control with no amendments, singular applications of sewage sludge at one and two percent, singular applications of the carbon-based composite fertilizer at 0.25 and 0.5 percent, and their various combinations to assess potential synergistic effects.

Treatment plan

T0: Control (No amendment)

T1: (Sewage Sludge=1%, Carbon-based composite fertilizer=0.25%)

T2: (Sewage Sludge=2%, Carbon-based composite fertilizer=0.5%)

T3: (Sewage Sludge=2%, Carbon-based composite fertilizer=0.25%)

T4: (Sewage Sludge=1%, Carbon-based composite fertilizer=0.5%)

T5: (Sewage Sludge=1%)

T6: (Sewage Sludge=2%)

T7: (Carbon-based composite fertilizer=0.25%)

T8: (Carbon-based composite fertilizer=0.5%)

A detailed soil analysis was performed using standardized laboratory protocols. Soil texture was determined via the hydrometer method, while the saturation percentage was assessed gravimetrically. The pH and electrical conductivity of the saturation extract were measured using calibrated digital meters. Soil organic matter was quantified using the Walkley and Black method, and the cation exchange capacity was determined through sodium acetate extraction followed by flame photometric analysis of sodium. Macronutrient analysis included the determination of total nitrogen by the Kjeldahl method, available phosphorus by spectrophotometry, and extractable potassium by flame photometry. The sodium adsorption ratio was calculated from the concentrations of sodium, calcium, and magnesium ions in the soil solution. The quality of the irrigation water was also assessed, revealing a pH of 8.57, an electrical conductivity of 0.73 dS m^{-1} , and a residual sodium carbonate value of -2.8 meq L^{-1} .

Rice cultivation was initiated using the Kinaat 1121 and Super Basmati varieties. A basal application of nitrogen, phosphorus, and potassium was administered using urea, diammonium phosphate, and sulfate of potash, respectively, in accordance with local agronomic recommendations. The carbon-based composite fertilizer was applied in two split doses, with the second application occurring two weeks after the initial dose. Weed management was implemented six weeks post-sowing using a selective herbicide to ensure unimpeded crop growth.

At physiological maturity, a suite of plant parameters was recorded. This included morphometric measurements such as plant height and root length, biomass assessments including fresh and dry weights of shoots and roots, and yield components including grain yield per plant and the weight of one thousand grains. Physiological evaluations were also conducted; chlorophyll content was measured non-destructively with a SPAD meter, and leaf relative water content was determined to assess plant water status using the standard formula involving fresh, turgid, and dry weights.

All collected data were subjected to rigorous statistical scrutiny. A one-way analysis of variance was performed to determine the significance of treatment effects. Where the ANOVA indicated significant differences, treatment means were separated using the Least Significant Difference test at a five percent probability level. The entire statistical analysis was conducted using the Statistix 8.1 software package to ensure robust and reliable interpretation of the experimental results.

3. Results and Discussion

Agronomic attributes

3.1 Plant height

The experimental findings revealed a significant increase in the plant height of rice (*Oryza sativa*) under the

T₂ treatment, which combined 2% sewage sludge (SS) and 0.5% carbon-based composite fertilizer (CBCF). This treatment produced the tallest plants ($\approx 137 \text{ cm}$), statistically grouped as “a,” indicating its superiority over all other treatments. In contrast, the lowest plant height was recorded in T₀ (control, without amendments), while T₇ (0.25% CBCF) also showed comparably lower growth, with both treatments placed in the “d” statistical group. These results highlight the substantial role of organic and carbon-based amendments in regulating rice growth, where the synergistic effects of SS and CBCF in T₂ markedly enhanced plant development compared to the control and lower amendment levels.

The observed increase in plant height under T₂ can be attributed to several complementary mechanisms. Sewage sludge provides abundant macronutrients (N, P, K) and micronutrients (Fe, Zn, Cu) that are essential for photosynthesis and protein synthesis, while CBCF enhances nutrient retention by increasing the soil’s cation exchange capacity and buffering ability, ensuring a steady nutrient supply to the crop (Lehmann et al., 2011). Moreover, the interaction between sewage sludge-derived labile carbon and the stable carbon fraction in CBCF promotes organo-mineral associations, reduces nutrient leaching, and improves soil aggregation and water-holding capacity, thereby creating favorable conditions for root growth and efficient nutrient uptake (de Jesus Duarte et al., 2019). This enhanced root-soil interaction is directly reflected in improved vertical growth of rice.

In addition, the combined amendment stimulates microbial biomass and enzymatic activity involved in C, N, and P cycling, facilitating the mineralization of nutrients into plant-available forms such as nitrate and phosphate (J. Zhou et al., 2019). The carbon-rich surface of CBCF also adsorbs potentially toxic compounds present in sewage sludge, reducing their inhibitory effects on plant physiology and fostering a healthier rhizosphere environment (Beesley et al., 2011). Importantly, the immobilization of heavy metals such as Cd, Pb, and Cr by functional groups on CBCF minimizes metal bioavailability and stress in rice plants, allowing metabolic energy to be invested in growth rather than defense responses (J. Zhang et al., 2016). Nutrient enrichment further stimulates the biosynthesis of plant growth hormones such as gibberellins, auxins, and cytokinins, with gibberellins in particular promoting stem elongation and contributing to the observed increase in plant height (Yatoo et al., 2021).

By contrast, the poor performance of T₇, amended with only 0.25% CBCF, suggests that such a low dose is insufficient to provide adequate nutrients, stimulate microbial activity, or create strong soil structural improvements. Similarly, the control treatment lacking any organic or carbon input exhibited stunted growth due to nutrient deficiency and poor soil conditions. The intermediate treatments (T₁, T₃, T₄, T₅, T₆, T₈) showed moderate effects but remained statistically lower than T₂, demonstrating that both the concentration and combination of SS and CBCF are critical for optimizing rice growth as in Figure 1.

Overall, these results demonstrate that T₂ (2% SS + 0.5% CBCF) was the most effective treatment for enhancing rice plant height, driven by synergistic mechanisms involving nutrient enrichment, soil carbon stabilization, microbial stimulation, heavy metal immobilization, and hormonal regulation. This integrated amendment strategy not only improves productivity but also offers a sustainable pathway for the safe utilization of sewage sludge in agriculture, providing an important approach for optimizing rice cultivation while mitigating environmental risks.

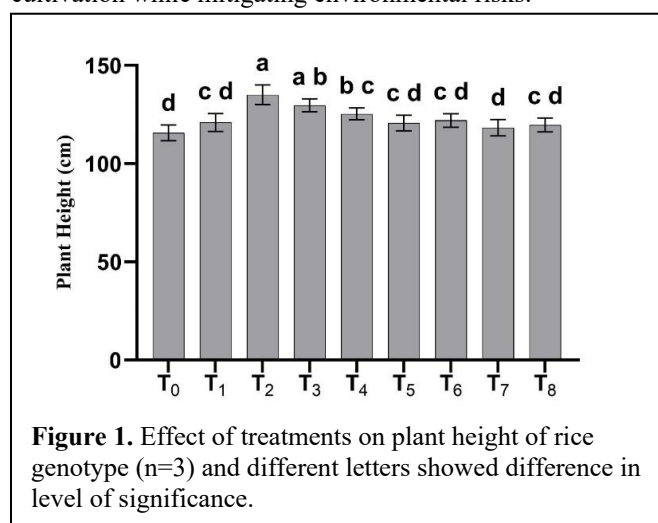


Figure 1. Effect of treatments on plant height of rice genotype (n=3) and different letters showed difference in level of significance.

3.2 Root Fresh and Dry weight

The results revealed that the root fresh weight of rice (*Oryza sativa*) was significantly influenced by the application of sewage sludge (SS) and carbon-based composite fertilizer (CBCF) at different levels. The maximum mean root fresh weight of 9.78 g was recorded under the combined application of 2% SS and 0.5% CBCF (T₂), whereas the minimum value of 6.73 g was observed in the control (T₀) as in figure 2. Treatments incorporating 2% SS consistently performed better than those with 1% SS, highlighting the importance of sufficient organic matter inputs for stimulating root biomass accumulation. The increase in root fresh weight with the application of SS and CBCF can be attributed to the combined improvement in soil fertility, structural stability, and microbial activity. Sewage sludge is rich in nitrogen, phosphorus, and organic matter, which enhance root elongation and biomass production, while CBCF provides stable carbon that improves cation exchange capacity, moisture retention, and the formation of organo-mineral complexes, leading to enhanced nutrient uptake and root growth efficiency (R. Singh & Agrawal, 2010).

The synergistic effect of SS and CBCF also plays a critical role in stimulating microbial-mediated nutrient cycling. Microbial activity stimulated by organic amendments enhances the mineralization of nutrients into plant-available forms, particularly nitrate and phosphate, which are crucial for root growth and metabolic processes (Y. Zhou et al., 2021). Furthermore, CBCF adsorbs and

immobilizes potential toxicants and heavy metals present in SS, reducing their bioavailability and protecting the root system from stress-induced damage (F. Zhang et al., 2020). This detoxification mechanism allows metabolic energy to be directed toward biomass accumulation rather than stress defense, contributing to greater root weight. Enhanced microbial interactions in the rhizosphere may also stimulate the production of plant growth-promoting substances such as indole-3-acetic acid (IAA), which further enhances root proliferation (Gutiérrez-Miceli et al., 2007).

The control treatment, which lacked any organic or carbon-based amendments, exhibited the lowest root fresh weight, reflecting nutrient deficiency, poor soil structure, and weak microbial activity. In contrast, treatments with balanced levels of SS and CBCF created more favorable physicochemical and biological conditions for root development. The results therefore emphasize that the co-application of 2% SS and 0.5% CBCF is the most effective strategy to promote root biomass accumulation in rice, ensuring both nutrient sufficiency and a healthier rhizosphere environment, thereby contributing to improved plant growth and productivity.

3.3 Plant fresh and dry weight

The application of sewage sludge (SS) and carbon-based composite fertilizer (CBCF) had a significant impact on both the fresh and dry weight of rice plants (*Oryza sativa*). The results demonstrate a clear positive effect on plant biomass accumulation, with the specific percentage of each amendment playing a crucial role in the outcome. For plant fresh weight, the maximum mean value of 71 grams was achieved with the specific treatment combination of 2% SS and 0.5% CBCF as in figure 3. This superior performance suggests a synergistic effect where the nutrient-rich composition of the sewage sludge is likely enhanced by the soil-conditioning properties of the carbon-based composite, improving nutrient availability and water retention. This is further supported by the general observation that treatments amended with 2% SS consistently resulted in greater fresh weight compared to those with 1% SS, indicating a dose-dependent response to the nutrient input from the sludge. In contrast, the control treatment (T₀), which lacked these amendments, yielded the minimum mean fresh weight of 59 grams, underscoring the necessity of supplemental fertilization for optimal growth.

A similar trend was observed for plant dry weight, a key indicator of the plant's accumulated solid biomass and overall health. The results highlight a maximum mean dry weight of 18 grams, although the specific treatment responsible for this peak is not explicitly stated in the provided text. The pattern of enhancement with higher SS application was consistent, as treatments containing 2% SS produced greater dry matter than those with 1%. This indicates that the benefits of the amendments are not merely due to increased water content but translate into substantial gains in permanent plant structure. The minimum mean dry weight of 13 grams was

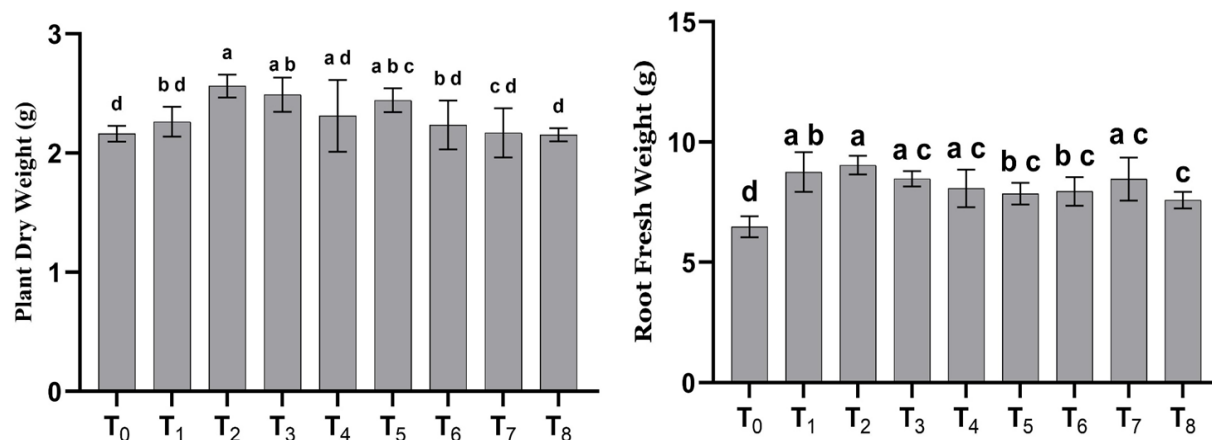


Figure 2: Roots fresh and dry weight under the influence of different treatments. (n=3) letters showed statistically significant values.

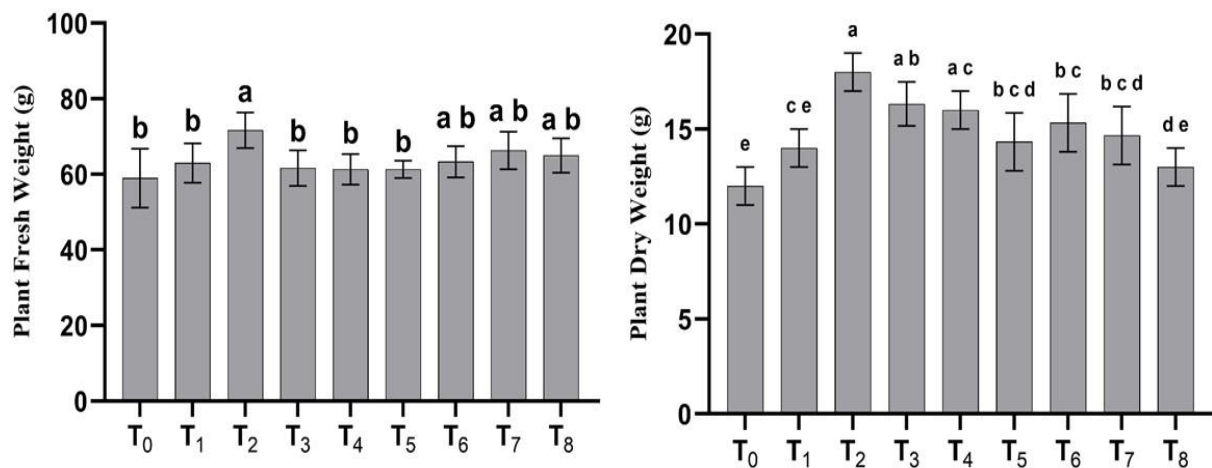


Figure 3: Plants fresh and dry weight under the influence of different treatments. (n=3) letters showed statistically significant values.

recorded for treatment T1. The fact that both fresh and dry weights were significantly influenced confirms that the application of SS and CBCF fundamentally improves the physiological growth and development of rice plants, likely through improved soil fertility, enhanced nutrient uptake, and potentially better root development (Bashir et al., 2023; Lehmann et al., 2011; Yatoo et al., 2021).

3.4 Yield parameters and mechanisms behind it

The application of sewage sludge (SS) and carbon-based composite fertilizer (CBCF) demonstrated a significant and multifaceted influence on the growth of rice (*Oryza sativa*), particularly in terms of biomass accumulation, while showing a more nuanced effect on the final grain yield. The data clearly indicate that these amendments are potent enhancers of vegetative growth. This was evidenced by the superior performance in both fresh and dry weight parameters, with the maximum mean fresh weight of 71 grams achieved under

the specific combination of 2% SS and 0.5% CBCF. The consistent finding that treatments with 2% SS outperformed those with 1% SS suggests a dose-dependent response, likely attributable to the higher nutrient load—particularly nitrogen, phosphorus, and organic matter—provided by the sewage sludge as in figure 4. The carbon-based composite fertilizer likely acted as a soil conditioner, improving soil structure, cation exchange capacity, and water retention, thereby enhancing the efficiency of nutrient uptake from the sewage sludge. This synergistic effect is starkly contrasted by the minimal biomass observed in the control treatment (T₀), which underscores the limitations of unamended soil in supporting robust plant development. The significant increase in dry matter, reaching up to 18 grams, confirms that the amendments contributed to the accumulation of essential structural biomass and not just transient water content. This points towards improved photosynthetic efficiency and

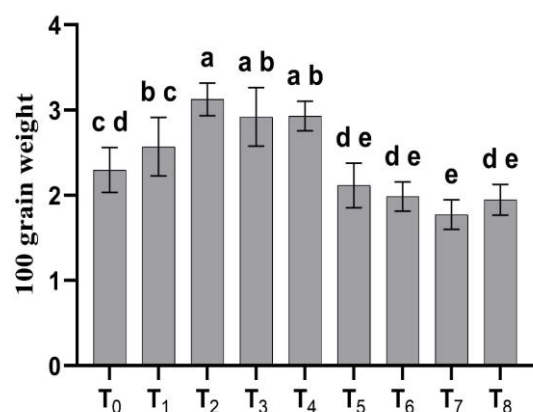


Figure 4: Yield values for 100 gm weight of rice production. (n=3)

overall plant health facilitated by the improved soil environment.

When considering the ultimate agricultural output, grain yield, the results present a critical distinction. While both SS and CBCF applications led to a statistically significant increase in grain yield compared to the control group, their effects were not significantly different from each other. This indicates that, despite their clear superiority over no treatment, the two amendments are similarly effective in promoting grain production in rice. The non-significant effect when comparing SS and CBCF directly suggests that both provide a comparable level of the essential nutrients required for the reproductive phase and grain filling. Therefore, the primary benefit of these amendments lies in their ability to alleviate soil nutrient deficiencies, which is a major constraint in the control group. Once this basic nutrient threshold is met by either SS or CBCF, additional factors beyond the specific type of organic amendment may become more influential in determining final yield differences. This highlights that for grain yield, the decision to use either SS or CBCF can be based on factors other than efficacy, such as availability, cost, or environmental considerations, as both are equally capable of enhancing yield over an unfertilized control.

4. Conclusions

In conclusion, this study demonstrates that the application of sewage sludge (SS) and carbon-based composite fertilizer (CBCF) serves as a highly effective strategy for enhancing the growth and yield of rice. The amendments significantly improved key vegetative growth parameters, with a clear, dose-dependent response observed for SS. The combination of 2% SS with 0.5% CBCF was identified as the most effective treatment, yielding the highest plant fresh and dry weights. This indicates a synergistic effect where the nutrient density of the sewage sludge is optimized by the soil-conditioning properties of the carbon-based composite, leading to improved nutrient uptake and plant development. Furthermore, while both SS and CBCF

significantly increased grain yield compared to the unamended control, their effects were statistically comparable to each other. This suggests that both organic amendments are viable and equally effective for boosting grain production. Finally, the improvements in post-harvest soil conditions suggest that these amendments can also play a crucial role in mitigating abiotic stresses such as salinity and water deficiency. Therefore, the incorporation of SS and CBCF into agricultural practice is recommended as a sustainable approach to enhance soil health, promote robust plant growth, and secure crop productivity.

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7. Authors Contribution:

Muhammad Zafar Iqbal: Investigations, Data Curation and Visualization, Writing Original Draft; Ahmer Saleem, and Usman Aslam: Supervision, Writing reviews and corrections.

8. Conflict of Interest:

Authors declare no conflict of interest.

9. Sustainable Development Goals

This study supports SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 6 (Clean Water and Sanitation).

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