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Research Article

Comparative effects of Organic and Inorganic Fertilization on the Morphological and Physiological traits of Sweet Corn (*Zea mays* var. *saccharata*)

Shobhana Singh[1*], Sumit Chaturvedi[1], Supriya[2] and Suranjana Biswas[1]

[1]*Department of Agronomy, College of Agriculture, G. B. Pant University of Agriculture and Technology, Pantnagar, U. S. Nagar, Uttarakhand, India*
[2]*ICAR-National Dairy Research Institute, Karnal*

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***Corresponding author:**
E-mail: shobhanasingh26@gmail.com

Abstract

The study was conducted at the Norman E. Borlaug CRC, GBPUAT, Pantnagar, Uttarakhand, during the Kharif season of 2020 to evaluates the impact of different fertilization strategies on the morphological and physiological traits of sweet corn (*Zea mays var. saccharata*), focusing on the efficacy of combining the Recommended Dose of Fertilizers (RDF) with enriched biochar (EB), vermicompost (VC), and micronutrients (µNM). The experiment was arranged in a RBD with eight treatments, including absolute control (T_1); 100% RDF through conventional fertilizer (T_2); 100% RDF with vermicompost (VC) 4t ha^{-1} (T_3); 100% RDF with EB 2t ha^{-1} (T_4); 75% RDF with VC 4t ha^{-1} (T_5); 75% RDF with EB 2t ha^{-1} (T_6); 75% RDF with VC 4t ha^{-1} +micronutrient mixture (T_7) and 75% RDF with EB 2t ha^{-1} micronutrient mixture(T_8).The 100% RDF + EB treatment was consistently superior in enhancing plant morphological and physiological parameters, including root dry weight, SPAD readings, and NDVI values, compared to conventional 100% RDF and other treatment combinations. Notably, the slow-release properties of biochar-coated urea in the EB treatments contributed to sustained nutrient availability, leading to improved chlorophyll content, photosynthetic efficiency, and net assimilation rates (NAR) during critical growth stages. These findings suggest that integrating biochar with conventional fertilization practices can optimize nutrient uptake, improve crop performance, and offer a sustainable alternative to traditional farming practices. This approach has significant implications for reducing reliance on chemical fertilizers while maintaining high productivity in sweet corn cultivation.

Key words: CGR, RGR, NAR, NDVI, Enriched biochar, BCU

1. Introduction

Sweet corn (*Zea mays* var. *saccharata*) is a highly valued crop, known for its sweet flavour and nutritional benefits (Barros and Passos, 2021; Qi *et al.* 2023). As the agricultural sector strives to balance productivity with sustainability, the choice between organic and inorganic fertilization practices has become a crucial topic of discussion (Climents and Giller. 2020; Zhang *et al.* 2022). While inorganic fertilizers are widely used for their immediate availability and nutrient content, they often lead to long-term soil degradation and environmental pollution (Ju *et al.* 2023). Conversely, organic fertilizers, derived from natural sources such as compost and manure, are praised for enhancing soil health and reducing environmental impact, though their effects on crop performance can vary (Nunes *et al.* 2023).

The morphological and physiological traits of sweet corn are critical indicators of plant health and productivity (Silva and Gama, 2022). Morphological traits, including plant height, root structure and leaf area, directly influence the plant's physical growth and yield potential (Tollenaar and Lee, 2002). Physiological traits, such as photosynthetic rate, chlorophyll content, and nutrient uptake efficiency, provide insight into the plant's internal processes and overall vitality (Evans, 1989). Understanding how different fertilization methods affect these traits is essential for optimizing agricultural practices.

This research aims to conduct a comprehensive comparison of the impacts of organic and inorganic fertilization on the morphological and physiological traits of sweet corn. By systematically analysing these effects, we seek to provide a clearer understanding of the benefits and limitations associated with each fertilization method. Our goal is to identify practices that maximize crop yield and quality while promoting sustainable agriculture.

The outcomes of this study will offer valuable insights for farmers, agronomists, and policymakers. By highlighting the specific advantages and potential drawbacks of organic and inorganic fertilizers, this research will contribute to more informed decision-making in the quest for sustainable and productive farming systems. Ultimately, the findings aim to support the broader adoption of practices that ensure both high agricultural output and long-term environmental health.

2. Materials and Methods

The field study was conducted at the Norman E. Borlaug CRC of G. B. Pant University of Agriculture and Technology, Pantnagar (located at the foothills of the Himalayas in the Tarai region at 29° North latitude, 79.3° East longitude, and an altitude of 243.83 meters above mean sea level) during the kharif season of 2020-21. The soil was sandy loam. In the experiment in case of Enriched biochar use of biochar coated urea was used and in rest of treatments conventional urea was used. An experiment laid in RBD design with 8 treatments viz., T_1: absolute control, T_2: 100% RDF through conventional fertilizer, T3: 100% RDF with vermicompost (VC) 4t ha^{-1}, T_4: 100% RDF with EB 2t ha^{-1}, T_5: 75% RDF with VC 4t ha^{-1}, T_6:75% RDF with EB 2t ha^{-1}, T_7: 75% RDF with VC 4t ha^{-1} +micronutrient mixture and T_8:75% RDF with EB 2t ha^{-1} micronutrient mixture.

2.1 Morphological parameters recorded

Such as LAI, CGR, RGR, NAR, and root dry weight were measured at 30, 45, 60 days after sowing (DAS) and at harvest

2.1.1 Leaf area index

The leaf area index (LAI) was calculated using the following formula:

$$\text{LAI} = \frac{\text{Average leaf area per plant(cm2)}}{\textit{Ground area per plant(cm2)}}$$

2.1.2 Crop growth rate

Crop Growth Rate (CGR) is the weight acquired per unit time in a unit area computed for intervals (0-30DAS, 30-60 DAS, and 60DAS-harvest) and represented as g $m^{-2}day^{-1}$. It was calculated by the formula:

$$\text{CGR} = \left(\frac{W_2 - W_1}{T_2 - T_1}\right)$$

W_1= dry matter production (g m^{-2}) at time t1

W_2= dry matter production (g m^{-2}) at time t2

T_1=days to first sampling

T_2= days to second sampling

2.1.3 Relative growth rate

Relative growth rate (RGR) is given as mg/g/day and is stated as the rate of growth per unit dry matter in a unit period for intervals (0-30 DAS, 30-60 DAS, and 60DAS-harvest).

It was calculated by the formula:

$$\text{RGR} = \frac{\text{Loge}W_2 - \text{Loge}W_1}{T_2 - T_1}$$

W_1= dry matter production (g m^{-2})) at time t_1

W_2= dry matter production (g m^{-2}) at time t_2

T_1=days to first sampling

T_2= days to second sampling

2.1.4 Net assimilation rate

Net assimilation rate (NAR) is the rate of net photosynthesis. The following formula was used to compute it.

Net assimilation rate (NAR) = $\frac{W2-W1}{t2-t1}$ x $\frac{loge\ A2 - loge\ A1}{A2-A1}$

W_1= dry matter production (g) at time t_1

W_2= dry matter production (g) at time t_2

t_1= days to first sampling

t_2=days to second sampling

A_1=leaf area (m^2) at time t_1

A_2=leaf area (m^2) at time t_2

It was computed and represented as g/m^2/day during the 30-45, 45-60, and 60 DAS-harvest stages.

2.1.5 Root dry weight

The root investigation was carried out at 60 DAS. Two plants that had been trimmed for dry matter were used for root sampling with the use of a core sampler of size (13 cm in height and 10 cm in diameter), and the average weight was expressed in grams per plant. Roots with soil were placed in a nylon net bag. To extract the roots, the dirt was carefully removed by washing under running water. The roots were dried in a drier at 70 ± 2^0C until they reached a constant weight.

2.2 Physiological parameters recorded

It including SPAD and GreenSeeker readings, were recorded at 60 DAS and at harvest, along with root dry weight at 60 DAS.

2.2.1 NDVI value

The NDVI value was measured using a green seeker, and readings were obtained at 60 DAS and harvest. The number offered a rough assessment of the health of the vegetation. The sensor emits red and infrared light and detects how much of each type of light is reflected by the plants. The crop will be healthier if the value is higher. The NDVI scale runs from -1 to +1.

$$\mathrm{NDVI} = \frac{NIRef - Redref}{NIRref + Redref}$$

Here, NIR_{ref} and Red_{ref} denote reflectance in the near infra-red and red band.

2.2.2 SPAD value

SPAD (Soil Plant Analysis and Development) displays plant greenness or chlorophyll content in terms of the chlorophyll content index, which is proportional to the plant's chlorophyll content and provides an indicator of the relative nitrogen content of the leaf. This device provides numerical information linked to leaf chlorophyll concentration by measuring transmitted radiation in the red (650 nm) and near infrared (940 nm).At 60 DAS and harvest, the SPAD value was determined from completely grown leaves. To prevent mistakes, the thick and pale veins of the leaves were avoided. The average value was taken noted of.

2.3 Statistical Analysis

The mean data on different characters were analyzed using ANOVA (analysis of variance) technique for the RBD design (Gomez and Gomez, 1984). Significantly different means were separated by critical difference test computed at 0.05 level of probability.

3. Results and Discussion

3.1 Morphological parameters

3.1.1 Leaf area index

The data presented in the **table 1** reveal a significant variation in leaf area index (LAI) as a result of different nutrient treatments. Specifically, the application of 100% RDF combined with EB led to an increase in LAI by 14.2% to 16.8% compared to 100% RDF alone. This enhancement was statistically similar to the treatments involving 100% RDF combined with VC, 75% RDF with EB, and 75% RDF with EB supplemented with micronutrients (µNM) at all observed growth stages (fig. 1). Similar result was reported by Zhang *et al.,* 2023. The observed increase in LAI is likely attributed to the optimized nutrient availability provided by these treatments, which facilitated sustained nutrient delivery throughout the crop's growth period (Singh *et al.*, 2023; Jang *et al.*, 2023). This, in turn, enhanced photosynthetic activity, thereby promoting superior leaf growth and development.

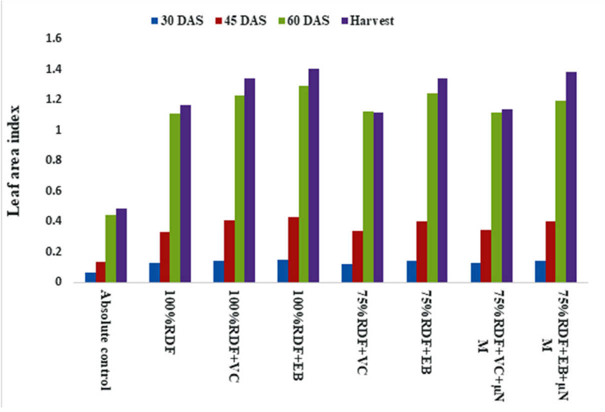

Fig 1: Effect of different treatments on leaf area index of sweet corn at different growth stages

Mithare *et al.* (2019) demonstrated that the application of various organic manures derived from livestock and poultry waste significantly enhanced growth parameters, including an increased leaf area index (LAI) reaching 5.57. Consistent with these findings, the current study revealed that the application of 100% RDF resulted in a significantly higher LAI compared to treatments that combined 75% RDF with organic amendments such as VC, EB, or their combinations with micronutrients (μNM). Although the addition of micronutrient mixtures to the 75% RDF treatments did not significantly elevate the LAI, the integration of 75% RDF+VC and its combination with micronutrients (75% RDF+VC+μNM) produced a notably higher LAI compared to the application of 100% RDF alone.

The observed superiority of 100% RDF in promoting LAI suggests that a full dosage of inorganic fertilizers may provide a more immediate and consistent nutrient supply, which is critical for maximizing leaf expansion and canopy development. This consistent nutrient availability likely supports higher photosynthetic efficiency, leading to more robust leaf growth. In contrast, while the 75% RDF treatments supplemented with organic inputs and micronutrients did enhance LAI, their effects were less pronounced, possibly due to the slower nutrient release rates from organic sources and the variable efficacy of micronutrient uptake (Singh *et al.,* 2023).

Table 1: Effect of balanced fertilization of organics and inorganics on leaf area index of sweet corn

Treatments	**Leaf area index**			
	30 DAS	**45 DAS**	**60 DAS**	**Harvest**
Absolute control	0.066	0.137	0.442	0.484
100% RDF	0.126	0.328	1.112	1.166
100% RDF+VC @ 4t/ha	0.141	0.407	1.232	1.341
100% RDF+EB @ 2t/ha	0.147	0.431	1.295	1.403
75% RDF+VC @ 4t/ha	0.121	0.340	1.120	1.117
75% RDF+EB @ 2t/ha	0.140	0.399	1.244	1.344
75% RDF+VC @ 4t/ha+μNM	0.126	0.342	1.118	1.138
75% RDF+EB @ 2t/ha+μNM	0.139	0.404	1.192	1.382
SEm ±	0.005	0.025	0.080	0.044
CD (5%)	0.014	0.07	0.241	0.133

3.1.2 Crop growth rate

CGR rate as measured by dry matter accumulation per day per unit area increased with crop age. The data indicated in table 2 that the crop growth rate peaked between 30-45 DAS and thereafter decreased. The treatment 100% RDF + EB resulted statistically at par CGR with 100% RDF+VC, 75% RDF+EB and 75% EB +μNM leading 12.30, 11.35, 11.75 and 11.25 g/m2/day, respectively greater CGR at 30-45 DAS (fig. 2). Furthermore, as compared to 100% RDF application, it produces non-significant effects after 45 DAS.

Mithare *et al.* (2019) found a similar trend in CGR during the crop period. In current study, 30-45 DAS, 100% RDF had a higher CGR value than 75% RDF treatments with various organics, *viz.*,75% RDF+VC, 75% RDF+EB, 75% RDF VC +μNM, and 75% RDF + EB +μNM. According to Islam *et al.* (2018), hybrid maize grown with varying amounts of rice husk biochar had a significant influence on maize growth. When soil was treated with rice husk biochar, it had the longest internodal length, the highest dry matter accumulation leading to the highest CGR. Application of micronutrient significantly increased CGR rate at 45-60 DAS as compared to non-micronutrient treatment application.

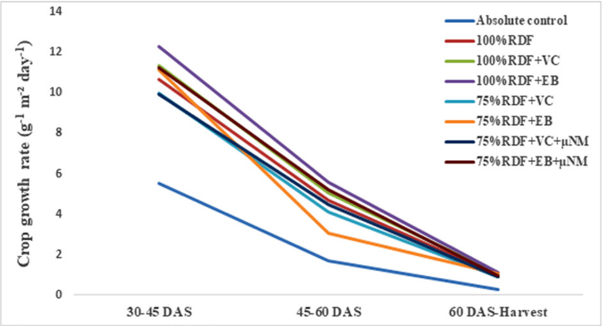

Fig 2: Effect of different treatments on crop growth rate of sweet corn at different growth stages

Table 2: Crop growth rate CGR (g^{-1} m^{-2} day^{-1}) of sweet corn under different treatment

Treatments	**CGR (g^{-1} m^{-2} day^{-1})**		
	30-45 DAS	**45-60 DAS**	**60- Harvest**
Absolute control	5.53	1.67	0.29
100% RDF	10.65	4.68	0.93
100% RDF+VC @ 4t/ha	11.35	5.03	1.08
100% RDF+EB @ 2t/ha	12.30	5.59	1.10
75% RDF+VC @ 4t/ha	10.00	4.12	0.89
75% RDF+EB @ 2t/ha	11.17	3.08	1.06
75% RDF+VC @ 4t/ha+µNM	9.94	4.45	0.90
75% RDF+EB @ 2t/ha+µNM	11.25	5.21	0.97
SEm ±	0.51	0.38	0.08
CD (5%)	1.55	1.14	NS

3.1.3 Relative growth rate

The RGR in **table 3** was determined by the ratio of newly generated photosynthates to existing ones per unit time. With the progression of plant growth, the RGR rapidly decreased from its initial high rate and stayed more or less constant between 45-60 DAS and 60DAS-harvest (fig. 3). At 30-45 DAS, the relative growth rate of 100% RDF+EB was the greatest, but it remained on par with 100%RDF+VC as compared to 100% RDF, there was an increase of 4.6%, respectively. Mithare *et al.* (2019) found a similar trend in RGR during the crop period. However, at 45-60 DAS and 60DAS-harvest, the difference was not significant. On the other hand, in present study when 75% RDF+EB and 75% RDF+EB+µNM with 100% RDF were compared and resulted out-yielded the RGR rate. The remaining treatments at a fertility level of 75% with organics produce negligible outcomes at RDF level of 100% effect of micronutrient resulted non-significant increment.

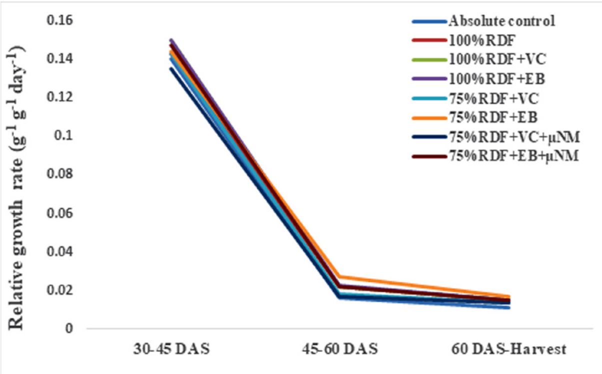

Fig 3: Effect of different treatments on relative growth rate of sweet corn at different growth stage

Table 3: Relative growth rate (g^{-1} g^{-1} day^{-1}) of sweet corn under different treatments

Treatments	**RGR (g/g/day)**		
	30-45 DAS	**45-60 DAS**	**60 Harvest**
Absolute control	0.140	0.016	0.011
100% RDF	0.143	0.022	0.015
100% RDF+VC @ 4t/ha	0.150	0.022	0.015
100% RDF+EB @ 2t/ha	0.150	0.023	0.015
75% RDF+VC @ 4t/ha	0.143	0.018	0.014
75% RDF+EB @ 2t/ha	0.144	0.027	0.017
75% RDF+VC @ 4t/ha+µNM	0.135	0.017	0.014
75% RDF+EB @ 2t/ha+µNM	0.147	0.022	0.015
SEm ±	0.003	0.002	0.001
CD (5%)	0.008	NS	NS

3.1.4 Net assimilation rate

The effect of various treatments on the NAR is detailed in table 4. During the 30-45 DAS period, there was a significant increase in NAR, with the highest recorded value of 9.20 g^{-1} m^{-2} day^{-1} under the 100% RDF combined with EB, followed by 100% RDF with vermicompost (VC) at 8.40 g^{-1} m^{-2} day^{-1}. This period is critical for vegetative growth, and the higher NAR values observed in these treatments indicate enhanced photosynthetic efficiency and biomass accumulation. The presence of biofertilizers and organic amendments likely contributed to improved nutrient uptake, leading to increased carbon assimilation and growth rates (Rehman *et al.*, 2023; Hnizil *et al.,* 2024).

During the 45-60 DAS period, NAR showed a substantial response to the treatments, with the highest rate of 4.92 g^{-1} m^{-2} day^{-1} observed in the 100% RDF + EB treatment. This remained statistically comparable to the 100% RDF + VC and 75% RDF + EB + μNM treatments, indicating that these combinations effectively sustained plant growth during this critical phase. The results suggest that the biofertilizer-enriched treatments continued to promote nutrient availability and uptake, thereby supporting ongoing photosynthetic activity and growth

In contrast, during the 60 DAS to harvest period, the NAR did not exhibit significant differences among the treatments. This lack of significant variation could be due to the natural decline in photosynthetic activity as the crop approaches maturity, where the demand for nutrients and growth rate slows down. The diminishing returns on NAR during this later stage highlight the importance of earlier nutrient management in maximizing crop productivity (Aloo *et al.*, 2022).

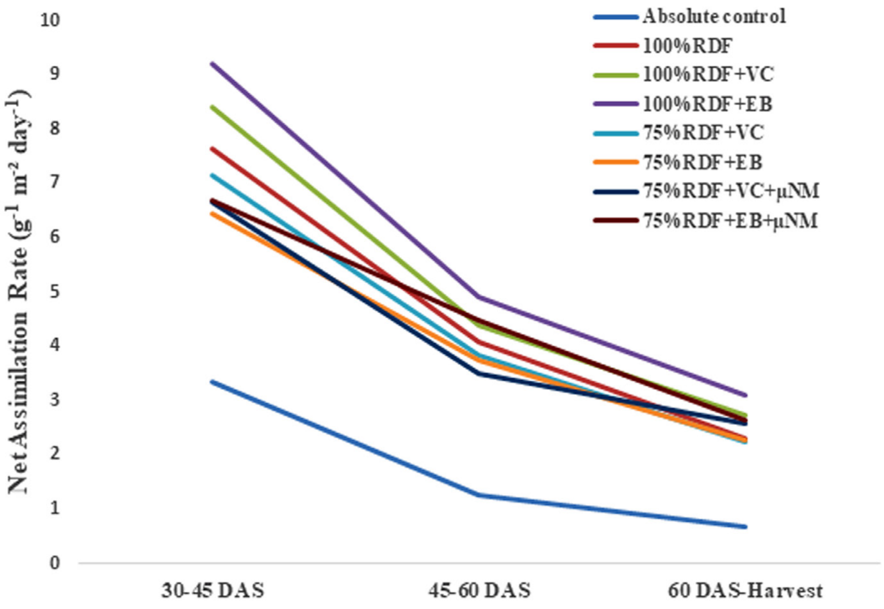

Fig 4: Effect of different treatments on net assimilation rate of sweet corn at different growth stages

Table 4: Net assimilation rate (g^{-1} m^{-2} day^{-1}) of sweet corn under different treatments

Treatments	**NAR (g^{-1} m^{-2} day^{-1})**		
	30-45	**45-60 DAS**	**60- HARVEST**
Absolute control	3.35	1.26	0.68
100% RDF	7.65	4.07	2.29
100% RDF+VC @ 4t/ha	8.40	4.39	2.73
100% RDF+EB @ 2t/ha	9.20	4.92	3.11
75% RDF+VC @ 4t/ha	7.16	3.84	2.25
75% RDF+EB @ 2t/ha	6.43	3.76	2.28
75% RDF+VC @ 4t/ha+μNM	6.66	3.50	2.59
75% RDF+EB @ 2t/ha+μNM	6.69	4.47	2.63
SEm ±	1.31	0.24	0.31
CD (5%)	NS	0.74	NS

3.1.5 Root dry weight

In **table 5**, the root dry weight at 60 DAS exhibited significant variations across different treatments. The application of 100% RDF combined with EB resulted in a notably higher root dry weight (34.9 g plant^{-1}) compared to the 100% RDF treatment alone (18.3 g plant^{-1}). This substantial increase in root biomass can be attributed to the enhanced nutrient availability and improved soil microbial activity facilitated by the enriched biofertilizers.

The current investigation further revealed that treatments involving the application of enriched biochar in combination with various nutrient management strategies (100% RDF + EB, 75% RDF + EB, and 75% RDF + EB + µNM led to significantly higher root dry weights, showing increases of 47.5%, 38.3%, and 38.3% respectively, compared to the 100% RDF treatment. This is likely due to the slow-release characteristics of biochar-coated urea, which ensures sustained nutrient availability over time, thereby promoting root development.

The use of granular biochar mineral urea composite (Bio-MUC) demonstrated the highest total fresh root weight, with a 25% increase observed in pot culture with maize. This improvement can be attributed to the slow release of nitrogen from Bio-MUC, which effectively promotes maize growth by retaining nitrogen through binding to biochar surfaces and forming stable carbon-nitrogen bonds. The ability of biochar to act as a slow-release carrier for urea highlights its potential as a sustainable alternative to conventional mineral urea in fertilizer mixtures, supporting enhanced root development and overall plant health. These findings are consistent with the study by Rehman *et al.* (2023) which demonstrated similar benefits of biochar-based fertilizers in promoting root biomass in maize. Additionally, the root dry weight obtained from treatments with 75% RDF combined with vermicompost was statistically comparable to the 100% RDF treatment, indicating that vermicompost can effectively replace a portion of the chemical fertilizers without compromising root growth. However, the application of micronutrients did not show a significant impact on root dry weight, suggesting that the primary benefits in root development were derived from the macronutrient and biochar components of the treatments.

Table 5: Root dry weight (g) of sweet corn as influenced by different treatments

Treatments	**Root dry weight (g plant^{-1}) at 60 DAS**
Absolute control	13.4
100% RDF	18.3
100% RDF+VC @ 4t/ha	29.9
100% RDF+EB @ 2t/ha	34.9
75% RDF+VC @ 4t/ha	24.0
75% RDF+EB @ 2t/ha	29.7
75% RDF+VC @ 4t/ha+µNM	24.3
75% RDF+EB @ 2t/ha+µNM	29.7
SEm ±	1.7
CD (5%)	5.3

3.2 Physiological parameters

3.2.1 NDVI value

In the table 6 presents the NDVI (Normalized Difference Vegetation Index) values for sweet corn plants, showing that the application of 100% RDF combined with EB yielded the highest NDVI values. This was closely followed by the 100% RDF combined with VC, with both treatments being statistically similar. The superior NDVI values in these treatments indicate enhanced vegetative development and greater greenness, which can be attributed to improved plant height and biomass accumulation. These results were comparable to those obtained with 75% RDF combined with EB and 75% RDF + EB + µNM.

At 60 DAS and harvest, NDVI values from plots treated with 100% RDF using conventional fertilizers were significantly lower than those treated with 100% RDF + EB, but were statistically similar to the 75% RDF level. This difference is likely due to the increased nutrient availability resulting from the slow-release characteristics of biochar-coated urea and the gradual nutrient release from EB, particularly when applied in splits. The slow-release and split application strategies help sustain nutrient availability over time, leading to enhanced vegetative growth and increased greenness compared to conventional fertilizer applications. The efficacy of biofertilizers like EB in improving NDVI values is supported by their ability to enhance soil microbial activity, which in turn improves nutrient cycling and availability, particularly nitrogen, a critical element for chlorophyll synthesis and plant growth (Aloo *et al.*,2022). Moreover, VC has been shown to improve soil structure and nutrient content, further supporting plant growth and leading to higher NDVI values (Rehman *et al.,* 2023).

Table 6: NDVI reading of sweet corn as influenced by different treatment

Treatments	**NDVI**	
	60DAS	**Harvest**
Absolute control	0.25	0.19
100% RDF	0.65	0.52
100% RDF+VC @ 4t/ha	0.74	0.66
100% RDF+EB @ 2t/ha	0.76	0.67
75% RDF+VC @ 4t/ha	0.67	0.57
75% RDF+EB @ 2t/ha	0.70	0.61
75% RDF+VC @ 4t/ha+µNM	0.65	0.55
75% RDF+EB @ 2t/ha+µNM	0.72	0.62
SEm ±	0.02	0.02
CD (5%)	0.06	0.07

3.2.2 SPAD readings

The SPAD readings in your study are critical for assessing leaf greenness, which is closely linked to the nitrogen status of plants. As observed, SPAD values generally decline as the crop matures due to a natural decrease in chlorophyll content, which reflects reduced nitrogen levels in the leaves. This phenomenon is particularly evident in the absolute control plots, where the lack of nitrogen input results in significant leaf yellowing and lower SPAD values at both 60 DAS and harvest (Table 7).

The application of 100% RDF combined with EB yielded the highest SPAD values, followed by treatments with 100% RDF + VC and combinations involving 75% RDF with EB and µNM. This outcome can be attributed to the enhanced nutrient availability and uptake provided by the biofertilizers and organic amendments, which improve nitrogen assimilation and chlorophyll synthesis, thus maintaining higher leaf greenness. Studies have shown that biofertilizers, particularly those containing plant growth-promoting rhizobacteria (PGPR), enhance nitrogen uptake efficiency, leading to increased chlorophyll content and improved SPAD readings in various crops (Hinzil *et al.*, 2024). Furthermore, VC is known for its ability to enhance soil fertility and promote plant growth by supplying essential nutrients and beneficial microorganisms. The combined application of chemical fertilizers with organic amendments like vermicompost has been reported to significantly improve nitrogen use efficiency and chlorophyll content in plants, contributing to higher SPAD readings and better overall plant health (Rehman *et al.*, 2024).

Table 7: SPAD reading of sweet corn as influenced by different treatments

Treatments	**SPAD**	
	60 DAS	**Harvest**
Absolute control	11.8	7.2
100% RDF	39.4	37.3
100% RDF+VC @ 4t/ha	52.1	51.1
100% RDF+EB @ 2t/ha	56.8	53.6
75% RDF+VC @ 4t/ha	45.4	41.2
75% RDF+EB @ 2t/ha	52.3	50.9
75% RDF+VC @ 4t/ha+µNM	45.5	44.0
75% RDF+EB @ 2t/ha+µNM	52.1	50.8
SEm ±	1.6	1.4
CD (5%)	4.9	4.1

Conclusion

The study demonstrated that the application of 100% RDF combined with EB consistently outperformed all other treatments in enhancing both morphological and physiological parameters of sweet corn. The superior results observed in plant growth, root biomass, SPAD readings, NDVI values, and NAR suggest that this integrated nutrient management strategy effectively promotes nutrient uptake, particularly nitrogen, leading to improved chlorophyll content, photosynthetic efficiency, and overall plant health. The slow-release properties of biochar-coated urea in the EB treatments contributed to sustained nutrient availability, which supported continued growth and productivity, particularly during critical growth stages. This approach not only enhanced vegetative development but also offered a sustainable alternative to conventional fertilization methods, potentially reducing the need for chemical fertilizers while maintaining high crop yields. These findings underscore the importance of incorporating biofertilizers and organic amendments into nutrient management practices to optimize crop performance and sustainability.

Author contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Conflict of interest

No

Declaration

The authors declare no conflict of interest.

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