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Journal of Soil, Environment & Agroecology

Journal homepage:
https://karyailham.com.my/index.php/sea/index
ISSN: 3030-5497

Integrating Biochar to Elevate Crop Productivity and Herbicide Effectiveness in Sustainable Farming

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ARTICLE INFO

Article history:
Received 23 November 2025
Received in revised form 21 January 2026
Accepted 1 February 2026
Available online 19 February 2026

ABSTRACT

Biochar is a carbon rich compound prepared through pyrolysis (burning of organic materials in deficiency of oxygen). Biochar has been widely recognized as a tool to mitigate global warming and enhance food security. However, its chemical and physical properties, including high porosity, carbonaceous nature, large surface area and aromatic structure, are considered to negatively affect the soil applied herbicides. Biochar is also known to improve crop productivity of quinoa crops under water limited conditions. This study evaluated the effect of biochar (fresh and coated) on herbicide efficacy, weed suppression, and crop performance under field conditions. Two treatment factors were employed including herbicide (control and Pendimethalin) and biochar (control, fresh biochar and coated biochar). Results revealed that herbicide alone achieved lowest weed germination (1.33 plant m^{-2}), highest weed control (99.07%) and herbicidal efficiency (97.88%). The addition of biochar reduced herbicidal performance, increased weed counts and lowered weed control efficiency to 82.84%, likely due to adsorption of herbicide on biochar surface. On the other hand, coated biochar improved herbicidal efficiency (83.07%) and maintained effectiveness of herbicide and weed suppression, indicating that coating of biochar surface is effective in mitigating herbicide sorption. Highest germination percentage was witnessed in fresh biochar (around 92%), showing its role in improving soil conditions for seed emergence, while coated biochar produced medium improvement. Highest grain yield was achieved by fresh biochar, flowed by coated biochar and no biochar. Harvest index remained stable across the treatments, whereas grain yield was highest in fresh biochar followed by coated biochar and no biochar. Overall, these findings demonstrate that the fresh biochar can impair herbicidal efficacy through adsorption, but clearly improved the grain yield, coated biochar efficiently balances weed control and crop productivity. Thereby coated biochar appears as a promising soil amendment for both herbicide

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Keywords:
Biochar; herbicid; crop productivity; coated biochar; herbicidal efficiency

performance and sustaining crop yield while fresh biochar was found to be best amendment in terms of crop productivity.

1. Introduction

Biochar (BC) is carbon rich product added to soil for agronomic as well as environmental purposes including carbon dioxide emission mitigation and nutrient source. Now a days, use of soil applied pre-emergence herbicide for weed control has become a common practice, however it is considered that biochar may interfere in degradation process of the agrochemicals which may increase or decrease their persistence. Long persistence time of herbicide in soil may be desirable in monoculture cultivation system, but it is undesirable in succession or crop rotation systems because the following crop may be sensitive against the herbicide, leading to the carryover problem [2]. Biochar is obtained through thermochemical processing of the biomass. Biochar is gaining attention these days as a soil amendment. Biochar is produced by pyrolysis, heating the organic matter (regardless of source) to hundreds of degrees Celsius in oxygen limited conditions. The quality of biochar depends on both the reaction conditions and the feedstock.

Studies reveal that the Biochar have properties to enhance the crop overall wellbeing by facilitating the chemical and physical properties of soil moreover by directly affecting crop growth [8]. Intense use of pesticides in agriculture has resulted in contamination of water, soil and air. This fact makes it inevitable to study the strategies which can minimize the adverse effects of these pesticides to the environment. Under this situation, biochar appears as a remedy to due to its ability to remove the chemical substances from environment, this is because biochar may be activated using various chemical agents and is highly effective in adsorption of hazardous substances [10]. Biochar has the potential to significantly increase the agricultural production in a sustainable and environment friendly way and biochar can be applied to address both agricultural as well as environmental problems. Use of biochar in agriculture has long term potential to mitigate climate change, sequester carbon and improve soil health. The spectrum of biochar use in agriculture has broadened, ranging from basic agriculture management to restore environment, energy sources and many more benefits [14]. Biochar acts as a sorbent possessing the ability to stabilize organic compounds in the soil and therefore, has the potential to reduce the bioavailability of such organic compounds. The biochar can be produced using locally available agricultural residues. The biochar produced from the rice husk and empty fruit bunches increased weed seeds germination and plant growth in heavy soil because of herbicide stabilization.

The effect of biochar produced from empty fruit bunches was higher than that of rice husk biochar because of its higher affinity towards herbicide. Higher application rates of biochar increased its effectiveness as a soil modifier [21]. Biochar can be a good source to increase soil organic carbon and to mitigate the negative effects of pesticides in soil. The mechanisms through which field aging of biochar affects its effects on herbicidal behaviour and microbial community in the soil are still poorly understood [5]. Biochar has been reported to increase soil moisture content at field capacity ranging from 1.8% to 11.22%, decrease the micropores by 10-46% and increase the micropores from 0.2% to 10% in three different textured soil [6]. Studies show the potential of biochar in improving water-use efficiency and crops yield. To get maximum benefits from biochar application in crop productivity, a systematic and comprehensive framework is required, involving proper application method, suitable biochar selection as well as consideration of climatic conditions, soil properties and crop species [20].The results from Structural Equation Modelling (SEM) revealed that biochar increased Soil Organic Carbon (SOC), and thereby promoted long term crop yields, this mechanism is more effective in the soils with high clay content or those with low organic carbon [12].

The food demands are increasing due to increase in global population. But soil nutrient pool is depleting day by day, making it inevitable to find the sustainable ways to improve the soil health, promote crop yields, and cope with environmental issues. The best approach under such circumstances in to consider addition of sustainable amendments to soil, such as biochar, which will be vital for soil health due to its affordability, reduced carbon footprint, large surface area and low reactivity [11]. Globally, the biochar is being used as a multipurpose carbon rich material to solve issues like improving plant growth and development and soil fertility, under normal as well as stressful circumstances. It promotes nutrient absorption, water retention and microbial activity, making a fertile environment able to support resilient and sustainable agriculture. In addition, biochar being a carbon sink, contributes to long term carbon sequestration and help to overcome harmful impacts of climate change [13].

Based on previous findings, the biochar use is a potential approach in tomato cultivation to overcome herbicide induced stress, particularly during the early plant development. Biochar reduced susceptibility towards damage, enhanced antioxidant regulation and improved plant Vigor. These benefits of biochar were consistent in all the tested conditions, showcasing the potential of biochar as a compatible input to traditional herbicide-based weed management [18]. Studies demonstrate that biochar improves drought tolerance of quinoa by influencing gas exchange and stomatal morphology. Adding 2% woody biochar (w/w) is recommended as an effective strategy to improve drought tolerance in quinoa under drought conditions [1]. Biochar, a carbon rich material, being eco-friendly and possessing potential to improve soil quality has gained interests by the researchers. The properties of biochar such as greater surface area, pH, nutrient content and cation exchange capacity influences positively on soil properties, ultimately improving soil fertility [17]. Hydroxyl and carboxyl are main surface functional groups of biochar and are responsible for biochar adsorption with pesticides. Biochar is known for remediation of soils polluted with pesticides, but its effectiveness depends on various factors and future efforts need to prioritize refining biochar qualities. This can be achieved by improving its capacity through surface modifications or combining it with other known remediation techniques, such as phytoremediation. Such enhancements can position biochar as potential approach for remediating soils contaminated with pesticides [19].

In view of the significant role that biochar can play in improving crop productivity and its effects on weed control efficacy, the current experiment has been structured to thoroughly assess crop phenotypic and morphological attributes, as well as the efficiency of weed management practices, within the framework of a sustainable farming system. This approach aims to generate deeper insights into how biochar contributes to both plant performance and effective weed suppression, thereby supporting environmentally friendly and resource-efficient agricultural practices.

2. Materials and Methods

2.1 Experimental Layout

A field experiment was conducted during late November 2024 at the research farm of Muhammad Nawaz Shareef University of Agriculture, Multan, Pakistan, to investigate the effect of biochar (fresh and coated) on herbicidal efficacy of Pendimethalin (455 g L^{-1} EC), on crop productivity and weed control efficiency under sustainable farming practices.

In this experiment, the treatments were arranged in a Randomized Complete Block Design (RCBD) with three replications. Each block comprised of 6 plots, represented the following treatments:

T1	Pendimethalin 455 g L^{-1} EC
T2	Pendimethalin 455 g L^{-1} EC + Fresh Biochar
T3	Pendimethalin 455 g L^{-1} EC + Coated Biochar
T4	Control (no herbicide, no biochar)
T5	Fresh Biochar alone
T6	Coated Biochar alone

Plot dimensions were kept 3 m x 4 m, with the row spacing of 30 cm. Throughout the experimental period, standard agronomic practices such as recommended irrigation and fertilization schedules were maintained. Pendimethalin was applied as pre-emergence herbicide and biochar was incorporated into the soil two weeks prior to sowing.

2.2 Parameters Measured

1.	Weed germination (count m^{-2})
2.	Weed control efficacy (%)
3.	Herbicidal efficiency (%)
4.	Germination percentage (%)
5.	Harvest index (%)
6.	Grain yield (kg ha^{-1})

Crop-related phenotypic and morphological attributes were recorded at suitable growth and maturity stages to investigate the treatments responses. Crop germination percentage (%) was determined by calculating the number of germinated seedlings in comparison to the total number of seeds sown. Harvest index (%) was obtained by dividing grain yield (economic yield) by the total above ground biomass and expressing the value in percentage. Grain yield (kg ha^{-1}) was measured from each plot after harvesting and threshing the grains, then converted into yield per hectare using standard procedures. These parameters provided insights regarding the effectiveness of the treatments, crop growth performance and yield potential.

Weed-related parameters were also recorded to find the effect of treatments on weed growth and suppression. Weed germination (count m^{-2}) was determined by calculating the number of weeds emerged in an area on 1 m^2 quadrat in each plot.
By comparing the weed density in treated plots to the untreated plots, Herbicidal efficiency (%) was calculated, using the standard formula as follows,

$$\text{Herbicidal Efficiency (\%)} = \frac{Wc - Wt}{Wc} \times 100$$

where W_c represents the population of weeds in the control plot and W_t represents the population of weed in the treated plot. Weed Control Efficiency (%) was determined by considering dry matter obtained by weeds and crop yield response, following established methods. These parameters provided brief insights regarding the effectiveness of the treatments in weed pressure suppression and improvement in crop productivity.

2.3 Statistical Analysis

Statistical analysis was performed using RStudio (2023). An analysis of variance (ANOVA) appropriate for a Randomized Complete Block Design (RCBD) was applied to the collected data. Treatment means were then separated using Tukey's HSD test at the 5% significance level ($p \leq 0.05$).

3. Results

3.1 Weeds Germination

Analysis of variance (ANOVA) showed highly significant effect of treatments on weeds germination count ($F = 161.98$, $p < 0.0001$) (Table 1). Within the treatments, the replications were found to be non- significant, suggesting similarity across the replications. Across the treatments, overall mean weed germination count was 34.39 plants m-2 with a coefficient of variation (CV) of 10.47%, indicating experimental reliability.

Table 1
Table represents the analysis of variance for weeds germination count

Source	DF	SS	MS	F	P
Replication	2	129.8	64.89		
Treatment	5	10492.9	2098.59	161.98	0.000
Error	10	129.6	12.96		
Total	17	10752.3			

The results show a clear and significant difference in weeds germination, based on the treatments applied. The highest weed germination count was found in no herbicide treatments ranging between 60 to 63 weeds germinated across all biochar types (no BC, fresh BC, and coated BC). In the absence of herbicide, the biochar themselves did not affect the weeds germination, the letter “A”, above all the grey bars indicate that biochar treatments have no statistically significant effect on weeds germination in herbicide absence. On the other hand, the herbicide application (Pendimethalin) reduced weeds count dramatically in all cases. However, its effectiveness showed variation depending upon the biochar treatment, where no BC treatment achieved highest efficacy with lowest germination count, close to 1 labelled as “C”; significant loss in efficacy was witnessed in the fresh BC treatment where the weed count was around 21 and labelled as “B”; and the coated biochar recovered herbicide effectiveness to a good extent, and germination count was nearly 11 and labelled as “C”, indicating its effectiveness to be statistically better than fresh BC and similar to that of no BC treatment.

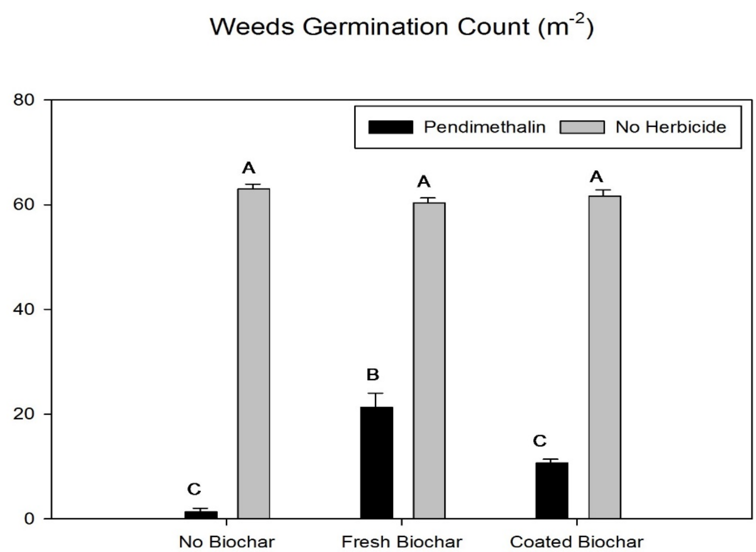

Fig. 1. Graphical representation of weeds germination count (m^{-2})

3.2 Weed Control Efficiency

Analysis if Variance (ANOVA) suggested a significant effect of treatments on weed control efficiency (F = 24.07, p = 0.0059) (Table 2). Within the treatments, the replications were found to be non- significant, suggesting similarity across the replications. Overall average weed control efficiency was 91.38%, and coefficient of variation (CV) was only 3.15%, showcasing excellent experimental precision.

These results show that treatments significantly varied in their weeds suppression ability. The low CV value also indicates the reliability and consistency in the differences observed across replicates.

Table 2
Table represents the analysis of variance for weed control efficiency

Source	DF	SS	MS	F	P
Replication	2	17.583	8.791		
Treatment	2	398.322	199.161	24.07	0.0059
Error	4	33.091	8.273		
Total	8	448.996			

The weed control efficiency under different biochar treatments varies significantly. Highest efficiency was achieved in no BC treatment where the weed control efficiency was nearly 100%. The fresh BC reduced the weed control efficiency dramatically to 82%. However, this lost efficacy was recovered by the coated BC, and efficiency was approximately 92%. Statistically no BC and coated BC had no significant difference and were classified together, labelled as A, whereas fresh BC was found statistically inferior to these treatments and was labelled as B. The results revealed that coating biochar is an appropriate strategy for maintaining weed control efficiency.

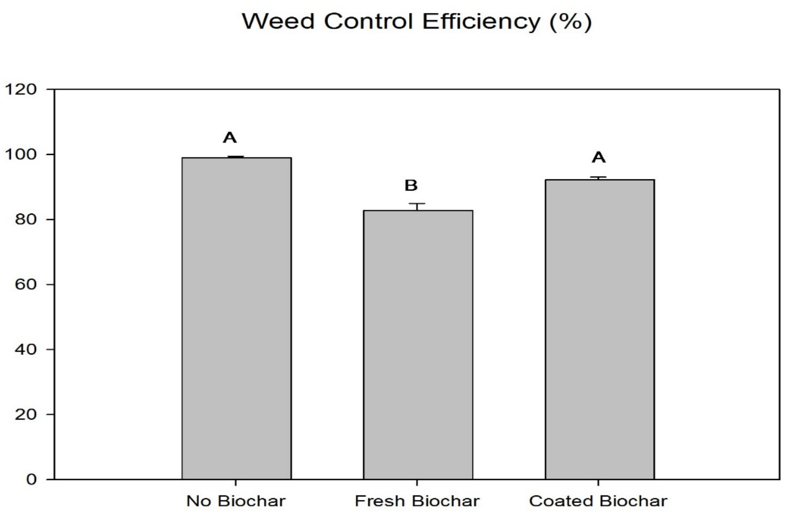

Fig. 2. Graphical representation of weeds control efficiency (%)

3.3 Herbicidal Efficiency

The Analysis of variance ANOVA table shows a significant effect of treatments over herbicidal efficiency (F = 21.29, p = 0.0074) (Table 3). Within the treatments, the replications were found to be non- significant, suggesting similarity across the replications. Overall, average herbicidal efficiency was found to be 82.36%, with a lower coefficient of variation (CV) of only 7.24%, indicating good experimental precision.

The findings show that the treatments significantly affected the herbicidal performance. The F-value suggests that the difference between the herbicidal efficiency were due to treatments instead of random variation.

Table 3
Table represents the Analysis of variance for herbicidal efficiency

Source	DF	SS	MS	F	P
Replication	2	44.23	22.116		
Treatment	2	1513.96	756.978	21.29	0.0074
Error	4	142.21	35.553		
Total	8	1700.40			

Clear impact of biochar application in herbicidal efficiency was witnessed in the experimental results. The no BC treatment achieved the highest herbicidal efficiency, approximately 98% and was labelled as A. The biochar alone application resulted in a drastic loss in herbicidal performance, dropping the efficiency to around 66% only and labelled as B. While coated BC application recovered the efficiency to a good extent, improving efficiency to about 84% and labelled as AB. The AB label showed that the coated BC performance about herbicidal efficiency was statistically intermediate and was in between the no BC and fresh BC, not significantly different from either one. These findings suggest that fresh biochar leads to a severe reduction in herbicidal performance while coating the biochar can partially improve herbicidal efficiency in biochar amended soils.

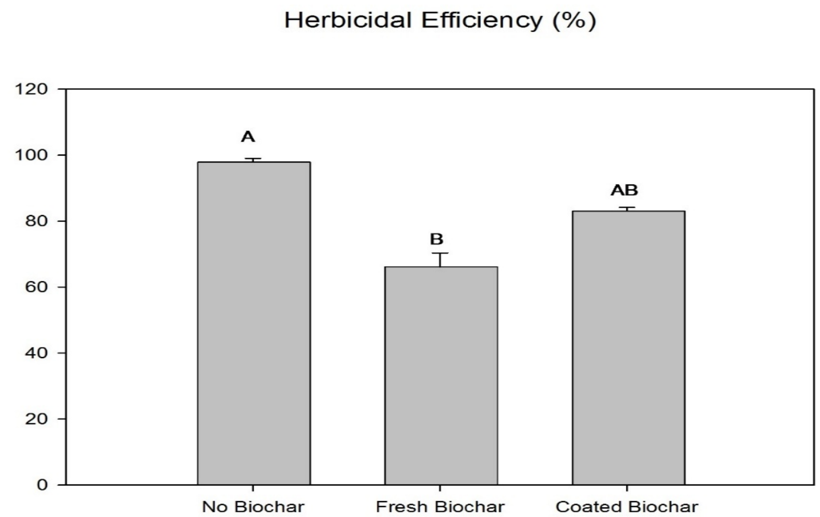

Fig. 3. Graphical representation of herbicidal efficiency (m^{-2})

3.4 Germination Percentage

Treatment effect on germination percentage was found be statistically different in the analysis of variance (ANOVA) (F = 15.46, p = 0.0131) (Table 4). Within the treatments, the replications were found to be non- significant, suggesting similarity across the replications. Overall average germination percentage was 80.06%, with a CV of 6.08%, showcasing experimental precision. The results revealed that the treatments significantly affected the seeds germination. The low CV and higher F-value indicate reliable and consistent variation among treatments, showing that some treatments increased germination percentage significantly.

Table 4
Table represents the Analysis of variance for germination percentage

Source	DF	SS	MS	F	P
Replication	2	2.722	1.361		
Treatment	2	732.722	366.361	15.46	0.0131
Error	4	94.778	23.694		
Total	8	830.222			

The results suggest a clear and significant effect of biochar on germination. The lowest germination was recorded approximately 70% in no BC treatment, which was statistically different and inferior from other treatments and was labelled B. The fresh biochar showed promising effect on germination percentage, which was approximately 92%, labelled "A", proving that fresh biochar promotes germination significantly. The coated biochar treatment was found in between no BC and fresh BC in terms of germination percentage which was recorded about 79% in this treatment labelled as AB, representing not significantly different from either no BC or fresh BC. Overall, the data indicates that biochar addition, particularly in fresh form, enhance the germination percentage significantly.

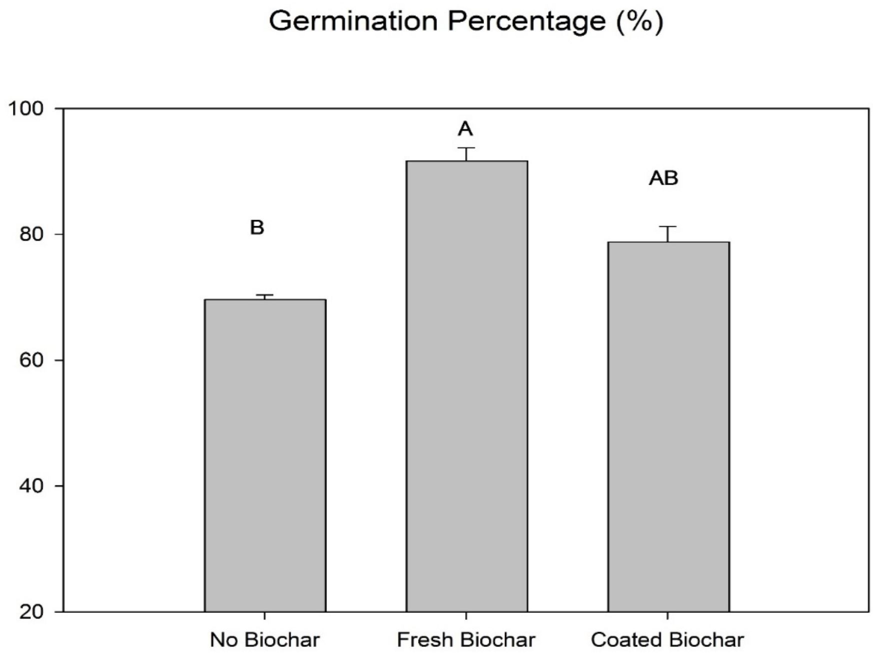

Fig. 4. Graphical representation of germination percentage (%)

3.5 Harvest Index

Analysis of variance (ANOVA) revealed no significant effect of treatments on harvest index (F = 0.69, p = 0.5547), as well as the effect of replications was also found non-significant (Table 5). The overall average harvest index among the treatments was 23.89%, with a coefficient of variation (CV) of 11.80%, suggesting adequate experimental precision. These findings suggest that the applied treatments did not cause any measurable differences in harvest index. The relatively low variation among treatments indicates that harvest index remained stable across experimental conditions, regardless of treatment combinations.

Table 5
Table represents the Analysis of variance for harvest index

Source	DF	SS	MS	F	P
Replication	2	24.2222	12.111		
Treatment	2	10.889	5.444	0.69	0.55347
Error	4	31.7778	7.9444		
Total	8	66.8889			

Little to no variation in harvest index was witnessed among the treatments and harvest index remained statistically consistent among all the treatments. Harvest index was slightly lower in the fresh BC treatment of approximately 22 %, 24% in no BC and was slightly higher in coated BC, around 26% than both treatments. Ultimately, letter A was placed above all the grey bars, there was no significant difference among the treatments regarding the harvest index. The application of biochar, either coated or fresh, has no significant effect on harvest index.

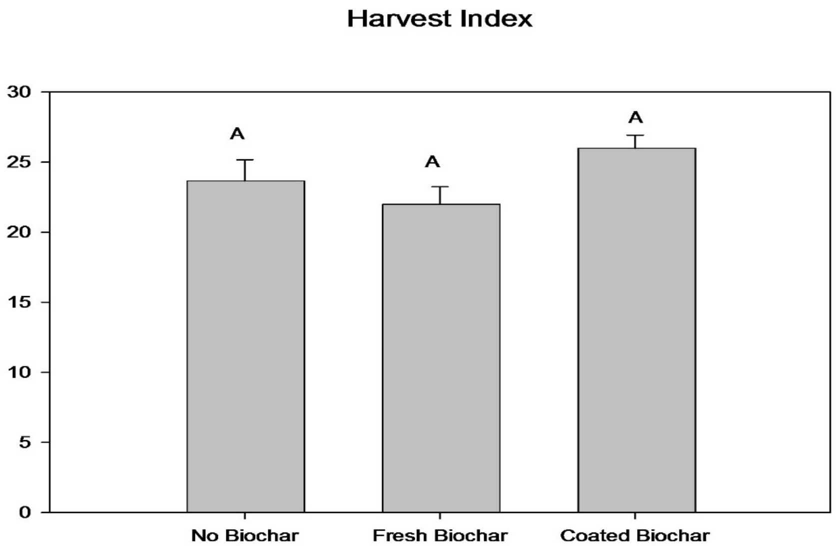

Fig. 5. Graphical representation of harvest index

3.6 Grain Yield

The treatments significantly impacted the grain yield, as demonstrated by the analysis of variance (ANOVA) (Table 6). The treatment effect was highly significant at P = 0.0002, indicating strong influence of treatments on grain yield. The mean square was 2073.44, substantially greater than error 14.44, leading to a large F-value 143.55, which confirms the significant variability due to treatment effects. Replication effect was statistically non-significant. Overall average grain yield was 248.56 kg ha-1, with a coefficient variation of1.53%, indicating excellent experimental precision and results reliability.

Table 6
Table represents the analysis of variance for grain yield

Source	DF	SS	MS	F	P
Replication	2	9.56	4.78		
Treatment	2	4146.89	2073.44	143.55	0.0002
Error	4	57.78	14.44		
Total	8	4214.22			

Significant influence of biochar treatments was found on grain yield. The fresh biochar (BC) treatment produced the highest yield at 270 kg ha^{-1}, with the coated BC treatment yielding the next highest at 255 kg ha^{-1}. The no BC treatment was inferior to the fresh and coated BC treatments and yield was only 220 kg ha-1 in this treatment. Statistical analysis indicated a significant difference among mean values of grain yields for each treatment. The mean values were labelled A, B and C according to their statistical comparison. Fresh BC application enhanced grain yield notably, as compared to coated BC and control, demonstrating positive effect of biochar on crop productivity, especially in fresh form.

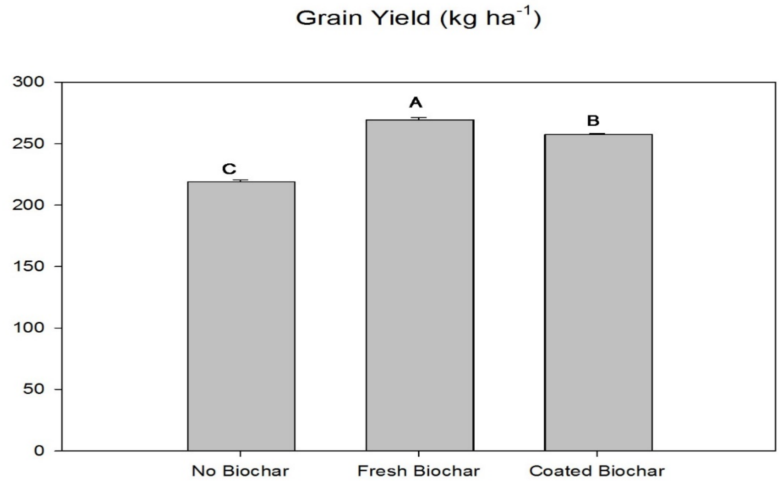

Fig. 6. Graphical representation of grain yield (kg ha^{-1})

4. Discussion

Weeds germination was highly decreased by herbicide application, lowest emergence witnessed in T1 (Herbicide + No biochar) where only 1.33 plant m-2 emerged. Combined application of herbicide with biochar showed different effects: T3 (herbicide + coated biochar, 10.67 plants m-2) suppressed weeds efficiently than T2 (herbicide + fresh biochar, 21.33 plants m-2), indicating that coated biochar may increase herbicide persistence while fresh biochar may reduce herbicide activity by adsorbing it. On the other hand, treatments without the herbicide (T4: control, T5: Fresh Biochar, T6: Coated biochar) had significantly higher weeds germination (around 63 plant m-2), indicating that alone biochar had no or little effect on weed germination suppression. Overall, herbicide was the reducing factor on weed emergence and biochar influenced its performance depending upon the form applied. Evidence from controlled-release herbicide carrier experiments strongly support the coated biochar results. The studies demonstrated that coating approaches or Innovative carrier can prolong the release and increase the persistence of herbicides in soil [16]. Maximum weed control efficiency and consistency (99.07%) were achieved in treatment where herbicide was applied without biochar. The addition of biochar dropped the efficiency markedly (82.84%), likely to be due to adsorption of herbicide on the biochar surface, leading to reduced bioavailability of herbicide for weed suppression. Contrarily, coated biochar showed improved control (92.24%) as compared to fresh biochar, indicating that coating the biochar reduces herbicide sorption and allows better activity.

Overall, while biochar can affect herbicide performance, coated biochar seems more compatible with herbicide compared to fresh biochar. Our findings are similar with Nag *et al.*, [15], who observed reduced bioavailability and persistence of trifluralin and atrazine in soil with wheat straw biochar produced at 450 OC, ultimately resulting in greater rye grass population and biomass as compared to non-amended soils. Their study showed reduction in herbicide efficacy due to biochar and a 3.5-fold increase in GR50 for atrazine in 1% biochar amended soil. These findings are like our results, where fresh biochar significantly reduced weed control efficiency, likely because of herbicide sorption, while this negative interaction was minimized by coated biochar. Herbicidal efficiency was influenced strongly by presence and type of biochar amendment. Highest weed control was witnessed in the treatment with herbicide alone, confirming maximum herbicidal efficacy when biochar was not applied. However, application of fresh biochar (T2), clearly reduced herbicidal efficiency to only 66.14%, with a high variability (STDEV 7.37), showing strong adsorption of herbicide on the biochar surface, which lead to its limited bioavailability for weed control. This trend aligns with the previous reports that fresh biochar can limited the mobilization of herbicide molecules; consequently, reducing their effectiveness in soil.

Contrarily, coated biochar (T3) showed better weed control efficiency (83.07%) compared to that of fresh biochar, though it was still lower than herbicide alone. This indicated that coating the biochar modifies its surface properties, resulting in reduced sorption of herbicides and increased their bioavailability. The decreased variability in the treatment T3 indicates more reliable performance compared to fresh biochar. Similar results were reported preciously by Gámiz *et al.*, [9], who reported a significant alteration in fate and efficacy of herbicides in the soil due to biochar amendments. Their study presented that biochar's produced at a higher temperature of 700 OC, adsorbed clomazone and bispyribac sodium strongly and reduced herbicidal efficacy of clomazone to suppress weeds. On the other hand, the biochar's produced at lower pyrolysis temperature ranging between 350-500 OC showed less effect on herbicidal activity. These reports a support our results, where fresh biochar showed higher amounts of sorption and reduced herbicidal efficiency and surface modified coated biochar minimized this negative effect. This highlights the importance of biochar preparation method, type and surface properties in establishing compatibility with herbicide-based weed management.

Germination percentage was also manipulated by the biochar treatments. Highest germination was seen in fresh biochar (91.67%), suggesting that biochar application influenced positively on seed emergence, may be by improving soil physical conditions, nutrient availability and water retention that played role in favour of seedling establishment. Contrarily, lowest germination was recorded in no biochar treatment (69.67%), showing that no amendments in soil may have restricted the favourable conditions for good germination. A better germination was witnessed in coated biochar (78.83%), better than no biochar but less than fresh biochar, maybe due to change in nutrient release patterns and surface chemistry. These findings indicate a superior effect of biochar on seed germination, while coated biochar improved it moderately.

Carril *et al.*, [3] reported similar findings, who witnessed variable effects of biochar amendments on seed germination depending upon biochar type, pre-treatment and concentration. They reported that washed biochar applied at appropriate concentration improved radicle length and germination index in tomato and basil and unwashed biochar or liquid fractions inhibited germination, may be due to phytotoxic compounds. These findings align with our results where fresh biochar improved germination percentage better than no or coated biochar, showcasing that biochar properties and type play crucial role in determining its influence on seed emergence. Harvest Index (HI) was almost similar and stable across all the treatments. This indicates that ratio of economic yield to total produced biomass was not influenced strongly by biochar amendments. The highest harvest index was observed in coated biochar (26%), followed by no biochar (23.67%) and fresh biochar (22%), but difference was small and in a narrow range. This indicates the biochar may influence growth parameters and total biomass, but its effect on allocation of biomass to economic potion is limited. In the coated biochar treatment, slightly higher harvest index may be due better soil conditioning or improved nutrient availability. Overall, these results show that biochar type may influence harvest index slightly, but this effect is quite less than that for the germination or weed control efficiency.

Carril *et al.*, [4] also reported effects of biochar on seed germination, effectiveness of biochar varies depending upon type, pre-treatment and concentration. Grain yield was greatly influenced by the biochar treatments. The highest yield was recorded in fresh biochar (269.33 kg ha-1), followed by coated biochar (257.33 kg ha^{-1}) and no biochar (219 kg ha^{-1}). The improved performance of fresh biochar may be due to better nutrient retention, availability of water and minerals and improved soil structure, which favoured grain filling and overall reproductive growth. Overall, the results indicated that biochar can be a promising amendment in soil for crop productivity, and type of biochar and preparation also play critical role in defining its effectiveness. Demirkaya *et al.*, [7] reported the similar observations where fresh and aged biochar's were applied in clayey soils in wheat crop. Their study revealed that biochar application, significantly improved grain yields up to 13-24% compared to that of control. These results are in line with our results where fresh biochar improves grain yield significantly, and coated biochar improves moderately.

5. Conclusion

This study demonstrates that biochar either fresh or coated, strongly influences weed suppression, herbicidal efficacy, and crop production. Herbicide application was the key factor for reducing weed emergence and highest weed control was achieved when herbicide alone was applied. Fresh biochar reduced herbicidal efficacy due to adsorption of the active ingredients, but coated biochar minimized this negative interaction and provided better weed control. These findings are in line with previous studies reporting biochar can reduce herbicide bioavailability depending upon its properties and treatment. Biochar influenced positively on crop germination and growth. Fresh biochar improved seed germination percentage may be by improving soil physical properties, nutrient availability and water retention, whereas coated biochar showed moderate improvement. Fresh biochar showed promising results in improving crop yield, resulting in highest grain yield followed by the coated biochar and no biochar. The harvest index showed minimal variation across treatments, suggesting that biochar had greater effect on total biomass production than on yield allocation.

Overall fresh biochar appeared as promising amendments that can improve crop germination and yield. Coated biochar performed moderately in both, crop productivity and herbicidal efficacy and showcased a good performance. These results show the importance of selecting adequate biochar type and surface modifications to balance crop performance and herbicide efficacy and providing a sustainable technique for integrated soil and crop management.

Declarations

Ethical Approval Certificate

Not applicable. This study did not involve any human participants, animals, or sensitive personal data requiring ethical approval or informed consent.

Author Contribution Statement

The sole author was responsible for the conception, literature review, manuscript drafting, and final approval of the version to be submitted. The work reflects the author original and independent research efforts.

Fund Statement
The author received no external funding for this study. The research was conducted independently without any financial support from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest
The authors declare no conflict of interest.

Acknowledgments
The author would like to thank all researchers whose publicly available data and findings contributed to the analysis in this study. Special thanks to colleagues and peers for their insightful discussions and informal feedback during the development of this manuscript.

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