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T Girwani
Ph.D. Scholar, Department of Agronomy, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India

Ganajaxi Math
Professor, Department of Agronomy, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India

Aravind Kumar
Professor, Department of Agronomy, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India

Swathi P
Scientist (Agronomy), LAM, Acharya NG Ranga Agricultural University, Guntur, Andhra Pradesh, India

Senthamil E
Ph.D. Scholar, Department of Agronomy, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India

Nandini KS
Ph.D. Scholar, Department of Agronomy, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India

Arpitha HC
Ph.D. Scholar, Department of Agronomy, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India

Corresponding Author:
T Girwani
Ph.D. Scholar, Department of Agronomy, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India

Transforming soil resilience: Biochar applications for enhanced erosion control in high rainfall areas

T Girwani, Ganajaxi Math, Aravind Kumar, Swathi P, Senthamil E, Nandini KS and Arpitha HC

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Abstract
Soil erosion caused by high rainfall, flooding, and waterlogging is one of the major environmental challenge that threatens soil stability, nutrient conservation, and agricultural sustainability worldwide, and is further intensified by climate change driven extreme precipitation. These conditions accelerate soil structural degradation, runoff, sediment transport, and nutrient leaching, leading to substantial losses of fertile topsoil and essential plant nutrients. Biochar, a carbon-rich material produced through biomass pyrolysis, has emerged as a promising soil amendment for mitigating erosion and improving soil resilience under excessive moisture conditions. This review synthesizes evidence from laboratory studies, rainfall simulation experiments, field investigations, and meta-analyses to assess the effectiveness of biochar in controlling soil erosion and nutrient losses in high-rainfall and flood-prone environments. The reviewed studies demonstrate that biochar application enhances soil aggregation, reduces bulk density, increases hydraulic conductivity. It improves water retention and infiltration, thereby reducing surface runoff, delaying runoff initiation, and lowering soil erodibility and sediment loss under intense rainfall. Biochar also significantly decrease nutrient leaching and gaseous nitrogen emissions by regulating nitrogen transformations, improving soil aeration, and enhancing rhizosphere biological activity under waterlogged conditions. In addition, biochar improves crop physiological and biochemical responses, including antioxidant activity and root growth, thereby increasing plant tolerance to flooding stress. Overall, biochar represents a multifunctional and sustainable soil management strategy for enhancing soil stability, conserving nutrients, and improving ecosystem resilience in regions vulnerable to high rainfall and flooding.

Keywords: Biochar, high rainfall, erosion, flooding, soil loss

1. Introduction

Soil erosion represents a critical pedo-environmental degradation process that threatens terrestrial ecosystem stability and agricultural sustainability across diverse regions worldwide. Globally, it is estimated that around 24 billion tons of fertile topsoil are lost each year due to erosion, highlighting the severity of the issue. (AbdelRahman, 2023) [1]. Soil erosion is a critical environmental challenge in high rainfall regions, where intense and frequent precipitation events accelerate the detachment and transport of topsoil. This not only leads to the degradation of arable land and diminished agricultural productivity but also contributes to sedimentation in water bodies, nutrient loss, and long-term ecological imbalance. Global climate change frequently triggers extreme weather events, leading to significant increases in soil shrinkage cracks (Mora *et al.*, 2017; Li *et al.*, 2023) [32, 26]. Soil cracks can disrupt the structural integrity of soil and substantially reduce both soil strength and stability. The preferential pathways created by cracks not only significantly diminish the water storage capacity but also pose a risk of groundwater contamination (Greve *et al.*, 2010; Li *et al.*, 2024) [16, 27]. Soil erosion contributes to the loss of essential nutrients and topsoil. As the fertile top layer is washed away, the soil's ability to support plant growth diminishes, which impacts crop yields and overall agricultural sustainability. The loss of nutrients crucial for plant growth (such as nitrogen, phosphorus, and potassium) further exacerbates the problem, necessitating the increased use of fertilizers, which have environmental and economic implications (Nathan *et al.*, 2022; Jiao *et al.*, 2023) [33, 18]. Biochar, a carbon-rich product of biomass pyrolysis, has shown promise as an effective tool for controlling soil erosion (Wani *et al.*, 2023) [54].

Biochar application exerts generally positive impacts on different forms of soil erosion, including wind, water, and cultivation erosion. In the context of wind erosion, biochar enhances soil moisture and structure by promoting aggregation and reducing susceptibility to wind-driven soil loss to some extent (Silva *et al.*, 2015) [52]. The water erosion is mitigated through biochar application with the improvement in water retention capacity, reduction in surface runoff, as well as enhancement in soil stability (Gholamahmadi *et al.*, 2023) [13]. Biochar application for soil erosion control directly aligns with several UN Sustainable Development Goals (SDGs), notably SDG 13 (Climate Action) and SDG 15 (Life on Land). Because biochar infuences the carbon dynamics and nutrient cycling in soil and also afects the carbon sequestration capacities of the soil i.e., supporting the objectives of SDG 13. By enhancing soil stability and reducing erosion rates, biochar contributes to the conservation of terrestrial ecosystems and the promotion of sustainable land management practices, i.e., supporting the objectives of SDG 15 (Lehmann, 2009) [24]. The implementation of biochar as a soil cover or mulch has also shown promising results in reducing the impact of intense rainfall on soil surfaces by effectively shielding the soil from erosive forces and promoting the development of a protective soil crust (Agegnehu *et al.* 2016) [3]. Recently, biochar has emerged as an intriguing option for a long-time carbon sequestration due to its inherent structure and increased stability in hill and mountainous ecosystems (Layek *et al.*, 2022) [23].

The surface of biochars large number of atoms of carbon and oxygen ions, which is called carboxylate group, and these groups get reaction with soil cations very strongly (Lehmann, 2007) [25]. Biochar is not a pure carbon, but rather an activated charcoal containing high carbon, hydrogen, oxygen, nitrogen and ash in different proportions.

High rainfall, flooding, and waterlogging significantly influence soil structural stability, nutrient dynamics, erosion rates, and crop productivity. Biochar has been identified as a promising amendment capable of improving soil physico-chemical and hydrological properties under such extreme moisture conditions. This review synthesizes findings from several studies evaluating the performance of biochar in flooded, waterlogged, and high-rainfall conditions across a range of soil types and experimental settings.

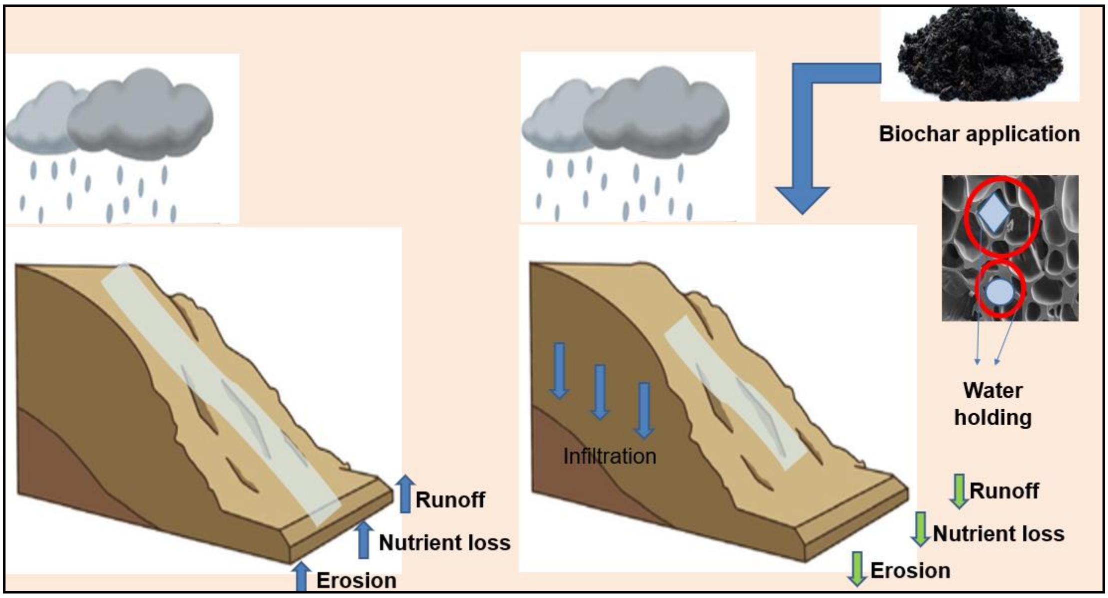

Fig 1: Effect of Biochar Application on runoff, infiltration, erosion, and nutrient loss under high rainfall Conditions

2. Effects of high rainfall and flooding on soil erosion

Flooding has been widely reported to adversely affect soil structure by disrupting soil aggregates. Aggregate breakdown occurs due to uneven swelling of clay colloids, pressure buildup caused by entrapped air and the destruction of cementing materials that bind soil particles (Ponnamperuma, 1972) [41]. Supporting this, De-Campos *et al.* (2009) [12] observed nearly a 20% reduction in soil aggregate stability after two weeks of flooding, accompanied by pronounced soil disaggregation.

Large-scale impacts of flooding on soil resources have also been documented in the present review. Natarajan *et al.* (2010) [34] observed severe soil loss following the floods of November 2009 in 13 affected northern districts of Karnataka. Nearly 287 million tonnes of soil were washed away during the flood period, with soil loss from black soils being almost three times higher than that from red soils owing to their poor infiltration rate. The floods also resulted in the loss of about 57.5 million tonnes of soil microbial biomass. Post-flood estimates indicated that approximately 287 million tonnes of topsoil, 8 lakh tonnes of soil nutrients and 39 lakh tonnes of soil organic matter were removed by floodwaters.

Flooding has also altered key soil physical and physicochemical properties. Njoku *et al.* (2011) [36] reported reductions in bulk density, available phosphorus and total nitrogen in soils after flooding compared to pre-flood conditions. At a broader scale, increasing precipitation trends have intensified crop damage and enhanced off-farm losses of soil and nutrients due to excess water movement (Morton *et al.*, 2015) [33]. Akpoveta *et al.* (2014) [6] observed that decreased levels of organic carbon, pH, total nitrogen, total phosphorous and cation exchange capacity but increased levels of electrical conductivity, following flooding. Significant declines were observed in potassium, important micronutrients like manganese and nickel and heavy metals lead to lead, cadmium and copper. The characteristics of soil influence the infiltration into an aquifer system and directly related to rate of runoff generation (Selvam *et al.* 2015) [49].

Region-specific assessments further confirm nutrient depletion under flood conditions. Arya *et al.* (2020) [7] evaluated soil quality under post-flood conditions in Kuttanad of Alappuzha district. Kuttanad was among the regions highly affected by floods in Kerala during the 2018 floods between July and August 2018. The high intensity rainfall associated with repeated flooding led to leaching losses of soluble nutrients. Available phosphorus and boron showed a declining trend in the post-flood soils of Kuttanad in Alappuzha district.

Such observations highlight the vulnerability of soils to breakdown under excessive moisture, emphasizing the need for soil amendments like biochar that can potentially enhance stability and resilience.

Numerous studies have investigated how biochar mitigates soil erosion under rainfall or simulated storm events.

3. Soil erosion dynamics and biochar interventions in high rainfall areas

3.1 Effect of biochar on soil moisture retention and hydrological improvements

Biochar has been widely reported to improve soil physical properties, particularly under conditions prone to high rainfall and water stress. Biochar application can significantly reduce soil erosion by increasing saturated hydraulic conductivity and suppressing surface runoff generation (Yin *et al.*, 2023) [57]. Improvements in soil water relations have been consistently documented, with Glaser *et al.* (2002) [15] reporting significantly greater water-holding capacity in soils enriched with biochar compared to adjacent non-charcoal soils. Similarly, Karhu *et al.* (2011) [20], in a short-term pilot field study, evaluated the application of 9 t ha^{-1} biochar to agricultural soil between sowing and canopy closure and observed an 11% increase in water-holding capacity relative to the control, although initial differences in soil water content were not statistically significant.

Biochar application alleviates excess water stress due to high rainfall and waterlogging by improving the drainage, assisted by increased hydraulic conductivity of soil. Wood derived biochar treated soil improved saturated hydraulic conductivity of clayey soil (Barnes *et al.*, 2014) [8]. Mankasingh *et al.* (2011) [30] reported a reduction in bulk density from 1.66 to 1.53 g cm^{-3} following biochar addition. Comparable results were observed by Pandian *et al.* (2016) [37], who demonstrated that the application of 5 t ha^{-1} biochar reduced bulk density from 1.41 to 1.36 g cm^{-3} in sandy loam soil, accompanied by a 2.5% increase in soil moisture content compared to the control. Reduced bulk density and improved pore structure may also contribute to better drainage under excess moisture conditions. In this context, Barnes *et al.* (2014) [8] reported that biochar addition to flood-stressed soils improved the drainage of standing water, likely due to changes in evaporation rates, bulk density, and hydraulic conductivity. Peake *et al.* (2014) [38] reported that the incorporation of sawdust-derived biochar at a rate of 0.1% led to reductions in soil bulk density ranging from 2.1% to 6.1% (mean 3.3%) across soils of differing textures following water settling and leaching.

Beyond bulk density and water retention, biochar has been shown to influence soil aggregation and structural stability. Yoo *et al.* (2020) [58] reported that biochar application altered aggregate size distribution by increasing aeration and the proportion of macro-aggregates (>250 μm), even under excessive waterlogging. Biochar may promote aggregate formation or act as stable aggregates themselves, while biochar particles can occupy spaces between macro-and micro-aggregates, thereby enhancing soil stability, resistance to compaction, and resilience to flooding. Furthermore, Shrestha and Pandit (2017) [51] highlighted the potential of cow urine-enriched biochar as an affordable and effective soil amendment, noting its capacity to increase soil pH, cation exchange capacity, water-holding capacity, nutrient retention, surface area, and porosity, while also offering potential monetary savings of approximately 45% for poor farmers and migrant workers.

3.2 Biochar effects on nutrient losses due high rainfall

Biochar has increasingly been recognized as a promising soil amendment for reducing nutrient leaching while simultaneously improving soil fertility and nitrogen use efficiency (Purakayastha *et al.*, 2015) [44]. Field-based evidence from North Queensland, Australia demonstrated that the application of organic amendments, including compost and biochar, resulted in lower N_2O emissions over time, highlighting their potential role in mitigating nitrogen losses under tropical field conditions (Agegnehu *et al.*, 2015) [4].

Several studies reported that biochar can effectively regulate nitrogen transformations, particularly under conditions of denitrification. Cho *et al.* (2023) [11] evaluated the effects of biochar and compost amendments on N_2O emissions from maize grown under high rainfall and waterlogged conditions in South Korea. The highest cumulative N_2O flux was observed in the compost-only treatment (217 mg m^{-2}), indicating enhanced denitrification under anaerobic conditions. In contrast, the biochar-amended treatment (WB) exhibited the lowest cumulative N_2O emissions (66.5 mg m^{-2}), suggesting that biochar mitigated nitrogen losses by improving soil aeration and regulating nitrogen transformation processes under waterlogged conditions.

Beyond its physicochemical effects, biochar has also been shown to influence soil biological processes that contribute to improved nutrient retention. Warnock *et al.* (2007) [55] reported that biochar application is often associated with enhanced mycorrhizal communities in the rhizosphere, which coincide with improved nutrient uptake by host plants and may contribute to reduced nutrient leaching. Concurrently, reductions in gaseous nitrogen emissions from biochar-amended soils have been documented (Rondon *et al.*, 2007) [45], while Masulili *et al.* (2010) [31] demonstrated that biochar amendment improved nitrogen retention in waterlogged soils, further supporting its role in mitigating nitrogen losses under anaerobic conditions.

The effectiveness of biochar in reducing nutrient leaching has also been reported to be dependent on application rate and biochar modification. Saptaparnee *et al.* (2021) [48] observed that higher doses of biochar resulted in lower nutrient leaching compared with lower application rates. In a soil column-based leaching-cum-retention experiment conducted on a sandy loam Inceptisol (Typic Haplustept) from Delhi, The engineered biochar treatments significantly decreased the leaching of NH_4^+-N, NO_3^--N, P, and K while increasing their retention. Among the tested material, rice straw biochar treated with ozone followed by $FeCl_3$-HCl at a rate of 4.46 g kg^{-1} (equivalent to 10 t ha^{-1}) emerged as the most promising amendment, increasing the retention of NH_4^+-N, NO_3^--N, P, and K by 33.7%, 27.8%, 15%, and

5.74%, respectively, compared with untreated rice straw biochar applied at the same rate.

Isotopic tracing studies further substantiate the role of biochar in enhancing fertilizer nitrogen retention. Chen *et al.* (2021) [10], using ^{15}N-labelled urea as the nitrogen source, demonstrated that bamboo biochar applied at rates of 3% and 6% significantly reduced NH_4^+-N, NO_3^--N, and total nitrogen leaching by 20.9%-91.9%, 35.1%-66.9%, and 40.0%-72.8%, respectively, in two soils under tea plantation systems. Biochar application at higher rates consistently produced greater reductions in nutrient leaching. Overall, biochar addition enhanced fertilizer-N retention by 3.2%-23.9%, thereby reducing nitrogen leaching by 28.8%-62.1%.

3.3 Simulated rainfall experiments assessing biochar impacts on soil erosion

Rainfall simulators are especially well suited for examining different treatment effects and erosional responses particularly soil erodibility under controlled conditions (Sheridan *et al.*, 2008) [50]. Abrol *et al.* (2016) [2] observed that application of 2% biochar increased final infiltration rate by 1.7 times and reduced soil loss by 3.6 times in non-calcareous loamy sand. In calcareous loam soil, infiltration remained unchanged, but soil loss was reduced by 30% due to enhanced surface roughness. Biochar also lowered bulk density (1.51 to 1.43 Mg m^{-3}) and reduced sodium adsorption ratio (SAR) by increasing Ca^{2+} and decreasing Na^+ concentrations in leachates. Similarly, Zhang *et al.* (2019) [28] also observed significant reductions in runoff, soil loss, and interrill erodibility with increasing biochar application in rainfall simulated soil boxes. Biochar may affect erosion rates is by improving soil structure, i.e. the size, stability, and spatial arrangement of soil aggregates (Blanco-Canqui, 2017) [9], and thereby changing time-to-runoff (infiltration capacity), runoff duration/amount, and soil erodibility

Gholami *et al.* (2019) [14] used sewage-sludge biochar at concentrations of 0.4-1.6 t ha^{-1} under four initial soil moisture conditions (10-30%) and found that higher biochar rates led to reduced runoff and soil erosion. Biochar concentration of 1.6 t ha^{-1} biochar at 10% soil moisture was found to be optimum. Li *et al.* (2019) [28] investigated three biochar particle sizes (<0.25 mm, 0.25-1 mm, and 1-2 mm) under rainfall intensity of 9 mm h^{-1}. After 8-month incubation period, the smallest particles were most effective in reducing erosion and runoff. Biochar was also observed to help maintaining soil physico-chemical attributes, aggregate stability, and hydraulic conductivity.

Laboratory studies using circular flume demonstrated that biochar application significantly decreased soil loss. The average soil loss decreased from 259 to 152 g m^{-2} h^{-1}, representing a 41% reduction compared with untreated control soils. At comparable runoff rates, soils without biochar exhibited greater erosion than biochar-amended soils, indicating that biochar effectively lowers soil erodibility (Khademalrasoul *et al.*, 2019) [21].

Kushwaha (2021) conducted a simulated rainfall experiment at GB Pant University in four consecutive stages using five rainfall intensities (7.06, 9.07, 11.05, 12.97, and 14.96 cm h^{-1}). The treatments included a control (no amendment) and biochar applied at rates of 1000, 1500, and 2000 g m^{-2}. In each stage, polyacrylamide (PAM) was applied at rates of 3, 4, and 5 g m^{-2}. Parameters such as runoff, sediment yield, biochar loss, and available N-P-K losses were evaluated under simulated rainfall conditions. The results indicated that a low dose of anionic PAM (3 g m^{-2}; 0.03 t ha^{-1}) across all conditions, combined with a high biochar dose (2000 g m^{-2}; 20 t ha^{-1}), was effective in reducing runoff, sediment yield, and major nutrient losses.

Maisyarah *et al.* (2023) [29] investigated nutrient retention and infiltration behavior in biochar-amended sloping soils using a rainfall simulator. Prolonged rainfall increased soil moisture, with saturation occurring after 60 min and moisture levels doubling by the end of the 120 min event. Soils amended with 2% biochar showed greater moisture retention than other treatments. Cumulative infiltration increased with rainfall duration and was highest under the HWB2 treatment, while the control exhibited the lowest infiltration. Infiltration rates declined over time, with maximum rates observed in HWB2 (44.2 mm h^{-1}) followed by W2 (42.0 mm h^{-1}).

Vahidi *et al.* (2025) [53] assessed the effects of organic amendments on soil erosion using a rainfall simulator over a 180 day period, with amendments applied as surface mulch or soil-incorporated. All amendments (barberry biochar, vermicompost, poultry manure, and wheat straw) significantly reduced runoff and sediment concentration compared to the control. However**,** biochar was the found to be most effective amendment**,** particularly when applied as surface mulch**.** Biochar consistently produced lower runoff coefficients and sediment losses**,** while improving soil fertility and resistance to erosion. Prats *et al.* (2018) [42] reported a 59 % increase in soil erosion after applying charcoal on the soil surface (i.e. <7 mm), while a straw-biochar co-application significantly reduced soil erosion by an average of 70 % in two burnt areas with different burn severity classes (Prats *et al.*, 2021) [43].

Sadeghi *et al.* (2016) [46] evaluated runoff and soil loss control using vinasse-produced biochar in a rainfall simulation study on sandy clay loam soil packed into 0.25 m^2 plots. Treatments included a control and biochar application at 8 t ha^{-1} applied 24 and 48 h before simulated rainfall (50 mm h^{-1} for 15 min). Biochar application increased time to runoff by 55.10% and 71.73% and reduced runoff volume by 98.46% and 46.39% for the 24 h and 48 h treatments, respectively. The lowest soil loss (1.12 ± 0.57 g) and sediment concentration (1.44 ± 0.48 g L^{-1}) occurred with biochar applied 48 h before rainfall, confirming its effectiveness in reducing runoff and soil erosion.

Gholamahmadi *et al.*, 2023 [13] conducted a global-scale meta-analysis evaluating the effects of biochar on runoff and soil erosion by water. The study demonstrated that biochar application significantly reduced soil erosion by an average of 16% and runoff by 25%. The erosion-mitigating effect was markedly stronger in tropical regions (≈30%) compared to temperate regions (≈9%). The analysis further indicated that biochar-amended, vegetated soils are more resistant to low-energy raindrop impacts from canopy interception than to high-energy rainfall on bare soil, highlighting an indirect erosion-control mechanism. Additionally, improvements in soil structure due to biochar application directly reduced soil erodibility, contributing to enhanced resistance against water-induced erosion.

3.4 Field Studies Across Slope Gradients

Slope position and hydrological processes further modulate the influence of biochar on soil erosion and moisture dynamics under rainfall conditions. Peng *et al.* (2019) [39]

evaluated the effects of biochar application on slopes ranging from 5° to 25° over a three-year period under natural rainfall, followed by simulated rainfall experiments. Across both experimental phases, biochar-treated plots consistently exhibited reduced soil erosion compared to the control, whereas surface runoff remained largely comparable between treatments. Notably, improvements in total organic carbon (TOC) export were observed on slopes ≤15°, indicating a slope-dependent response of carbon retention to biochar application.

In a subsequent study, Peng *et al.* (2026) [40] investigated the effects of biochar on soil moisture dynamics on cultivated karst slopes (10° and 20°) in southwestern China under natural rainfall conditions. Biochar application at rates of 30 and 60 t ha^{-1} reduced surface soil moisture while increasing subsurface moisture at depths of 20-30 cm relative to the control. Biochar treatments delayed downward water infiltration, as evidenced by longer response lag times and extended duration periods, while simultaneously reducing mean and maximum infiltration rates. However, total soil water storage was not significantly increased by biochar application. These findings suggest that biochar primarily modifies infiltration behavior and post-rainfall soil water redistribution rather than enhancing overall moisture availability during rainfall events.

3.5 Biochar effects on soil rhizosphere and crop physico biochemical traits under high rainfall

Research has demonstrated that the biochar application greatly influences the response of rhizosphere soil respiration to abrupt fluctuations in soil moisture levels caused by rainfall events. Zu *et al.* (2025) [61] demonstrated that rhizosphere soil respiration (Rs) was significantly influenced by biochar application rate, rainfall amount, and the interval between rainfall events. Across the growing season, biochar-amended soils exhibited consistently higher soil respiration than the control, with the strongest response observed at the highest application rate (45 t ha^{-1}). The pronounced increase in soil respiration under biochar application at 45 t ha^{-1} treatment coincided with periods of prolonged and intense rainfall. This suggested that high rainfall conditions may amplify biochar-induced stimulation of rhizosphere microbial and root respiratory activity. Biochar increased the soil pore volumes by more than 5 µm, which eventually improves microbial abundance and diversity (Yang *et al.*, 2022) [56].

The enhancement in antioxidant activities with BC could result in improved water uptake, root growth, and soil properties (Ahmad *et al.*, 2019) [5]. At the cellular level, biochar may relieve oxidative injuries by using metabolic pathways more effectively in scavenging ROS, and leading to less membrane damage and improved plant performance (Hasanuzzaman *et al.*, 2021; Salim *et al.*, 2021) [17, 47]. The addition of biochar and KE149 (*Rhodobacter sphaeroides* strain) improved plant morphological traits, such as length of shoot and root, and soybean biomass under waterlogging stress. In waterlogging conditions, biochar treatment maintained the root growth and vitality of maize, thus ensuring high yields (Wang *et al.*, 2020) [26]. Jinhua *et al.* (2024) [19] studied the role of biochar in improving antioxidative defense of *Brassica* under flooding stress and observed that application of biochar at 2.5 percent, increased APX, CAT, POD, and SOD activities by 42.29, 45.58, 40.56, and 36.67 percent, respectively, compared to control. They opined that biochar application enhanced antioxidant activity under both normal and flooding stress conditions.

4. Conclusion

The synthesis of existing literature clearly demonstrates that high rainfall, flooding, and waterlogging substantially accelerate soil erosion, disrupt soil structure, and intensify nutrient losses, thereby undermining soil fertility and agricultural sustainability. The breakdown of soil aggregates, increased runoff, preferential flow through cracks, and enhanced leaching of nutrients collectively exacerbate land degradation under extreme moisture conditions. Across diverse experimental settings, biochar has consistently been shown to mitigate these adverse effects by improving soil physical structure, enhancing water retention and infiltration, reducing bulk density, and increasing resistance to erosive forces. Biochar application effectively reduces surface runoff, soil loss, and nutrient leaching, while also suppressing gaseous nitrogen emissions under waterlogged conditions. Furthermore, biochar-mediated improvements in rhizosphere processes, microbial activity, antioxidant defense, and crop physiological traits contribute to improved plant performance and resilience under flooding stress. Evidence from simulated rainfall experiments, slope-based field studies, and global meta-analyses confirms that biochar's erosion-control effectiveness is influenced by application rate, particle size, placement method, and site-specific conditions. Overall, biochar represents a viable and sustainable soil management strategy for enhancing soil stability, conserving nutrients, and improving ecosystem resilience in high rainfall and flood-prone regions, while simultaneously supporting long-term carbon sequestration and sustainable land-use objectives.

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