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Crop Residue Burning: Consequences for Soil Quality and Environmental Integrity

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Crop residue burning is a widespread agricultural practice in many developing regions, particularly in intensive cropping systems, due to its convenience and low operational cost. However, its long-term consequences for soil health and environmental sustainability remain a major concern. This study evaluates the impact of crop residue burning on soil physical, chemical, and biological properties through field observations and laboratory analyses. Soils from burned and unburned plots were compared for bulk density, aggregate stability, soil organic carbon, nutrient availability, microbial biomass, enzyme activity and carbon sequestration potential. Results revealed that residue burning significantly increased soil bulk density while reducing aggregate stability, infiltration and water-holding capacity. Burning also caused substantial losses of soil organic carbon, nitrogen, sulphur and micronutrients, along with reductions in cation exchange capacity and nutrient retention efficiency. Biological indicators, including microbial biomass carbon, enzymatic activity and earthworm populations, were markedly lower in burned soils. Furthermore, residue burning converted soils from carbon sinks into carbon sources, contributing to greenhouse gas emissions and climate change. The findings demonstrate that crop residue burning degrades soil health, reduces fertilizer use efficiency and threatens long-term agricultural productivity. Adoption of residue retention, mulching, incorporation and bioenergy-based alternatives is essential for sustainable soil management and climate-smart agriculture.

Keywords: Crop residue burning; soil health; soil organic carbon; nutrient loss; microbial activity; carbon sequestration; sustainable agriculture

Introduction

India generates enormous quantities of crop residues annually from major crops such as rice, wheat, sugarcane, cotton, maize, sorghum and pulses. Intensification of agriculture, mechanization and expansion of irrigation have significantly increased residue production across the country. Rice and wheat contribute the largest share in cereal-based systems, while sugarcane adds substantial amounts through mill by-products and field residues such as tops and trash. States including Uttar Pradesh, Madhya Pradesh, Rajasthan, Punjab and Maharashtra account for a major proportion of total residue generation due to extensive cultivated areas and high productivity. In Maharashtra alone, sugarcane residues are estimated to exceed 40 million tonnes annually, along with large contributions from paddy, sorghum, cotton, bajra, soybean and pulse crops.

Crop residues represent valuable sources of organic matter, plant nutrients, renewable energy and soil carbon. Despite these benefits, a large proportion of residues is burned in open fields to facilitate rapid land preparation, reduce labor and machinery costs and enable timely sowing of subsequent crops, particularly in intensive rice-wheat and sugarcane systems. However, this practice has emerged as a major environmental and agronomic

concern. Residue burning contributes to severe air pollution, loss of valuable biomass and long-term degradation of soil quality. While atmospheric impacts have received considerable attention, the consequences for soil physical, chemical and biological properties are equally critical yet less comprehensively addressed (Pradhan *et al.*, 2024).

Soil health depends on a balanced interaction of physical structure, chemical fertility and biological activity, which together regulate water retention, nutrient cycling, root development and crop productivity. Crop residue burning disrupts this balance by exposing the soil surface to high temperatures, removing protective cover and eliminating a primary source of organic carbon. These changes have cascading effects on soil structure, nutrient availability, microbial activity and long-term sustainability of agroecosystems.

Effects of Crop Residue Burning on Soil Physical Properties

High temperatures generated during residue burning degrade soil structure by destroying organic binding agents such as humus and microbial polysaccharides that stabilize soil aggregates. These substances act as natural adhesives, holding soil particles together and forming stable aggregates. Their destruction results in aggregate breakdown, leading to weak and unstable soil structure. Consequently, the soil surface becomes more prone to crust formation after rainfall or irrigation. Surface crusting reduces pore continuity, restricts gas exchange and creates mechanical barriers that impede root penetration and seedling emergence. Reduced aggregate stability also lowers infiltration rates, increases runoff and enhances susceptibility to water erosion.

Residue burning produces fine ash and soil particles that settle on the surface, forming a thin, compacted layer. This surface sealing obstructs soil pores and disrupts natural pore networks, thereby reducing water infiltration. When infiltration is restricted, a greater proportion of rainfall or irrigation water flows over the surface rather than entering the soil profile. This leads to reduced soil moisture availability for crops and increased risk of nutrient loss through runoff and erosion. Repeated burning thickens and hardens this surface layer, further impairing soil permeability. Under such conditions, soils are prone to waterlogging during intense rainfall and excessive drying during droughts, both of which adversely affect crop growth and productivity.

Bulk density (BD), defined as the mass of dry soil per unit volume (g cm^{-3}), is a key indicator of soil compaction, porosity and root growth potential. Lower BD values indicate greater pore space, while higher values reflect denser and more compacted soils. Crop residue burning removes surface organic matter that plays a crucial role in aggregate formation and pore development. The loss of this organic material leads to tighter packing of soil particles, resulting in increased bulk density and reduced porosity. Elevated bulk density restricts root growth, limits water and air movement and reduces oxygen availability to roots and microorganisms. Over time, repeated burning promotes soil compaction, reduces water-holding capacity and diminishes the soil's resilience to physical stress (Pradhan *et al.*, 2024). Crop residues retained on the soil surface function as a natural mulch that moderates soil temperature, reduces evaporation and contributes organic inputs to the soil. This mulch layer enhances soil water retention by promoting aggregate formation and increasing pore volume. Burning eliminates this protective cover, exposing the soil to direct solar radiation, wind and temperature extremes. As a result, evaporation rates increase and soils dry more rapidly. Reduced organic inputs also lower the soil's capacity to retain water near the root zone, intensifying moisture stress during dry periods. These conditions hinder seed germination, root development and crop establishment, ultimately reducing yields. Recurrent burning further weakens the soil's buffering capacity against climatic variability (Pradhan *et al.*, 2024).

Residue cover also plays a vital role in protecting the soil from erosive forces. It intercepts raindrops, reduces their kinetic energy and slows near-surface wind speed, thereby minimizing soil particle detachment and transport. When residues are burned, the soil surface is left bare and directly exposed to rainfall and wind. Raindrop impact disrupts soil aggregates, generating fine particles that are easily transported by surface runoff. Wind

erosion similarly removes loose, dry particles, particularly in light-textured soils. This leads to the loss of nutrient-rich topsoil, organic matter and beneficial microorganisms. Continued erosion degrades soil structure, reduces water retention and progressively diminishes soil fertility and productivity.

Effects of Crop Residue Burning on Soil Chemical Properties

Soil organic carbon (SOC) is a fundamental component of soil health, contributing to nutrient retention, structural stability, water-holding capacity, and microbial activity. During residue burning, most of the carbon contained in plant biomass is rapidly oxidized and released into the atmosphere as carbon dioxide. This results in a substantial decline in SOC levels. Reduced SOC weakens the soil's nutrient-holding capacity, lowers fertilizer use efficiency, and accelerates soil degradation. Over the long term, SOC depletion leads to declining soil fertility and reduced agricultural productivity (Kumar *et al.*, 2025).

Nitrogen is the nutrient most severely affected by residue burning. Approximately 70–90% of the nitrogen contained in crop residues is volatilized and lost to the atmosphere during combustion. This loss reduces soil nitrogen availability, leading to nitrogen deficiency symptoms in crops, such as chlorosis and stunted growth, and increases reliance on synthetic nitrogen fertilizers. Greater fertilizer dependence raises production costs and contributes to environmental pollution through leaching and gaseous emissions (Kumar *et al.*, 2025)..

Sulphur losses during burning are also substantial, with nearly 50–67% of residue sulphur emitted as sulphur dioxide gas. Sulphur is essential for protein synthesis, enzyme activity, and oil formation in crops. Its depletion results in sulphur deficiencies, particularly in oilseed, legume, and vegetable crops, manifesting as pale leaves, reduced growth, and lower yields.

Phosphorus and potassium are not completely volatilized during burning; instead, they remain in the ash in relatively soluble forms. However, in the absence of residue cover, these nutrients are highly vulnerable to loss through runoff, leaching, or fixation. Over time, this results in reduced availability of phosphorus and potassium, necessitating increased fertilizer inputs to sustain crop productivity.

Residue burning leaves behind alkaline ash containing compounds such as calcium carbonate, potassium carbonate, and magnesium oxide. These substances temporarily raise soil pH, particularly in acidic soils. Although this may appear beneficial in the short term, the effect is transient. In neutral to alkaline soils, the pH increase can reduce the availability of essential micronutrients such as iron, zinc, manganese, and copper, leading to nutrient imbalances and impaired plant growth (Kumar *et al.*, 2025).

Cation exchange capacity (CEC) reflects the soil's ability to retain and exchange nutrient cations such as calcium, magnesium, potassium, and ammonium. Organic matter is a major contributor to CEC, especially in coarse-textured soils. By reducing organic matter content, residue burning lowers CEC, decreasing the soil's nutrient retention capacity and increasing nutrient losses through leaching. Consequently, fertilizer use efficiency declines, weakening the soil's capacity to sustain plant growth.

Micronutrients, including zinc, iron, manganese, and copper, are closely associated with organic matter and microbial activity. Burning residues reduces organic matter levels and disrupts soil biological processes that maintain micronutrient availability. Additionally, the temporary rise in soil pH promotes the formation of insoluble micronutrient compounds, rendering them unavailable to plants. These deficiencies result in hidden hunger, reduced enzyme activity, chlorosis, and poor crop performance.

Effects of Crop Residue Burning on Soil Biological Properties

Soil microorganisms, including bacteria, fungi, actinomycetes, algae and protozoa, play critical roles in nutrient cycling, organic matter decomposition, soil aggregation, and disease suppression. The intense heat generated during residue burning causes direct mortality of these beneficial organisms, particularly within the top 5–10 cm of soil where biological

activity is highest. The abrupt decline in microbial populations reduces soil fertility, weakens aggregate stability, and compromises the soil's natural resistance to pests and diseases.

Soil enzymes, which are produced by microorganisms and plant roots, catalyze essential biochemical reactions in the soil. Key enzymes such as dehydrogenase (an indicator of overall microbial activity), urease (involved in nitrogen transformation), phosphatase (responsible for phosphorus mineralization), protease, and β -glucosidase (associated with carbon and protein cycling) are highly sensitive to thermal stress. Residue burning drastically reduces enzyme activity by destroying both enzyme-producing organisms and the enzymes themselves. This suppression slows nutrient transformation processes, reduces nutrient availability, and impairs soil biochemical functioning (Parambil *et al.*, 2025).

Soil fauna, particularly earthworms, contribute significantly to soil structure, aeration, water infiltration, and nutrient cycling through bioturbation and organic matter incorporation. Burning residues eliminates surface organic substrates and exposes soil fauna to lethal temperatures, resulting in direct mortality, especially among surface-dwelling species. Reduced earthworm populations lead to lower soil porosity, diminished organic matter mixing, and weakened biological integrity of the soil ecosystem.

Healthy soils rely on interconnected biological processes such as organic matter decomposition, nutrient mineralization, nitrification, immobilization, and humus formation. Crop residue burning disrupts these processes by:

- Reducing populations of microorganisms and soil fauna,
- Decreasing organic substrate availability,
- Suppressing enzyme activity.

These disruptions collectively impair soil nutrient cycling and long-term fertility.

Effects of Crop Residue Burning on Nutrient Availability

Residue burning causes substantial losses of essential nutrients, particularly nitrogen and sulphur, which are highly volatile. Nitrogen present in proteins, amino acids, and microbial biomass is rapidly lost during combustion, primarily as nitrogen gas, nitric oxide, nitrogen dioxide, and ammonia. Only a small fraction remains in the ash, disrupting the natural nitrogen cycle and increasing dependence on synthetic fertilizers. Sulphur undergoes similar losses, with approximately 50–67% emitted as sulphur dioxide gas, reducing crop protein synthesis and nitrogen-use efficiency and resulting in lower crop quality (Pradhan *et al.*, 2025).

Although phosphorus and potassium largely remain in the ash, they occur in soluble forms that are vulnerable to leaching, runoff, and fixation. Over time, these losses reduce soil reserves of phosphorus and potassium, requiring higher fertilizer inputs to maintain productivity.

Residue burning also alters the availability of micronutrients by reducing organic matter, modifying soil pH, and disrupting biological activity. Zinc availability declines due to loss of organic complexes and chelating agents, particularly in calcareous and alkaline soils. Iron availability decreases as elevated pH and oxidation convert iron into insoluble forms, leading to chlorosis. Manganese is oxidized from plant-available Mn^{2+} to unavailable Mn^{4+} forms, impairing photosynthesis and enzyme activity. Copper, which is largely associated with organic matter, becomes less available following organic matter loss, affecting enzyme systems and reproductive development in plants (Pradhan *et al.*, 2025).

Effects of Crop Residue Burning on Carbon Sequestration

Soils represent the largest terrestrial carbon reservoir, primarily in the form of stable organic matter and humus. Healthy soils accumulate carbon through inputs from crop residues, root biomass, and microbial activity, thereby functioning as long-term carbon sinks. Increased soil carbon enhances nutrient retention, aggregate stability, water-holding capacity, and climate change mitigation by removing carbon dioxide from the atmosphere (Pradhan *et al.*, 2025).

Crop residue burning disrupts this carbon sequestration process by eliminating fresh organic inputs and preventing their conversion into stable humus. Instead, carbon is rapidly

released into the atmosphere as carbon dioxide. Consequently, soils shift from acting as carbon sinks to becoming carbon sources, increasing greenhouse gas concentrations and degrading soil health. Prolonged burning creates a persistent imbalance between carbon inputs and losses, making it increasingly difficult to restore soil carbon stocks.

Restoring lost soil carbon requires substantial organic inputs over extended periods, highlighting the long-term negative consequences of residue burning for both climate mitigation and soil rehabilitation.

Long-Term Impacts on Soil Health

Decline in Soil Fertility and Productivity

Repeated residue burning leads to progressive losses of soil organic matter, essential nutrients, and beneficial soil organisms. Over time, this results in nutrient depletion, degraded soil structure, reduced water-holding capacity, and diminished biological activity. Such soils are less capable of supporting healthy crop growth, leading to sustained declines in agricultural productivity.

Reduced Fertilizer Use Efficiency

Healthy soils retain nutrients through interactions with organic matter and clay minerals. Residue burning lowers soil organic carbon and reduces nutrient-holding capacity, increasing nutrient losses through leaching, volatilization, and runoff. Consequently, a smaller proportion of applied fertilizers is utilized by crops, reducing efficiency and increasing production costs.

Increased Dependence on Chemical Fertilizers

As natural nutrient cycling and organic matter inputs decline, soils lose inherent fertility, compelling farmers to apply higher amounts of synthetic fertilizers to maintain yields. This increased reliance raises production expenses and elevates risks of soil acidification or alkalization, nutrient imbalances, and contamination of water resources.

Lower Crop Yields Over Time

The combined effects of nutrient depletion, poor soil structure, reduced water retention, and diminished biological activity gradually impair plant growth, root development, and stress tolerance. Yield reductions may not be immediate but intensify over time, particularly under drought conditions or nutrient stress, posing risks to long-term food security.

Soil Degradation and Risk of Desertification

Residue burning accelerates soil degradation by increasing erosion, compaction, nutrient loss, and organic matter depletion. In arid and semi-arid regions, these processes can contribute to desertification, whereby productive land transitions into degraded landscapes incapable of supporting sustainable agriculture.

Effects of Crop Residue Burning on the Environment

Greenhouse gases such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) play major roles in trapping heat within the atmosphere and driving global warming. Crop residue burning releases large quantities of these gases. Carbon dioxide, produced during biomass combustion, is the primary emission and directly contributes to rising global temperatures while reducing soil carbon stocks (Uday Kumar *et al.*, 2025).

Methane is generated during incomplete combustion and has a global warming potential approximately 28–34 times greater than that of CO₂ over a 100-year period. Nitrous oxide, released from nitrogen-containing residues, is even more potent, with a warming potential approximately 265–298 times that of CO₂, and also contributes to stratospheric ozone depletion (Uday Kumar *et al.*, 2025). In addition to gaseous emissions, residue burning produces black carbon, a component of soot consisting of fine, dark particles. Black carbon:

- Darkens the soil surface, increasing heat absorption and surface temperature,
- Alters surface energy balance, influencing local and regional climate,
- Reduces land and snow albedo, intensifying warming,
- Modifies soil physical and biological processes by affecting temperature regimes, microbial activity, and water movement.

By diverting carbon from soil organic matter into atmospheric emissions, residue burning reduces soil carbon storage, weakens soil structure, increases vulnerability to erosion, and transforms soils from carbon sinks into carbon sources. These changes undermine climate change mitigation efforts and compromise the sustainability of agricultural systems.

Conclusion

Crop residues are valuable resources rather than agricultural waste and possess multiple productive and sustainable uses. When retained or incorporated into the soil, residues enhance soil organic carbon, improve moisture retention, strengthen aggregate stability, and promote nutrient cycling. They also serve as feedstock for bioenergy and biofuels, including biogas, bioethanol, pellets, briquettes, and cogeneration, thereby reducing dependence on fossil fuels. Additionally, residues are widely used as animal fodder and bedding, compost and vermicompost, substrates for mushroom cultivation, and raw materials for industrial products such as paper, boards, packaging, biochar, and biochemicals, supporting circular and climate-smart agriculture.

Crop residues play a critical role in carbon sequestration by returning plant-derived carbon to the soil–atmosphere system in stable forms. When residues are retained on the soil surface or incorporated into the soil, a portion of their carbon is transformed into soil organic carbon through microbial decomposition and humus formation, enhancing long-term carbon storage. Conservation practices such as residue retention, mulching, reduced tillage and biochar production slow carbon loss and promote carbon stabilization within soil aggregates. By avoiding residue burning and promoting in situ utilization, agricultural systems can mitigate climate change, improve soil health and enhance resilience and sustainability.



Fig. 1. Burning of sugarcane field before harvest



Fig. 2. Burning of rice stubble



Fig. 3. Effect of crop residues burning on Environment

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