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Impact of Crop Residue Management for Soil Health Improvement

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Crop residues such as straw, stalks, leaves, stubble, and husks left in the field after harvest, constitute a substantial and underutilized resource within Indian agriculture (Shinde et al., 2022; Sarkar et al., 2024). India produces an estimated 500 million tonnes of such residue annually, the majority originating from cereal-based cropping systems (Nowmika et al., 2025; Sairam et al., 2023). Burning remains the dominant disposal method because it clears fields rapidly at negligible cost, yet the practice depletes soil nutrients and organic carbon while contributing to severe air pollution and associated health risks (Shinde et al., 2022; Kaur et al., 2022; Leharwan et al., 2023). Evidence from multiple reviews indicates that alternative practices like retention, mulching, incorporation, composting, biochar application, and microbial decomposition, improve the physical, chemical, and biological condition of soil and support more sustainable production systems (Shinde et al., 2022; Sarkar et al., 2024; Brichi et al., 2023). In the rice–wheat belt of Punjab and Haryana, mechanized interventions such as the Happy Seeder and Super SMS have made in-situ residue management considerably more feasible for farmers operating under tight sowing windows (Kaur et al., 2022; Singh et al., 2025). Adoption nonetheless remains constrained by machinery cost, competing demands for residue as fuel or fodder, and limited farmer awareness (Turmel et al., 2015; Singh et al., 2025). Sustained progress will depend on the wider uptake of conservation agriculture, bio-decomposers, carbon-oriented policy incentives, and management strategies adapted to local agro-ecological conditions (Panneerselvam et al., 2024; Sarker et al., 2022).

Introduction

Crop residues comprise the non-economic plant material remaining in the field once the marketable portion of a crop has been harvested, including rice straw, wheat stubble, maize stalks, cotton sticks, sugarcane trash, husks, and leaves (Shinde et al., 2022; Sarkar et al., 2024). The volume of residue generated continues to rise, driven by intensive cultivation practices and increasing cropping intensity, both of which raise total biomass output per unit area (Sarkar et al., 2020; Fu et al., 2021; Sairam et al., 2023). Because cereal crops dominate Indian agricultural production, rice and wheat systems account for a disproportionate share of national residue generation, which explains the concentrated research attention these systems receive (Nowmika et al., 2025; Kaur et al., 2022).

The underlying concern is not residue generation per se, but the manner in which residue is managed after harvest. In the rice–wheat belt of Punjab and Haryana, the short interval between rice harvest and wheat sowing leaves farmers with limited time to clear fields, a constraint that has historically favoured burning as the fastest and least expensive option (Kaur et al., 2022; Korav et al., 2024; Leharwan et al., 2023). This practice carries substantial long-term costs. Burning elevates particulate matter and greenhouse gas emissions, disrupts nutrient recycling, damages soil microbial communities, and progressively erodes soil fertility (Kaur et al., 2022; Gupta et al., 2024). Soil health is central to this discussion because it governs water storage capacity, nutrient cycling, root development, and resilience to drought and climatic stress (Nowmika et al., 2025; Kumar et al., 2025). It is for this reason that crop residue management has become integral to conservation agriculture, a framework built on minimal soil disturbance, permanent soil cover, and crop diversification (Sarkar et al., 2020; Sairam et al., 2023; Qiu et al., 2026).

Residue Management Options

Residue can be managed either in situ or ex situ. The principal in-situ approaches are surface retention, mulching, and direct incorporation into the soil (Shinde et al., 2022; Sarkar et al., 2020). Retention protects against erosion, conserves moisture, and improves infiltration, whereas incorporation contributes to the gradual accumulation of soil organic matter and nutrient reserves (Sarkar et al., 2020; Fu et al., 2021; Sairam et al., 2023).

Ex-situ options include composting, vermicomposting, biochar production, use as livestock feed, mushroom cultivation, and bioenergy generation (Shinde et al., 2022; Singh et al., 2025). These pathways can reduce the incentive to burn residue and generate supplementary income, though they entail additional labour, collection, and transport costs, and they forfeit the soil-cover benefits associated with retaining residue in the field (Shinde et al., 2022; Turmel et al., 2015). The evidence on open-field burning is unambiguous across the reviewed literature: the practice wastes recoverable nutrients and accelerates both environmental and soil degradation, and is consistently discouraged (Sarkar et al., 2020; Singh et al., 2025).

Within India, progress in residue management has been closely tied to mechanization. The Happy Seeder enables wheat to be sown directly into standing rice residue without prior burning or conventional tillage, while Super SMS units and straw chopper-spreaders improve the distribution of residue behind the combine harvester (Korav et al., 2024; Kaur et al., 2022; Singh et al., 2025). Such technologies are particularly significant in northwestern India, where delays in wheat sowing translate directly into yield losses (Kaur et al., 2022; Leharwan et al., 2023).

Effects on Soil and Crops

Soil Physical Properties

Residue retention and incorporation are associated with improved soil aggregation, reduced bulk density, increased porosity, and enhanced water infiltration across a range of studies (Gupta et al., 2024; Fu et al., 2021; Sarker et al., 2022). Residue cover further reduces evaporative loss and helps conserve soil moisture (Nowmika et al., 2025; Singh et al., 2025). In Haryana, Korav et al. (2024) reported that zero-till wheat grown with retained rice residue held 13.4–23.6% more soil moisture than conventional wheat grown without residue. These effects have direct implications for erosion control and drought tolerance in the field (Kumar et al., 2025; Leharwan et al., 2023).

Soil Chemical Properties

Residue return is among the more reliable mechanisms for building soil organic carbon and recycling nutrients within cropping systems (Turmel et al., 2015; Kumar et al., 2025). Residue contains carbon along with meaningful quantities of nitrogen, phosphorus, potassium, and micronutrients, which are released progressively during decomposition (Fu et al., 2021; Korav et al., 2024). In a long-term rice–wheat trial, Gupta et al. (2024) recorded a 73.9% increase in topsoil organic carbon under residue retention or incorporation relative to conventional practice. A broader meta-analysis by Zhao et al. (2020) reported comparable gains, with soil organic carbon pools increasing by 12.3–36.8% alongside

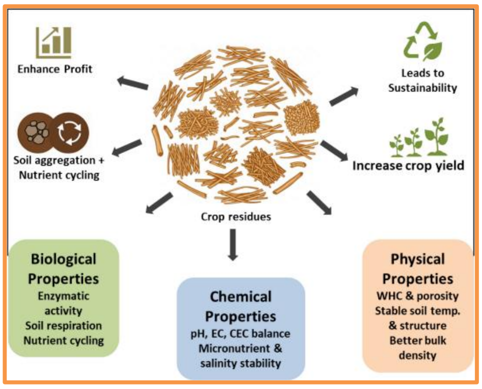

Figure 1. Effects of crop residue management on soil properties, crop productivity and agricultural sustainability.
Source: Baloch et al. (2025).

improvements in nutrient reserves and soil water content. Residue management also influences nitrogen and phosphorus dynamics within the soil. While nutrients are recycled back into the system, high-carbon cereal residue can temporarily immobilize nitrogen when it is not accompanied by adequate fertilizer or decomposer support (Fu et al., 2021; Turmel et al., 2015). This is one reason integrated nutrient management approaches tend to outperform residue return applied in isolation (Kumar et al., 2025).

Soil Biological Properties

Crop residues supply carbon and energy to soil microorganisms, sustaining the biological component of the soil system (Fu et al., 2021; Sarkar et al., 2020). Across the reviewed studies, residue-managed soils consistently exhibit higher microbial counts, greater enzyme activity, and enhanced overall biological function relative to soils that have been burned or stripped of residue (Gupta et al., 2024; Korav et al., 2024). In Haryana, Korav et al. (2024) recorded increases of 47.9–60.4% in microbial counts, 59.0–73.1% in diazotrophs, and 47.3–55.2% in actinomycetes under Happy Seeder-based residue retention relative to burning or removal. In Odisha, Panneerselvam et al. (2024) found that microbial consortia applied alongside residue incorporation or retention improved soil organic carbon, enzyme activity, and nitrogen, phosphorus, and potassium availability, while raising yield by 8.4–17.8%.

Productivity, Challenges, and Future Scope

Selected evidence linking crop residue management with yield, profitability, emissions reduction, and system sustainability

Aspect	Main message	Example
Productivity	Residue management usually improves yield	Wheat yield reached 56.8 q ha^{-1} with mulcher + Happy Seeder in Haryana (Leharwan et al., 2023)
Profitability	No-burn systems can improve returns	Happy Seeder with full residue retention gave the highest net return in Haryana (Korav et al., 2024)
Climate	Burning worsens emissions; better use cuts them	India–Bhutan interventions reduced about 26,000 t CO2 (Dey et al., 2020)
Diversification	Residue incorporation works best with diverse systems	Jute-based systems with residue + recommended fertilizer had the highest productivity and sustainability (Kumar et al., 2021)

The productivity gains reported across the literature reinforce the case for residue retention. Zhao et al. (2020) found a 7.8% average yield increase under residue retention in a national meta-analysis conducted in China. Korav et al. (2024) reported wheat yield increases of 9.8–11.3% under Happy Seeder-based systems relative to burning and removal in Haryana. Sarker et al. (2022) documented comparable gains in Bangladesh, where conservation tillage combined with residue retention increased rice, maize, and overall system yields by 9.2%, 14.0%, and 14.12% respectively. In eastern India, Kumar et al. (2021) found that combining residue incorporation with crop diversification improved both productivity and sustainability at the system level.

These benefits are accompanied by genuine constraints. Residue often has competing uses as livestock feed, fuel, or raw material, which limits the quantity farmers are willing to leave in the field (Turmel et al., 2015; Korav et al., 2024). Some systems experience temporary nitrogen immobilization, reduced soil temperature, waterlogging, or elevated pest pressure (Turmel et al., 2015; Fu et al., 2021). Broader adoption is further constrained by machinery cost, labour requirements, inadequate infrastructure, and gaps in farmer awareness (Sarkar et al., 2020; Singh et al., 2025).

The evidence suggests that no single method is sufficient on its own; rather, effective residue management requires practices adapted to local conditions. Conservation agriculture, Happy Seeder-based sowing, Super SMS, biochar production, composting, and microbial decomposers each have a role depending on the specific crop, soil type, and climate involved (Sairam et al., 2023; Panneerselvam et al., 2024; Singh et al., 2025). Carbon-focused incentives combined with direct farmer support are likely to accelerate adoption, particularly in regions where burning remains widespread (Sarker et al., 2022; Singh et al., 2025).

Conclusion

Crop residue management represents a practical and evidence-supported pathway to improved soil health and more sustainable agricultural production. When residue is retained, incorporated, mulched, composted, or biologically decomposed rather than burned, soils generally show measurable gains in carbon content, nutrient availability, moisture retention, and biological activity, and crops respond with improved yield and resilience. The strongest evidence for these outcomes comes from conservation agriculture systems and from India's rice–wheat regions specifically, where machinery and policy support have made no-burn approaches increasingly feasible for farmers. Crop residue should therefore be regarded not as agricultural waste but as a resource with direct relevance to soil restoration, climate resilience, and long-term food security.

Key Take-Home Messages

- Crop residues are a valuable farm resource, not simply waste (Sarkar et al., 2020).
- India produces roughly 500 million tonnes of residue every year (Nowmika et al., 2025).
- Open burning damages soil, air quality, and human health (Kaur et al., 2022).
- Retaining residue improves aggregation, porosity, and infiltration (Gupta et al., 2024).
- Residues help build soil organic carbon and recycle nutrients (Zhao et al., 2020).
- Residue-managed soils support more microbial activity and enzyme function (Korav et al., 2024).
- The Happy Seeder and Super SMS are key no-burn tools in northwestern India (Kaur et al., 2022).
- Microbial decomposers can speed up residue breakdown and raise yields (Panneerselvam et al., 2024).
- Crop diversification strengthens the benefits of residue incorporation (Kumar et al., 2021).
- Better residue management supports SDG 2, SDG 13, and SDG 15 through food security, climate action, and soil restoration.

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