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Effect of Crop Residue Management on Soil Health and Crop Performance

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Abstract

As global populations increase, the amount of crop residues generated annually continues to rise. Traditionally used for energy and animal feed, crop residues are now often treated as waste due to changes in living standards. Rich in nutrients and easily decomposed by microorganisms, crop residues offer significant potential for soil enrichment when managed properly. Returning crop residues to the soil instead of burning them is a sustainable practice that enhances soil health and reduces environmental damage. However, poor agricultural practices and industrial activities often degrade soil quality, and residues can aid in soil improvement and contamination remediation. While incorporating crop residues can improve soil texture, nutrient content, and microbial activity, it can also lead to negative effects such as pest infestations and increased methyl mercury levels in contaminated soils. This review examines the composition, nutrient content, and structural characteristics of crop residues, emphasizing their role in soil enhancement and contamination cleanup. A nuanced understanding of residue management is essential for promoting soil health and environmental sustainability.

Keywords: Crop Residues, Soil Quality, Soil Remediation, Heavy Metals.

Introduction

As the global population continues to grow, the quantity of crop residues generated each year increases. Historically, these residues were utilized as energy sources and animal feed. However, with economic development and rising living standards, they are now often regarded as agricultural waste. Crop residues, rich in nutrients and capable of decomposition

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by microorganisms, offer substantial potential for soil enrichment when properly managed. Rather than burning them, returning crop residues to the soil is recommended as a sustainable agricultural practice that enhances soil health and reduces environmental impact (Kumar *et al.* , 2020; Lal, 2005).

Declining soil quality is frequently the result of poor agricultural practices, such as continuous monocropping, overuse of chemical fertilizers, and excessive application of pesticides and herbicides (Zhang et al. , 2018). Additionally, human activities, including mining and industrial processes, can lead to soil contamination. Numerous studies have demonstrated that the incorporation of crop residues into the soil can improve its quality and even aid in the remediation of contaminated soils (Wang *et al.* , 2019; Liu *et al.* , 2016).

However, the benefits of returning crop residues to soil are not guaranteed in every case. For example, residue decomposition can sometimes promote pest infestations and plant diseases. In certain conditions, the application of rice straw may lead to the loss of dissolved organic carbon, potentially harming soil and groundwater quality. Furthermore, adding rice straw to mercury-contaminated soils has been shown to increase harmful methyl mercury levels in crops like wheat and rice (Zhu *et al.* , 2014). The outcomes of crop residue incorporation depend on various factors, including the type and quantity of residue, the methods of application, tillage intensity, fertilizer use, climate conditions, and soil characteristics (Singh *et al.* , 2021).

This review explores the composition, nutrient content, and physical structure of crop residues, focusing on their role in soil improvement and contamination cleanup. A clear understanding of these effects is crucial for ensuring that the use of crop residues in agricultural practices supports both soil health and environmental sustainability.

Characteristics of Crop Residues:

Composition: Crop residues, which are the plant remains left after harvesting, primarily consist of three main components: cellulose, hemicellulose, and lignin (Lal, 2005; Kumar *et al.* , 2020). Cellulose (40–50%): Cellulose is a biopolymer composed of glucose units linked together in long chains. These chains align in parallel to form strong microfibrils that make up the plant's cell walls. The high percentage of cellulose in crop residues gives them structural strength and resilience (Somerville *et al.* , 2004).

Hemicellulose (15–25%): Hemicellulose is more structurally complex than cellulose, consisting of a mixture of various sugars such as xylans, xyloglucans, arabinoxylans, and glucomannans. Unlike cellulose, hemicellulose is more easily broken down due to its

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amorphous nature, playing a crucial role in the flexibility and hydration of plant cell walls (Gomes *et al.* , 2013).

Lignin (20–30%): Lignin is a phenolic polymer composed of three primary alcohols: p-coumaryl, coniferyl, and sinapyl alcohols. It cross-links cellulose and hemicellulose, forming a rigid and complex three-dimensional structure in the plant's cell walls. Lignin provides mechanical strength and resistance to microbial degradation, contributing to the durability of crop residues (Ralph *et al.* , 2004).

In simpler terms, crop residues consist of cellulose fibers, which are surrounded by hemicellulose and bound together by lignin. This combination results in a tough and stable structure that serves as a natural defense against environmental factors and decomposition.

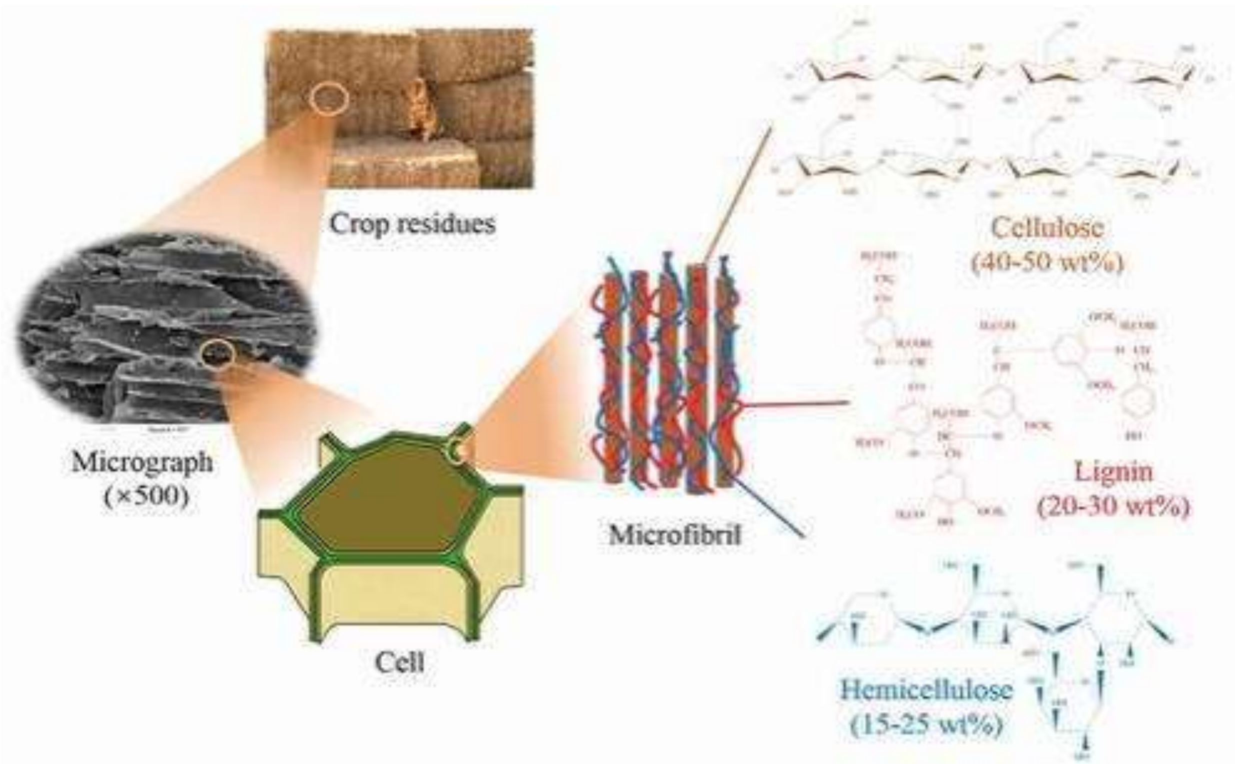

Figure.1. Structure and composition of crops

Nutrient content:

Crop residues are rich in nutrients essential for plant growth. They mainly contain carbon (40%-45%), nitrogen (0.6%-1%), phosphorus (0.45%-2%), potassium (14%-23%), and small amounts of other important minerals. These nutrients help balance soil nutrients and can improve the effectiveness of inorganic fertilizers.

The rate at which these nutrients are released into the soil depends on several factors:

Properties of the residues: The carbon-to-nitrogen (C/N) ratio and the chemical makeup of the residues influence how quickly they break down. For example, a C/N ratio greater than

25:1 usually means that nitrogen is temporarily locked up, while a lower ratio leads to faster nutrient release.

Climate: Warmer temperatures and proper soil moisture can speed up the decomposition of residues and the release of nitrogen.

Soil conditions: Factors like soil pH and water content also affect the breakdown and nutrient release.

Application method: Whether crop residues are directly added to the soil or applied indirectly can also impact how nutrients are released.In summary, crop residues not only add organic matter to the soil but also provide essential nutrients that can enhance soil fertility and support crop growth.

Physical structure:

Crop residues have a unique tubular structure with thick walls, making them lightweight. Their hollow structure is made up of cell walls with many small pores. These pores differ in size and arrangement, depending on the type of crop residue.

Rice straw: Inside rice straw, there are many vascular bundles, cavities, and other porous tissues. It has a relatively low surface area (0.77 m^2/g) and a small pore volume (0.0059 m^3/g).

Wheat straw: Wheat straw has a linear, multi-cavity structure that creates a complex network of connected pores. The average pore size is 13.90 nm, and it has a cumulative pore volume of 0.01 cm^3/g.

Corn stalks: Corn stalks have mostly nanometer-sized pores (5–100 nm). These small pores contribute to a large total surface area of 31.88 m^2/g and a high porosity of 73.33%.

Cotton stalks: Cotton stalks mainly consist of larger pores (macro-pores) and have a low surface area (1.95 m^2/g) with a total pore volume of 0.0115 m^3/g. In simple terms, different crop residues have different pore structures that affect their overall properties, such as how much surface area and pore volume they have, which can influence how they interact with soil and other materials.Bulk density measures how tightly packed crop residues are. This varies depending on the type of crop residue and how uniform they are.

Wheat straw: Has a very low bulk density because it has hollow stems and a lightweight outer layer.

Maize straw: Also has a low bulk density due to its loose structure.

Soybean straw and cotton stalks: Have higher bulk densities because they have solid stems and a more compact structure. In simpler terms, crop residues like wheat and maize are lighter and less tightly packed, while soybean and cotton residues are denser and more tightly packed.

Crop residues for soil improvement

Texture

Returning crop residues to the soil can greatly enhance the physical properties of the soil in various ways:

- **Soil Moisture Content**: Incorporating crop residues can help increase soil moisture by reducing surface runoff and evaporation and improving water infiltration and absorption. For instance, a study observed that covering soil with straw improved moisture content from 12.3% to 16.6% over two years (Chen *et al.* , 2019). However, initially, soil moisture may drop as residues and microorganisms absorb water, requiring timely irrigation to compact the soil and improve contact between residues and the soil (Zhang *et al.* , 2020).
- **Soil Bulk Density**: Bulk density refers to how compact the soil is. Adding crop residues can reduce bulk density, improving soil structure. One study found that incorporating maize and wheat straw reduced soil bulk density by 5.7% in the top 20 cm of soil over seven years and by 9.5% during a single growing season (Li *et al.* , 2018).
- **Soil Porosity**: This refers to the space between soil particles, which is essential for air and water movement. Crop residues can increase soil porosity. For example, wheat straw additions increased soil porosity by about 5% in various soil layers (Wang *et al.* , 2021). However, excessive porosity may hinder seed-to-soil contact, requiring proper watering and soil compaction.
- **Soil Aggregate Stability**: Soil aggregates are clusters of soil particles crucial for maintaining soil structure. Incorporating crop residues can increase both the size and stability of these aggregates, thereby enhancing soil's capacity to retain water and nutrients. For example, wheat straw additions improved aggregate stability, as indicated by the mean weight diameter (MWD) and geometric mean diameter (GMD), which reflect better soil structure (Yu *et al.* , 2020). In simpler terms, adding crop residues can improve soil moisture retention, reduce compaction, increase porosity, and enhance aggregate stability, promoting healthier and more productive soil.

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pH and Cation Exchange Capacity (CEC)

- **Soil pH Changes**: Crop residues can influence soil pH, particularly in soils with low buffering capacity. In some cases, decayed crop residues increase soil pH, reducing acidity. A study reported that using decayed residues increased acidic soil pH by 55%-75% (Fan *et al.* , 2021). However, in practices like no-till farming or rotary tillage, adding straw reduced pH slightly, from 7.7 to 7.2 (Sun *et al.* , 2019). These effects can persist for over two years, depending on factors like residue type and nutrient cycling.
- **Cation Exchange Capacity (CEC)**: CEC measures a soil's ability to hold and exchange nutrients. Returning crop residues enhances organic matter, which increases CEC. For example, retaining 30% of crop residues raised CEC by 11.3% compared to retaining 15%, and by 27.32% compared to complete residue removal (Zhao *et al.* , 2020). Another study showed wheat residues increased CEC by 9.39% to 21.59% over five growing seasons (Huang *et al.* , 2022). In summary, crop residues can either raise or lower soil pH, and their management can significantly improve nutrient retention and exchange in the soil, supporting healthy plant growth.

Organic Carbon and Soil Nutrients: Decaying crop residues recycle vital nutrients, including organic carbon, nitrogen, phosphorus, and potassium.

- **Organic Carbon**: Crop residues contain around 40% organic carbon, which enhances soil stability through larger aggregates. For example, adding garlic stalks increased organic carbon content by 50% in two years (Liu *et al.* , 2021). Returning residues also mitigates carbon loss.
- **Nitrogen**: Nitrogen is essential for proteins and DNA synthesis in plants. The nitrogen in crop residues can be converted into ammonium (NH_4^+) and nitrate (NO_3^-), which are usable by plants. Incorporating straw and fertilizers increased available nitrogen by 64% in the top 20 cm of soil (Wang *et al.* , 2020). However, residues with a high carbon-to-nitrogen ratio may immobilize nitrogen, necessitating supplemental fertilizers.

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- **Phosphorus**: Microorganisms decompose phosphorus in residues into plant-available forms. Long-term straw additions significantly boosted phosphorus use efficiency from 43% to 72% after 30 years (Li *et al.* , 2019).
- **Potassium**: Potassium is readily released from residues, replenishing soil levels. Garlic stalks and soybean residues have been shown to significantly increase potassium availability (Zhang *et al.* , 2019). In summary, returning crop residues enriches the soil with essential nutrients that improve plant growth and soil health over time.

Allelochemicals: Allelochemicals are bioactive compounds in crop residues that influence plant growth.

- **Phenolic Acids (Pas)**: These are well-known allelochemicals that can inhibit seed germination and seedling growth. For instance, lignin decomposition produces Pas, which can reduce weed seed germination by up to 100% at high concentrations (Zhou *et al.* , 2021).
- **Beneficial Effects**: Pas have antifungal properties and can reduce weed growth and stabilize soil aggregates, enhancing soil structure (Jiang *et al.* , 2019). Fertilization can help manage the release of harmful allelochemicals, ensuring residues benefit the soil and subsequent crops.

Microbial Activity: Crop residues support soil microbial communities by enhancing organic matter.

- **Microbial Diversity**: Retaining sugarcane straw for months increased fungal diversity in topsoil (Xu et al. , 2020). However, different residues have varying effects. For instance, corn straw reduced fungal diversity compared to wheat straw (Su *et al.* , 2021).
- **Long-Term Effects**: A 30-year study showed that combining rice straw with fertilizers improved fungal diversity without affecting overall bacterial counts (Zhao *et al.* , 2020).

In summary, crop residues boost beneficial soil microbes, but their impact depends on the type of residue and its management.

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Conclusion

Crop residues are rich in carbon and contain essential nutrients like nitrogen, phosphorus, potassium, and trace elements. Adding these residues to the soil is a sustainable way to improve soil quality without disrupting its natural balance. As crop residues break down, they increase the levels of organic carbon and available nutrients like phosphorus and potassium in the soil, which benefits both microorganisms and crops. Additionally, crop residues help improve soil moisture, structure, and porosity. While some chemicals in crop residues can negatively affect crop growth, proper management of residue returning can minimize these effects. However, the impact of crop residues on soil pH and heavy metals is mixed, with some studies showing that residues can reduce the availability of certain heavy metals under specific conditions. Crop residues can also reduce the bioavailability of some soil pollutants, help control certain soil-borne diseases, and improve saline-alkaline soils.

To maximize the benefits of crop residue returning, it's important to match the nutrient release from residues with the nutrient needs of the crops. Combining crop residues with partial nitrogen fertilizers, straw decomposition agents, and lime can enhance the breakdown of residues by boosting soil microbial activity. However, factors like soil conditions, climate, and the quality of crop residues can affect the decomposition process and may sometimes cause negative effects. Therefore, a systematic approach to crop residue returning is needed to ensure long-term soil health.

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