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REVIEW PAPER

A comprehensive review on sustainable management of rice straw for resource conservation and environmental protection

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Abstract

This article provides information about the crop residue management present in rice-wheat cropping system in China and Indian Subcontinent. It focuses on the importance of sustainable crop residue management for environmental conservation, crop productivity and health risk mitigation. The study brings attention to what is usually viewed as residue has value, it stresses on the importance of converting residue to enhance soil fertility and to fulfill crop nutrient requirements. The incorporation of wheat and rice residues into the soil is shown to support sustainable crop production and increases soil organic matter and nutrient levels. On the other hand, combusting these residues results in environmental pollution, various health hazards and reduction of valuable nutrients. There are several ways for rice straw management, some of which are discussed here i.e., off-farm composting and *in-situ* incorporation. Although these methods have advantages, they are also laborious and time consuming. These limitations are solved by innovative methods such as the Turbo Happy Seeder. Moreover, the article emphasizes the necessity for farmers to shift from burning residues (which causes several hazards) to eco-friendly alternatives backed up by financial incentives and technological innovations. It addresses the potential of biochar, a carbon-rich byproduct produced due to biomass pyrolysis, for improving soil quality and lowering emissions of greenhouse gases. Biochar has the capacity to retain nutrients and water due to which it is regarded as a valuable soil amendment that enhances soil quality. It also emphasizes the efficiency of energy conversion in thermal processes using rice straw as biomass feedstock, which contributes to sustainable energy generation source. In conclusion, it stresses the role of rice straw management in fortifying soil fertility and ensuring agricultural sustainability within rice-based cropping systems. Managing the residue not only helps farmers but also helps in resource preservation and environmental protection.

Keywords: Crop productivity, Environmental protection, Health hazards, Rice-wheat cropping system, Soil fertility, Sustainable rice straw management

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Introduction

Crops reside management is a considerable challenge within the wheat (*Triticum aestivum*) - rice (*Oryza sativa*) cropping system which is largely cultivated across China and Indian Subcontinent, containing approximately 22.5 × 106 hectares. This problem originates from the short time between wheat sowing and rice harvesting (Parsad et al., 1999). In order to address this issue, two field experiments were carried out to compare three residue management practices: residue removal, residue burning, and residue incorporation for wheat and rice residues. The findings demonstrated that combining both rice and wheat residues has no negative effects on future rice or wheat crops (Prasad et al., 1999). Additionally, residue incorporation significantly enhanced soil fertility by increasing organic carbon, available phosphorus, and potassium levels. It is imperative to prioritize residue incorporation over burning due to the loss of essential plant nutrients, along with environmental and health risks associated with burning residues. Incorporating rice residues primarily straw after crop maturity is vital as these residues retain approximately 40% nitrogen (N), 30-35% phosphorus (P), 80-85% potassium (K), and 40-50% sulfur (S). This process helps in utilizing the remaining stubble nutrients and preserving long-term soil nutrient reserves. Although short-term effects on wheat grain yield might be marginal, the enduring advantages are substantial. When mineral fertilizers are employed alongside straw incorporation, it aids in maintaining and potentially increasing soil reserves of N, P, K, and Si over time (Dobermann & Fairhurst, 2002).

Crop residues represent the plant remnants left in fields after harvest and threshing. Traditionally viewed as waste necessitating disposal, these residues are increasingly recognized as vital natural resources, not waste materials (Mendal et al., 2004). Recycling these residues offers the advantage of converting surplus farm waste into valuable products that meet the nutrient demands of crops. Moreover, this practice contributes to maintaining soil physical and chemical conditions, fostering overall ecological balance within the crop production system (Mendal et al., 2004). In South-East Asia, rice cultivation dominates, encompassing nearly 59.16 million hectares, while wheat covers about 42.55 million hectares, yielding annual grain outputs of approximately 181.35 million tons and 109.07 million tons, respectively. Notably, the rice-wheat system spans 13.5 million hectares across four consortium countries: India, Pakistan, Bangladesh, and Nepal, with respective areas of 10.0, 2.2, 0.8, and 0.5 million hectares (Mendal et al., 2004). Burning crop residues in open fields elevates soil temperatures, causing nitrogen loss by up to 23–73% and an immediate reduction in fungal and bacterial populations to a depth of 2.5 cm in the soil. For instance, according to a study by the Department of Soils at PAU, Punjab generates roughly 23 million tons of paddy straw and 17 million tons of wheat straw annually. The resultant burning significantly alters the soil's carbon-nitrogen balance, leading to the release of carbon as CO_2 into the atmosphere and the conversion of nitrogen into nitrate. This process results in a substantial reduction of about 0.824 million tons of NPK from rice crop soils. The adverse impact of burning crop residues on soil fertility leads to a depletion of essential nutrients in the soil. Additionally, burning eliminates soil-borne hazardous pathogens and pests (Gupta et al., 2004).

Crop residue is often considered as a problem, yet correct management can dramatically improve soil organic matter dynamics and nutrient cycling. This in return encourages a more favorable environment for rice cultivation (Singh et al., 2005) In rice-based cropping systems, intelligent crop residue management and utilization are critical for improving soil quality and crop yield. The best option is to leave crop remains on the field and avoid burning. Instead of looking at it as a waste, it should be viewed as a precious natural resource. According to research, approximately 25% of nitrogen (N) and phosphorus (P), 50% of sulfur (S), and 75% of potassium (K) consumption by cereal crops is present with crop residues (Singh et al., 2005). Incorporation of rice straw in wheat and wheat straw plus green manure in rice resulted in higher physiological efficiency, leading to increased soil carbon accumulation and organic matter. Crop residues have versatile uses; they can be utilized as feedstock in gasification processes, producing syngas containing carbon monoxide (CO) and hydrogen (H_2) (Hofstrand, 2008). Syngas serves various purposes, including electricity generation, chemical production, and the creation of ethanol, gasoline, and diesel. Biomass, including crop residues, can also be used to produce biogas, mainly composed of methane (CH_4) and carbon dioxide (CO_2), which serves as an inexpensive source of heating, cooking, and power generation. Moreover, crop residues can be directly burned to produce heat and steam. Steele et al. (2009) highlighted novel uses of rice residue, suggesting the extraction of herbicides from waste black liquor obtained from pulping rice straw. The herbicide, comprising waxes, carbohydrates, and inorganic materials from rice straw, exhibited satisfactory performance on rice crops.

In-situ residue incorporation and composting (*ex-situ*) are promising management options for on-farm utilization of rice residue, addressing the issue of burning and promoting soil health in rice-wheat cropping systems. However, these methods are energy and cost intensive and time restrictive. For instance, residue incorporation requires multiple tillage operations, the use of a chopper to reduce residue size, an additional irrigation, and an extra dose of urea to expedite decomposition. Consequently, despite their benefits, these methods have not been widely adopted by farmers. The time required for residue decomposition, typically 10-20 days between rice harvest and optimal wheat sowing, negatively impacts wheat productivity. This challenge has been mitigated by the innovative Turbo Happy Seeder, recognized as a significant technological advancement for in-situ residue management (Sindhu et al., 2015). Uddin and Fatema (2016) identified various ways to utilize crop residues, including as animal feed, cooking fuel, organic fertilizer through tillage incorporation, and mulching. However, farmers predominantly view crop residues as a means of adding organic matter to fields, followed by mulching and animal feed. Recycling resources between crop retention and livestock presents a substantial opportunity to reintroduce plant nutrients into rice-based crop production systems, benefiting both crops and livestock through resource interdependencies.

Enhancing soil fertility and economic opportunities in rice-based cropping systems

Continuous cultivation of cereal-based crops often leads to low yields and extensive depletion of soil nutrients, causing a decline in soil fertility. Allowing the land to remain fallow during the summer or pre-kharif season further exacerbates this issue, resulting in decreased productivity within the cropping system. Hence, it's crucial to incorporate crops that can actively enhance soil fertility. The development of short-duration, heat-resistant rice varieties has encouraged the cultivation of multiple crops, diversifying the cropping system. Introducing a range of crops such as pulses/legumes and oilseeds during the summer fallow periods can expand agricultural horizons. These crops are known to enhance soil organic matter through processes like biological nitrogen fixation, root exudates, leaf shedding, and increased biomass. Utilizing rice straw directly or indirectly as construction material presents another opportunity. Research conducted at the Construction Research Institute and Minofiya University in Egypt revealed that when rice straw is burned, it produces Rice Straw Ash (RSA), which is highly pozzolanic. This ash, containing about 82 percent silica, is suitable for lime-pozzolanic mixes and can serve as a partial replacement for Portland cement. For every ton of straw burned, around 150 kg of RSA is generated, potentially resulting in an annual production of 300,000 tons of RSA from 2 million tons of straw. However, it's important to note that burning crop residues, as highlighted in a report by DAWN (2009) titled "Crop Residues for Soil Fertility" is not a recommended practice. Burning stubbles and crop residues leads to air pollution and substantial loss of nitrogen, with estimates suggesting that 40-80 percent of nitrogen in wheat crop residue is lost as ammonia during burning. The resulting ash left on the soil surface can increase urea activity but may also cause nitrogen losses and deteriorate soil's physical properties. Choosing to incorporate crop residues into the soil is far more beneficial due to its organic nature, contributing to improved soil structure and fertility. In contrast, burning residues leads to a subsequent reduction in soil fertility. While burning residues might initially supply nitrogen to succeeding crops, it has a detrimental long-term impact on overall nitrogen supply and the status of soil carbon.

Burning of agricultural residue remains a prevalent practice in Punjab, serving as a swift method to prepare rice fields for subsequent wheat crops. While it is often considered the quickest and most cost-effective approach, not all farmers resort to burning their residue. In specific scenarios, burning can present practical benefits, particularly when the time gap between rice harvesting and sowing the following wheat crop is minimal, or when farmers utilize a 'combine harvester' for rice harvesting. Conversely, farmers who rear livestock, such as cattle, tend to refrain from burning residue, opting to repurpose it as feed for their animals. Encouragingly, financial incentives and technological advancements can play a pivotal role in steering farmers away from burning practices towards less environmentally harmful alternatives (Ahmad & Ahmad, 2013). Research by Ahmad and Ahmad (2014) highlights the untapped potential of rice straw, estimating its capability to generate substantial electric power within the rice-wheat cropping system—162.51 MW, 296.13 MW, and 396.44 MW. To address the challenge of transporting rice straw and to minimize associated costs, establishing decentralized power plants at the village level emerges as a viable solution. Furthermore, utilizing rice crop residue as an energy source holds the promise of reducing reliance on foreign energy resources, given that four kilograms of crop residue can effectively substitute one liter of furnace oil or one cubic meter of natural gas. Beyond the environmental advantages, leveraging crop residues for power generation can create new income streams for farmers through the utilization of rice residue. This approach also fosters additional job opportunities and sustainable economic activities.

Enhancing rice straw management with biochar

Biochar is a substance known for its similarity to charcoal and it is a carbon-rich residue formed by the pyrolysis of biomass. It usually contains at least 50% of carbon by weight, 75% of which being fixed carbon (Anjali et al., 2022). Unlike raw biomass, applications that require high heating values biochar is advantageous as it has high carbon levels and reduced oxygen content. This unique behavior of biochar is due to the release of volatile components due to pyrolysis of biomass. As featured by Ali et al. (2020), minute nitrogen and sulfur content in biochar play a very important role in controlling the emissions of nitrogen and sulfur oxides into the surroundings. It has unique water holding capabilities due to which it acts as effective water reservoir. Biochar serves multiple purposes in agriculture, for instance increasing soil quality, enhancing crop yields, and mitigating greenhouse gas emissions (Awasthi et al., 2017). Moreover, biochar has the ability to incorporate nutrients into the soil structure resultantly reducing nutrient loss (Janus et al., 2015). Generally, biochar has alkaline or neutral pH, it helps improve overly acidic soils (Ahmad et al., 2014). For slow pyrolysis rice straw was utilized as raw material, according to the research investigation carried out by Janus et al. (2015). The study aimed to investigate the yields and characteristics of biochar generated at various temperatures. The results show that biochar produced from rice straw has high surface alkalinity. Moreover, biochar produced from high temperature pyrolysis has significant amount of carbon, which contains aromatic compounds that make the soil resilient to carbon sequestration.

Energy conversion efficiency with rice straw biomass in thermal processes

The energy conversion efficiency, also known as thermal efficiency is defined as a useful output of an energy conversion machine and the input, in energy terms. The input as well as output may be electrical, thermal or light. Utilizing rice Straw as a biomass feedstock, it is possible to achieve an energy conversion efficiency of approximately 60%. In their investigation, Nam et al. (2015) used energy recovery methods to measure the energy content of pyrolysis products. Char showed higher energy recovery in bench-scale auger-type and fixed-bed pyrolyzers, but bio-oil emerged as the primary energy product in the fluidized-bed reactor. According to Park et al. (2014), slow pyrolysis produced char with a high concentration of biomass energy. On the other hand, gasification showed competitive energy efficiency, with an efficiency ranging from 52% to 61%, in contrast to other thermal processes. Although Darmawan et al. (2018) findings were based only on a simulated process and did not correspond with actual experimental results, they did indicate a somewhat lower energy output.

Conclusion

Managing crop remainder is crucial in rice-wheat cropping systems. The remainders have significant nutritional content, which, when recycled into the soil, improves soil fertility and long-term crop yields. Incorporating crop remainders into soil is a better option than burning them, which could result in nutrient loss and pose severe environmental and health problems. Crop residue should be preserved in the field and used as a resource rather than a waste since they play an important role in soil organic matter dynamics and nitrogen cycling. Furthermore, the remainder can be a valuable resource, serving as a feedstock for a variety of applications, such as creating syngas for energy generation. Effective crop residue management and utilization can make a substantial contribution to the adoption of sustainable agriculture practices that benefit both farmers and the environment.

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