

Rice residue management: Alternative strategies and emerging technologies for a sustainable ecosystem



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(Received January 6, 2024; revised April 3, 2024; accepted June 3, 2024)

ABSTRACT

Rice straw, which is produced after the harvest of rice, is a major agricultural waste in the world. Rice straw has a high carbon/nitrogen ratio and is more resistant to microbial degradation than other straws because its main constituents are cellulose and hemicelluloses encrusted by lignin. When rice straw is burned, hazardous substances such as carbon dioxide, methane, carbon monoxide, and nitrogen monoxide are released into the air as smoke (less than 10 μm -sized particles). The rise in the burning of rice straw has contributed to too many accidents and health issues in the general population residing in Haryana, Punjab, and Uttar Pradesh of India. These states are being urged by the National Green Tribunal to generate money instead of burning rice straw. Even though these lignocellulosic materials might be beneficial, not much has been carried out with them. This overview covers the properties of rice straw and husks, the numerous procedures used to create valuable products, and various applications that may be made for them. These include energy sources, environmental adsorbents, building supplies, and specialist commodities.

Key Words: biochar, biomethanation, burning, composting, *in situ* decomposition, lignocellulosic, mulching, rice husk, rice straw

Citation: Parshad J, Kumar R, Chhokar V, Patil N, Beniwal V, Singh N, Kumar A, Singh N, Yogi R, Kumar M, Vikram P, Chauhan A, Kumar A. 2025. Rice residue management: Alternative strategies and emerging technologies for a sustainable ecosystem. *Pedosphere*. 35(1): 53–66.

INTRODUCTION

Rice (*Oryza sativa* L.) is the most common cereal consumed by more than 60% of the global population. About 90% of the world's total production and consumption of rice comes from the Asian region (Yogi *et al.*, 2023). In India, rice accounts for approximately 43% of all food grain output and 55% of all cereal production, providing a means of subsistence for rural households. Rice is grown on 167 million hectares worldwide, primarily in Asia. Additionally, Asia produces the majority of the world's total amount of rice straw (370–520 Mt) (van Hung *et al.*, 2020; Yogi *et al.*, 2020).

In India, one of the most popular farming systems is the rice-wheat system, which yields a significant amount of rice straw in the Indo-Gangetic plains of northwestern India. Rice production and yield are increasing every year in the central

states of India. Rice is the second most important grain crop in the world, and India is the world's second largest producer of this crop. India produced 2 390 kg ha⁻¹ of rice in 2016 on approximately 43.86 Mha of land (Alexaki *et al.*, 2019).

The management of rice residues is the most critical issue because it hinders the planting of wheat. There are numerous ways for farmers to deal with the leftover cereal crop residues, including mulching, baling, burning, incorporating, surface retention, and removing the straw. Due to the high silica concentration, only a few rice cultivars are acceptable for animal feeding (Aquino *et al.*, 2020). To avoid a delay in wheat sowing, most farmers burn the leftover rice residue. The extensive burning of paddy residues in northern India has brought huge air pollution problem. Due to lack of economically viable options, farmers are compelled to burn the rice residues. There are no other quick and efficient management methods for rice straw, so farmers use the

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burning method. Rice straw burning causes emission of huge amounts of toxic gases, *e.g.*, carbon monoxide (CO), nitrous oxide (N₂O), methane (CH₄), sulfur dioxide (SO₂), and carbon dioxide (CO₂), and smoke (Ordou and Agranovski, 2019), which leads to respiratory problems. It also causes greenhouse effect which results in a rise in the average temperature of the planet. Ploughing of agricultural waste increases soil fertility, but it is very costly to incorporate and dispose such a large amount of crop residues in a short time (Jethva *et al.*, 2019). Straw burning causes loss of renewable organic sources in addition to release of greenhouse gases (Badarinath *et al.*, 2006). Kumar *et al.* (2015) conducted a study which concluded that the contribution of particulate matter from stubble burning to Delhi City air was about 100–200 µg m⁻³. Severe increase in the air quality index can be seen during wheat and rice harvesting seasons.

Residue burning can be reduced by educating farmers about the issue and creating alternative technologies for managing residues on farms, such as residue retention and integration of residues into the field through microbial intervention to improve the use of nutrients (Gupta *et al.*, 2004). Therefore, waste management is becoming a significant issue because of the enormous volumes of waste generated. To deal with the problems caused by rice straw, microbes may provide new insights for their management. The enzymes released by microbes hasten the decomposition of straw and encourage nutrient recycling, which boosts soil nutrient status (Qian *et al.*, 2012; Sharma *et al.*, 2014). The carbon (C)/nitrogen (N) ratio is another important factor influencing decomposition. The microbial activity and organic matter breakdown can be accelerated by using biosurfactants (Kalaimurugan *et al.*, 2022).

Rice straw mainly contains cellulose (32.0%–38.6%), hemicellulose (19.7%–35.7%), and lignin (13.5%–22.3%) (Goodman, 2020). Cellulose is a long polymer composed of around 12 000 α-glucopyranose units joined together *via* β-1,4 bonds to create rigid fibers that form bundles and serve as the main structural support of plant cell walls. Hemicelluloses are non-covalently linked to cellulose chains and are heterogeneous polymers composed of xylans, mannans, and arabinans. Lignin is a complex aromatic polymer composed of phenyl-propanoid units joined by ether bonds and non-carbohydrate compounds such as *p*-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol (Anwar *et al.*, 2014).

The study of Pérez *et al.* (2002) on the biodegradation of the three primary polymers, *i.e.*, cellulose, hemicelluloses, and lignin, showed that a variety of microorganisms could break down these polymers. Microorganisms produce extracellular enzymes like laccases, lignin peroxidases, manganese peroxidases, endoglucanases, β-glucosidases, exoglucanases, cellobiases, xylanase, and protease, which are substrate-specific and depolymerize polymeric components

into monomeric residues. It has been shown that microbial consortia (including cellulolytic and non-cellulolytic microorganisms) digest lignocellulosic material effectively (Takano and Hoshino, 2018).

Crop residue is a good source of nutrients (Table I) and is vital for the stability of agricultural ecosystems. The vegetative parts of rice contain significant amounts of essential nutrients like N, phosphorus (P), potassium (K), and silicon. These elements play crucial roles in the growth and development of rice (Dobermann and Witt, 2000). However, rice straw contains high C but low N, which is a challenge for decomposition. To effectively break down the straw, external N sources, such as vegetable waste, poultry manure, cattle manure, and cow dung, are often added, which not only aids in the rapid decomposition of rice straw but also contributes to soil fertility, reduces environmental pollution from straw burning, and promotes sustainable agricultural practices. Pandey *et al.* (2009) composted rice straw separately with chicken manure, farmyard manure, and soyabean waste in duplicates, one inoculated with a fungal consortium (*Aspergillus nidulans*, *Aspergillus awamori*, *Phanerochaete chrysosporium*, and *Trichoderma viride*), and the other uninoculated. Following soybean waste and farmyard manure, chicken manure (inoculated) had a much superior C/N ratio (8.15) and the highest accessible P (2.32%). The C/N ratio of rice straw that had not been inoculated or supplemented did not change significantly after the composting period (Sarma *et al.*, 2022). This review discusses the characteristics of rice straw and husks, the various processes used to produce useful goods, and the various uses that can be applied to them.

TABLE I

Nutrient contents of rice straw (Goswami *et al.*, 2020)

N	P	K	Ca	Mg	Si	Zn	S	Fe	Mn	Cu	B
g kg ⁻¹						mg kg ⁻¹					
6.5	1.0	14.0	3.0	2.0	55	30	750	350	450	3	10

RICE RESIDUE CHARACTERISTICS

The physical properties of rice straw such as density, thermal conductivity, and heat capacity are influenced by its form. For instance, loose rice straw collected from the field can have a density of 13–18 kg m⁻³ based on dry matter (Migo, 2019). When cut into pieces between 2 and 10 mm in size (Chou *et al.*, 2009), the density of rice straw is 50–120 kg m⁻³ (Liu *et al.*, 2011), subject to the tools employed. Depending on the tools used, rice husks have a density of 86–114 kg m⁻³ (Mansaray and Ghaly, 1997). There are a variety of techniques for size reduction to increase straw density, but they all require additional energy input for tools (van Hieu *et al.*, 2018), including

tabletizers, agglomerators, cubers, briquette presses, screw extruders, roller presses, and piston presses (Satlewal *et al.*, 2018). Chemical components, such as cellulose, hemicelluloses/carbohydrates, lignin, lipids, proteins, simple sugars, hydrocarbon, and other compounds, determine the nutritional quality of rice straw, whereas plant species, variety, tissue type, and other growth parameters determine the contents of its constituents. According to Yokoyama and Matsumura (2008), rice straw is a lignocellulosic material that comprises 38% cellulose, 25% hemicelluloses, and 12% lignin. Ashes of rice straw, which include non-combustible residues, are 18.67%–29.1%. Hemicellulose is a short, cross-linked polymer with additional sugars in addition to glucose monomers like xylose, galactose, mannose, rhamnose, and arabinose. In contrast, cellulose is a long, straight-chain polymer only containing β -glucose monomers. The oxidative coupling of 4-hydroxyphenylpropanoids, notably *p*-coumaric, coniferyl, and synapyl alcohols results in lignin, which has a polymeric aromatic structure (Ralph *et al.*, 2004). These polymers combine to form lignocellulose, which has a very stable and complex three-dimensional structure and is found in cell walls. Hemicellulose and lignin form a matrix around the cellulose, which is then embedded within it.

RICE RESIDUE REMOVAL

When harvested manually, rice residues are piled up at a threshing place where the residues are also dried up significantly. The residues are either used as animal fodder or sold to paper or other industries at low prices. Many farmers adopt this approach since it rapidly prepares the ground for the following crop and provides them with extra income. However, during the recent decade, farmers have adopted mechanized harvesting due to labor shortage, resulting in straw disposal problems (Fig. 1). Residue removal accelerates evaporation and increases soil temperature variation throughout the day. It also reduces the quantity of organic material added to the soil to raise its water-holding capacity. Eliminating nutrient-rich residual materials decreases macronutrients and micronutrients in soil and also causes loss of soil organic matter in the runoff. The earthworm population is significantly decreased by residue clearance.



Fig. 1 Photos showing the collection (a), baling (b), and transportation (c) of rice straw.

Removing residue also lowers microbial biomass C and N (Blanco-Canqui and Lal, 2009). Soil organic C decreases with the annual removal of residue, but it can be maintained with the incorporation of crop residue (Spiegel *et al.*, 2018).

RICE RESIDUE DEGRADATION

Rice straw is a lignocellulosic material, and the stability of such material makes it challenging to separate the individual cell wall polymers, though there are a number of physical, chemical, and biological processes that can be used to liberate the sugars and phenols that make up the cell wall polymers (Fig. 2).

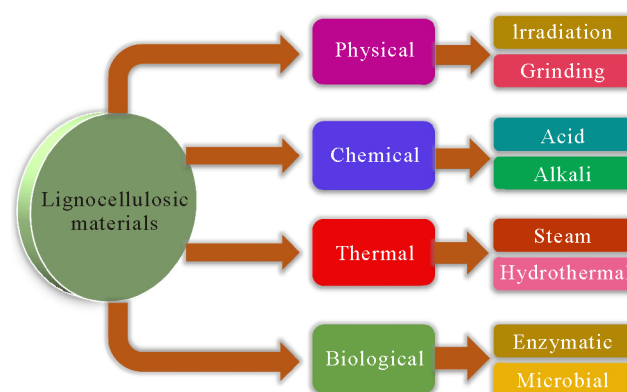


Fig. 2 Summary of main approaches used for breakdown of lignocellulosic materials (Goodman, 2020).

Although the pyrolysis temperatures and subsequent further treatments significantly impact chemical composition, surface chemistry, structure, morphology, and reactivity, thermal decomposition products like chars and ashes nevertheless have beneficial qualities. Although field burning and the piling of rice straw in the soil are still standard practices that harm the environment by causing air pollution or ecosystem damage, high-value applications of rice-derived biomass are still in their infancy (Wi *et al.*, 2013; Srivastava *et al.*, 2023).

It is necessary to first disassemble the bulk structure before processing leftover rice biomass. Different technologies have been developed and can be broadly categorized as

biological, physical, chemical, thermal, and a mix (Fig. 2). Typically, a pretreatment procedure eliminates lignin and hemicelluloses, alters the composition of the cell wall, and promotes the accessibility of cellulose. Generally, biological pretreatment procedures move slowly. Additionally, some chemical and physical treatment methods are expensive (Mosier *et al.*, 2005; Kaur *et al.*, 2024), while eco-friendly pretreatments are occasionally ineffective (Li *et al.*, 2012; Gadewar *et al.*, 2024). Therefore, a substitute method for increasing cellulose concentration is to produce plants with either lower lignin levels or lignin compositions susceptible to chemical breakdown (Vanholme *et al.*, 2010; Dixit *et al.*, 2023; Chauhan *et al.*, 2024).

It is necessary to remove the protective silicified waxy surface on rice straw before dealing with the lignocellulosic polymers. Hydrothermal method can be carried out utilizing steam treatment (Fig. 2). Though lignin is susceptible to high alkali, only fungi from the Basidiomycota and Ascomycota phyla degrade lignin in nature. As a result, the deep eutectic solvents urea and choline chloride are used to dissolve the lignin from rice straw selectively (Pan *et al.*, 2017). It can also be removed from rice straw using aqueous ammonia. The cellulose structure is slightly disturbed, and most of the hemicelluloses are eliminated (Kim *et al.*, 2011). Zhao *et al.* (2020) studied the use of ammonia-based pretreatments in lignocelluloses biorefining and discussed the physicochemical mechanisms and outcomes of several methodological approaches for parameters such as cell wall porosity, cellulose crystallinity, and lignin/hemicelluloses structure. The effectiveness of acid pretreatment of rice husks prior to enzymatic hydrolysis depends on the acid concentration and heating time. The value of lime pretreatment for using xylan, starch, and sucrose in addition to cellulose in enzymatic saccharification and fermentation has been discussed by Park *et al.* (2010).

Despite often being burned, lignin provides a rich source of aromatic chemicals that could replace petroleum-based ingredients in creating many biobased goods. The main groups derived from rice husks include alkanes (from waxes), aldehydes, and ketones (from cellulose and hemicellulose), as well as phthalates and arenes due to the non-specificity of hydroxyl radical reactions (from lignin). Recently, reports of etherease enzymes have been made by Gall *et al.* (2017). As etherease catalyzes the dissociation of ether bonds in lignin, the co-substrates glutathione and nicotinamide adenine dinucleotide are recycled. This innovative approach shows promise even though the lignin substructure considerably affects the depolymerization activities in rice straw (Lou *et al.*, 2018). Biological engineering may also make it easier to separate its breakdown components, which could lead to lignin with better homogeneity and specific working properties (Ragauskas *et al.*, 2014; Singh *et al.*, 2023). It has

been demonstrated that rice straw alkali extracts processed with an actinomycete isolate have high saccharification efficiency and levels of lignin recovery, delignification, and cellulose enrichment (Saritha *et al.*, 2013). Furthermore, it has been shown that the lignin concentration of pretreated rice straw is significantly decreased by the newly found lignolytic micromycete fungus, *Myrothecium roridum* LG7. This might be retrieved as a valuable commodity because enzymatic hydrolysis that succeeded yielded more reducing sugars than untreated straw (Tiwari *et al.*, 2013).

Cellulase, which is produced by *Trichoderma reesei*, effectively transforms pretreatment cellulose from rice straw into glucose, which is then fermented using yeasts such as *Saccharomyces cerevisiae* to make ethanol (Belal, 2013). Additionally, *Streptomyces griseorubens* produces cellulolytic enzymes that break down cellulose into reducing sugars, and the hydrolyzed wasted cells can be used as a N source for the production of crude cellulase enzymes (Zhang *et al.*, 2016), which are highly efficient at saccharifying sugars and show how a simple enzyme can replace a cellulase, a commercial enzyme. Additionally, pretreating rice husks with various alkalis and acids results in cellulose and lignin with larger pore sizes and volumes than untreated rice husks. Finally, polyethylene glycol and non-ionic surfactants are added to increase cellulose conversion into fermentable sugars during enzymatic hydrolysis, which should be beneficial to fungal growth during fermentation (Ang *et al.*, 2013).

RICE RESIDUE MANAGEMENT STRATEGIES AND TECHNOLOGIES

Farmers commonly use machinery to handle crop residue, and regular farmers may perform all the tasks themselves. Crop leftovers can be processed, moistened, pelleted, or diced to reduce particle size before being used in various ways (Fig. 3).

The rice cropping system generates a large quantity of residues and poses several management challenges. In



Fig. 3 Photos showing major rice straw management options of burning (a), surface retention as mulch (b), incorporation into the soil (c), and baling for removal from the field (d).

the northern region of India, harvesting rice is typically performed with a combine harvester, which also leaves behind a considerable amount of rice residues that must be removed before sowing the wheat. The management options available for farmers are alcohol production, as fuel, for algal control in ponds, production of biogas, as mushroom bed, *etc.* (Fig. 4). Farmers choose these management options as per their convenience and resource availability.



Fig. 4 Rice straw uses in different fields to increase the income of farmers and achieve sustainable agricultural production.

Burning

Residue burning is the most preferred method of managing residues in which farmers intentionally set fire to the residues immediately after harvesting or after a few days of harvesting. Due to a recent labor shortage in rice-growing regions, farmers were forced to use machine harvesting, which resulted in enormous amounts of crop waste on the field itself. Farmers have little alternative but to burn crop remnants in the field to clear the land because there is not much time between the harvest of rice crop and the sowing of wheat crop, which interferes with the upcoming wheat crop tillage and planting processes. Moreover, farmers do not want to spend extra money to incorporate stubble into the soil. Harvesting the crops with machines makes stubble unusable as fodder. Rice, wheat, millet, jute, rapeseed-mustard, cotton, maize, sugarcane, and groundnuts are among the crops with residues burned after harvest. However, the problem is exacerbated in the irrigated Indo-Gangetic plains, particularly in the mechanized rice-wheat systems in Punjab, Haryana, Uttarakhand, and western Uttar Pradesh of northwestern India (Gupta *et al.*, 2004). Every season, this belt is believed to yield 34 Mt of rice straw, of which 23 Mt comes from fields

harvested by combine and is burned in less than a month from mid-October to mid-November. Using sickles, the crop is manually harvested and cut nearly to the ground. After threshing, the resulting rice straw is sold to the packaging and paper industries or used in a variety of ways, such as animal feed. However, because the plants are cut by combine harvesters 50–60 cm above the ground, there are scattered straws across the entire field, making it difficult to gather, store, and use. Additionally, rice straw is thought to be a poor animal feed because of its high lignin and silica contents and poor digestibility.

Burning rice straw releases N_2O (2.09%), CO (7%), CH_4 (0.66%), and CO_2 (70%) as gases (Gupta *et al.*, 2004) (Fig. 5). These gases affect human health because they lower the overall air quality, aggravating eye and skin conditions. In addition, poor visibility also causes traffic accidents. Besides the atmospheric pollution problem, residue burning incurs huge fertility loss and physical deterioration of the soil. One tone of rice straw contains 400 kg C, 5.5 kg N, 1 kg P, 20.7 kg K, and 1.2 kg sulfur (S). Approximately 50%–70% of the micronutrients are lost when rice straw is burned. Burning has a substantial negative impact on soil temperature, pH, moisture, and organic matter, in addition to the loss of nutrients. Burning also results in the decline of beneficial soil microbial communities (Mandal *et al.*, 2004). The microbial population is permanently decreased by frequent burning in field. Burning for a long time reduces topsoil total N and C contents and mineralizable N content.

Extensive burning of crop residues leads to severe environmental issues due to air deterioration associated with the release of smoke and soot particles, resulting in aggravation of chronic eye, skin, heart, and lung diseases. For every tone of rice straw burned, 3 kg particulate matter, 60 kg

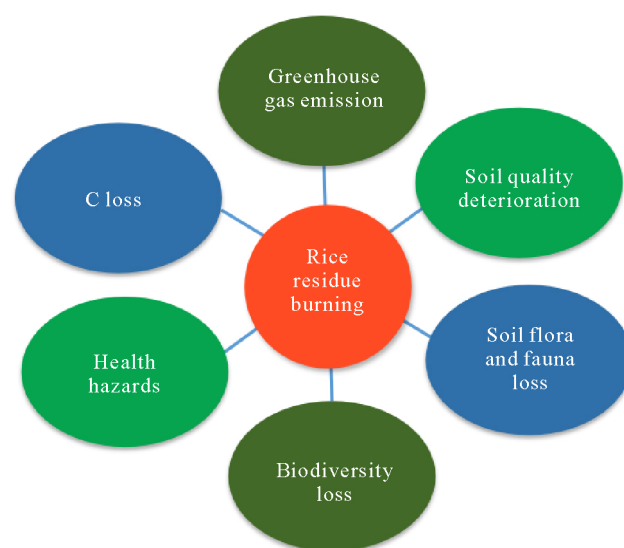


Fig. 5 Effects of rice residue burning on soil, environment, and human health.

CO, 1 460 kg CO₂, 199 kg ash, and 2 kg SO₂ are produced, and 5.5 kg N, 2.3 kg P, 25 kg K, 1.2 kg S, and 400 kg C are lost (Abdurrahman *et al.*, 2020). Furthermore, burning provides an easy solution to farmers due to the unavailability of fine-tuned machinery to handle the residue. Farmers also face difficulties incorporating rice residue prior to wheat planting due to the short time between rice harvest and wheat planting. The high silica content, low temperature, and high C/N ratio often cause microbial N immobilization and a brief drop in N that is accessible to plants, which reduces the yield of the next crop (Singh and Nain, 2014; Fuhrman *et al.*, 2018). Due to this situation, farmers are forced to burn the leftover rice, which causes a considerable loss of plant nutrients (primarily N, S, and C) and problems with the environment and human health. Hence, rigorous efforts are needed to optimize the *in situ* decomposition to utilize rice straw in fields efficiently. Therefore, there is a need to supplement the available microbial biomass with effective microbial-based consortia to hasten *in situ* microbial-driven decompositions.

In situ decomposition

The *in situ* incorporation of rice residues into the soil with special agricultural machinery facilitates the appropriate sowing of the following crop. Crop leftovers can either be integrated into the soil entirely or partially. The best method for incorporating residue is plowing. It is challenging to handle rice residues before wheat is sown because of the chilly temperatures and the short time between rice harvest and wheat sowing. As a result, wheat crop may experience N deficiency due to the short-term microbial immobilization of soil and fertilizer N. By allowing enough time (10–20 d) between its integration and the seeding of wheat crop, rice straw can be handled appropriately in place and N insufficiency caused by N immobilization can be avoided (Singh and Sidhu, 2014). Moreover, the incorporation requires an additional ploughing operation and hence increases the cost of cultivation for farmers. Long-term addition of organic residue under high fertility soil conditions or without constraints is found to increase productivity and available N (Dick and Christ, 1995). The application of N as a starter dose during the stage of straw incorporation results in the reduction of weed density and an increase in wheat grain and straw yield (Dastgheib, 1989). Utilizing straw in soil improves soil fertility and the sustainability of crop production (Kesarwani *et al.*, 2017). *In situ* residue management, according to a number of researchers, improves soil characteristics, makes N available to plants at a later stage, and sustains crop yield (Badarinath *et al.*, 2006; Ghimire *et al.*, 2017). Straw return increases crop output, soil organic C, and total N by 7.0%, 10.1%, and 11.0%, respectively in a 10-year field experiment (Wang *et al.*, 2015).

However, site-specific characteristics need to be taken into account. Straw incorporation changes the microbial communities like fungal population, bacterial abundance, activities of enzymes like β -glucosidase, β -xylosidase, and *N*-acetyl-glucosaminidase (Zhao *et al.*, 2016, 2017; Chen *et al.*, 2017).

The application of N sources with straw incorporation increases living organisms. Vijayaprabhakar *et al.* (2017) observed the highest population of bacteria, fungi, and actinomycetes at all stages after the addition of N source during straw incorporation. In relation to that, the highest decomposition rate was also observed in that same treatment. A high C/N ratio must be corrected by adding N fertilizer, even though incorporating agricultural residues into the soil is beneficial for recycling nutrients because it also results in the immobilization of some nutrients, such as N (Singh *et al.*, 2005; Bijay-Singh *et al.*, 2008).

The short-term immobilization of soil N by soil microbes is the key contributor to N shortage. How long the immobilization will continue depends on several factors, including the quality of the residue, the soil conditions, and the amount of time required for the crop residue to decompose before the subsequent crop is seeded. For instance, wheat yield initially decreased before increasing in fields where the crop had been sown and long-term residue assimilation had taken place (Singh *et al.*, 2005). In China, straw is frequently used to preserve agricultural yields and soil fertility. Crop yield, soil organic C, and total N increased dramatically by 7.0%, 10.1%, and 11.0%, respectively, due to long-term straw inclusion (Wang *et al.*, 2015). A study conducted over six years indicates that *in situ* incorporation of rice straw has no detrimental effects on wheat or later rice grain yield (Yadvinder-Singh *et al.*, 2010). The next rice harvest is unaffected by adding rice straw to the wheat field. In a few experiments, soil N is immobilized in crop residues with high C/N ratios, which results in low wheat yield in the first 1–3 years following the incorporation of rice straw. However, wheat yield is not adversely affected in the following years. Adding rice straw dramatically enhanced wheat yield in Pakistan, from 2.91 t ha⁻¹ with straw removal to 3.5 t ha⁻¹ with straw integration (Mandal *et al.*, 2004). Adding rice straw three weeks before planting wheat significantly boosted wheat yield on clay loam soils but not sandy loam soils (Kataki and Babu, 2001). Bacon (1987) discovered that adding rice straw to the soil imprisoned nitrate and reduced wheat production by about 40% in subsequent seasons. Wheat yield (mean of 10 years) was reduced from 0.54 to 0.08 t ha⁻¹ by straw incorporation with N applications of 60 and 180 kg ha⁻¹. Because of this, techniques and correct quantity of N should be used based on the soil type and agroecological region (Yadvinder-Singh *et al.*, 2010).

However, there is no standardized *in situ* decomposition of rice straw available in our country and other rice-producing countries. Hence there is a need to optimize the microbe-driven decomposition with nutrient (N and calcium) support to moderate the yield reduction in succeeding crops (wheat) associated with initial low N availability. Besides screening and product-based multiplication of microbes, *in situ* decomposition can be fine-tuned with appropriate nutrient application to support microbial growth. Moreover, in rice fields, incorporating rice straw with a high C/N ratio into soil could substantially increase greenhouse gas (CH₄ and N₂O) emissions. Agricultural waste can be plowed into the ground to increase soil fertility, but it is costly to quickly incorporate and remove such a large quantity of crop residues (Jethva *et al.*, 2019). Moreover, burning instead of recycling causes the loss of renewable organic sources and the release of greenhouse gases (Badarinath *et al.*, 2006). Surface retention offers many advantages, including better soil health, weed suppression, temperature regulation, and moisture conservation.

Residue management practices also impact crop water requirements, nutrient availability, weed dynamics, insect and pest infestation, herbicide efficacy, and long-term climate change mitigation. Suitable planting and harvesting machinery is crucial for optimal crop establishment under *in situ* residue management procedures (Jethva *et al.*, 2019). In order for crop residue equipment to function correctly, the height of the anchored straw should also be kept as constant as possible. This will help to reduce the amount of loose straw present. Through early sowing and minimizing *Phalaris minor* Retz, no-tillage and residue retention in the wheat season under the rice-wheat system can help improve wheat production. As part of the alternatives for *in situ* residue management, the timing and methods of fertilizer application must be modified. For instance, N topdressing should be applied just before irrigation to prevent residual surface residue from interfering, which can increase volatilization and immobilization losses of N. By raising the spray volume and altering herbicide application timing and location, it may also be possible to achieve higher efficacies of pre-emergence herbicides in surface retained residue conditions (Gadde *et al.*, 2009). A paradigm shift in agronomic approaches for managing rice straw is necessary to increase system production and resource use effectiveness.

An effective strategy for managing farm waste may involve microbial interventions to hasten decomposition. A field experiment was carried out at the Indian Agricultural Research Institute Farm in New Delhi in 2017–2018 with three treatments: residue removal (absolute control), straw retention (at the rate of 3 t ha⁻¹), and inoculation of a fungal consortium. Due to the addition of straw and the fungal consortium, the population of microorganisms drastically

increased. The fluorescein diacetate hydrolase, alkaline phosphatase, carboxymethyl cellulase, dehydrogenase, and xylanase activities were higher in the fungal consortium-treated plot. The role of inoculation in hastening the breakdown process is demonstrated by the fact that microbial intervention in residue management increased CO₂ emissions 2–3 times within 15–60 d. Microbial priming can be a good option for *in situ* treatment of rice straw (Ravindra *et al.*, 2019). To further understand the potential of microbial priming and N supplementation toward improving the *in situ* decomposition of rice straw, a field experiment was conducted. After the rice was harvested, there were still stubbles in the field. Two effective lignocellulolytic fungal strains *Coprinopsis cinerea* LA2 and *Cyathus stercoreus* ITCC3745 were added as a consortium. There were five treatments: straw was removed (T1), straw was kept (T2), straw was kept along with the fungal consortium and urea (T3), straw was kept along with urea (T4), and straw was kept along with the fungal consortium (T5). The T3 treatment resulted in increases in bacterial (17%), fungal (14%), and cellulolytic (20%) microorganisms at 30 d after treatment. In this treatment, the activities of soil hydrolytic enzymes nearly doubled. After a month, there were 2.6- and 2.8-fold rises in cellulase and glucosidase activities, respectively, indicating that the straw had broken down. Numerous markers of soil microbial activity and CO₂ emissions were measured to demonstrate the efficiency of T3 treatment. According to the study, microbial inoculation combined with N priming may be a quick and straightforward method for degrading crop residues *in situ*. This method will also aid in the long-term formation of soil organic C and boost the grain yield of the following wheat crop (Kumar *et al.*, 2022). Borah *et al.* (2016) experimented with preparing a consortium of microorganisms for the fast degradation of rice stubbles. A consortium of cellulose-degrading microorganisms (CDMs), *Azospirillum* sp., and *Bacillus* sp. performed better during the degradation of rice stubbles. In another study, it was shown that microorganism consortia hastened the degradation rate of residues by decreasing dry weight and organic C (Borah *et al.*, 2016). By increasing the N-fixing and P-solubilizing microorganisms in soil, microbial *in situ* residue management increases biological activity and substantially impacts the decomposition of rice straw (Sannathimmappa *et al.*, 2015). Similar to this, higher yields of grains and straw show how efficiently microbes break down organic material. As a result, microbial inoculants, a mixture of bacteria and fungus meant to speed up straw decomposition, are increasingly used in the agricultural sector in China (Wang *et al.*, 2020).

Therefore, there is a need to investigate further how microbial consortium influences rice residue degradation and soil quality. Using a consortium of bacterium (*Bacillus* sp.) and fungus (*Trichoderma* sp.) has revealed significant

increases in the rate of wheat straw breakdown. Microbial treatments significantly impact soil pH, carbonate content, total C, soil organic C, humus, and bioavailable P and K (Bjelić *et al.*, 2020). In the study of Borah *et al.* (2018), microbial inoculums were sprayed onto the stubbles of the rice varieties Mahsuri and Ranjit after the crops were harvested. The microbial inoculums were laboratory cultures of CDMs, commercial yoghurt, and a combination of CDMs and yoghurt with glyphosate (0.205% solution in water). After being treated with CDMs and CDMs combined with yoghurt containing glyphosate solution, Mahsuri demonstrated faster breakdown than Ranjit at the end of the fourth month, with drops in dry biomass and organic C by up to 61.1% and 45.3%, respectively, in Mahsuri straw and up to 47.1% and 46.4%, respectively, in Ranjit straw. Plots with higher straw decomposition showed a noticeable increase in weed variety regarding the number of species.

Composting

Composting involves the microbe-mediated conversion of organic resources such as crop residues and animal waste into stabilized, nutrient-enriched compost. The quality of the raw materials, the composting conditions, and the caliber of the final product all affect how quickly the composting raw material decomposes. Organic materials like crop residues can be composted using the pit (Fig. 6) or windrow method.



Fig. 6 Photos showing the beginning (a) and end (b) of rice residue composting using the pit method.

Microbial compost inoculants accelerate composting and help in the preparation of high-quality compost rapidly. Microbial consortium-accelerated decomposition processes take 75–90 d to degrade completely. For example, one ton of rice straw will generate about 700–800 kg of high-quality compost in approximately three months (Singh and Nain, 2014). Composting has become the most prominent technological option for lowering the weight and volume of waste material in recent years (Benito *et al.*, 2009). Compost maturity and stability are two critical factors in this regard. The deterioration or decomposition of phytotoxic organic compounds formed during the composting process is referred to as compost maturity (Wu *et al.*, 2000). Compost stability represents the level of microbial biomass activity, which

can be evaluated through oxygen uptake, CO₂ generation, and heat emitted as a result of microbial activity (Iannotti *et al.*, 1994). Bacteria consume organic waste for nutrition and in exchange reduce its odor, pollution, and volume. Microbial communities play a dominant role in maintaining a sustainable biosphere. However, microbial diversity is still largely unknown, and about 80%–90% of microorganisms are unidentified in nature.

Therefore, co-composting of rice straw with mix-culture consortia along with optimized additives may be an effective strategy in crop residue management and soil improvement. Agricultural residues are disposed of, despite being a valuable source of nutrients, because of their weight and lack of management practices. Environmental pollution causes harm to both human and animal health. Therefore, these crop remnants must be recycled in order to improve soil resilience and health. These agricultural wastes can be successfully composted on a large scale using composting and helpful microorganisms. Compost is thought to shield plants from soil-borne diseases and provide them with nutrients like N, P, and K (Pandey *et al.*, 2009; Singh *et al.*, 2012).

Rice straw has a C/N ratio of up to 80 because of its extremely high C content (430–450 g kg⁻¹) and extremely low N content (7–9 g kg⁻¹). The addition of N supplements can lower this ratio. Poultry manure, cattle manure, cow dung, urea, and mustard cake are some examples of often utilized N additives. For instance, adding swine dung to cassava pulp reduced the C/N ratio to 30, raised the temperature during the thermophilic phase, improved decomposition, and lowered the coliform count (Kamolmanit and Reungsang, 2006). Ghasemzadeh *et al.* (2022) used vinasse, chicken manure, and three bacterial strains as starter cultures for composting rice straw. After being treated with powerful bacteria and chicken dung, the bulk density, color, smell, pH, and temperature (55 °C) underwent significant alterations. The nutritional content was significantly increased following the application of chicken manure and efficient microbes. The application of this compost (5%, weight/weight) had a substantial impact on several wheat growth variables, including height of plants, fresh and dry weights, and specific leaf area, in the subsequent additional experiment.

Sharma *et al.* (2014) enhanced the composting of rice straw combined with poultry manure by adding inoculants *Aspergillus nidulans*, *Aspergillus awamori*, *Phanerochaete chrysosporium*, and *Trichoderma viride*, along with a microbial consortium comprising *Candida tropicalis*, *Streptomyces globisporus*, *Lactobacillus* sp., and *Phanerochaete chrysosporium*. The process was further optimized by incorporating photosynthetic bacteria. The composting process was completed within 60 d. The compost obtained had a C/N ratio of 15 and a humus content of 48.2 g kg⁻¹ and was not only rich in essential nutrients but also beneficial for soil structure and fertility, making it a valuable

amendment for agricultural use. Batham *et al.* (2014) used a microbial consortium of *Trichoderma viride*, *Phanerochaete chrysosporium*, and *Bacillus cereus* to compost paint sludge and distillery effluent at a 2:1:1 ratio with water hyacinth saw dust and cow dung, with subsequent vermincomposting by *Perionyx excavates*. The two industrial wastes were employed at varied concentrations in different treatments, and a temperature of 26 °C was maintained. Other than 100% industrial trash, the other combinations produced good compost, demonstrating that hyacinth bulking was successful. Rathnan *et al.* (2015) used a consortium of *Penicillium citrinum*, *Aspergillus oryzae*, and *Trichoderma viride* to perform bioconversion of paper waste and observed that all three fungal isolates performed successful saccharification of paper in isolation and together. Shukla *et al.* (2016) carried out rice straw composting with a psychrophilic bacterium (*Bacillus atropheus*), psychrotrophic fungi (*Eupenicillium crsutaceum* and *Paecilomyces* sp.), and mesophilic fungi (*Aspergillus nidulans*, *Aspergillus awamori*, *Phanerochaete chrysosporium*, and *Trichoderma viride*) and produced agriculturally beneficial and mature compost. Zhao *et al.* (2017) used a consortium of *Aspergillus japonicas*, *Aspergillus versicolor*, *Brevibacterium epidermidis*, *Penicillium digitatum*, and *Paenibacillus polymyxa* to compost fruit and vegetable peels with kitchen wastes, resulting in a 65.87% volume reduction and lower ammonia emissions. Sarangi *et al.* (2021) isolated seven strains of *Trichoderma* (*T. harzianum*, *T. erinaceum*, *T. atroviride*, *T. hebeiensis*, *T. parareesei*, *T. longibrachiatum*, and *T. reesei*) and reported that all seven strains accelerated the degradation of rice straw. Seed treatment with these strains enhanced seedling vigor and total chlorophyll and reduced mean germination time in rice.

Microbial activity, population, and biomass are the main variables that can be used to explain the dynamics of the composting process (Tiquia *et al.*, 2001). At the beginning of the composting process, mesophilic bacteria are the predominant degraders of fresh organic waste. It is also stated that mesophilic organisms are partially destroyed or inactivated during the thermophilic stage (40–60 °C), while the species diversity of thermophilic/thermotolerant bacteria, actinomycetes, and fungi become dominant. Dehydrogenase activity is a crucial indication of microbial activity because it quantifies microbial respiration. This enzyme oxidizes organic material by transferring protons and electrons from the substrate to the acceptor (Das and Varma, 2010). Dehydrogenase activity reflects the presence of biodegradable material such as glucose left in compost and a decline in its activity denotes compost stability. Chaudhary and Mishra (2019) observed that after seven days of inoculation, the bacterial and fungal population of the compost grew rapidly. As compost was more mature and contained more essential

nutrients after the 14th day, the microbial species equaled what it was before the enrichment stage and then gradually declined. Chen *et al.* (2021) observed that the number and activity of microorganisms were shown to be inhibited by high temperatures during the thermophilic phases. During the thermophilic phase of solid waste, protease and nitrite reductase activities fell by 79.2% and 96.0%, respectively, while N content decreased as a result of enzyme metabolism.

Aeration and moisture content are interdependent factors in composting process. The biological process will be slowed down if the composting material is too dry. Some bacteria move slipping and sliding to another area of the pile via the water coating. The organic part of municipal solid trash can be composted effectively at an initial moisture content of around 75% (Makan *et al.*, 2013). Composting material having a moisture of 30%–100% will be aerobic if properly aerated. High moisture content must be avoided in practical aerobic composting since it results in anaerobic conditions because water pushes air out of the spaces between the particles. Low moisture content, however, also deprives organisms of the water they need for metabolism and hinders their activity. Similarly, Kaur *et al.* (2019) found that rice straw and maize stalks at the ratios of 2:1 and 1:1 had compost moisture levels of 61.3% and 63.4%, respectively, at the start of composting. In a study by Chaher *et al.* (2021), the moisture levels for garden waste, unprocessed food waste, and cooked food waste were found to be 41.12%, 62.14%, and 54.23%, respectively. Moisture level should be 60%–70% for an effective composting process.

One of the most important composting indicators is temperature. Its primary determinants are the heat generated by microorganisms and the heat lost through aeration and surface cooling. The majority of the mesophilic bacteria in the initial stage of composting are suited to mesophilic temperatures (15–40 °C). After the mesophilic phase, the temperature increases to 50–70 °C, which causes the mesophilic microorganisms to be replaced by thermophilic ones. Because compost has a high insulating capacity, when organic matter breaks down, heat is released, which causes the temperature to rise and cool down when the process is stopped. Wang *et al.* (2022) studied the effect of inoculating the thermophilic fungus *Aspergillus fumigates* Z5 and bacterium *Geobacillus stearothermophilus* B5 on rice straw composting and observed a rise in the temperature of the mesophilic phase as well as an increase in the breakdown of cellulose and hemicelluloses. In addition, it is essential to determine the pH of the degradable waste. Microorganisms in compost function best in neutral to acidic conditions (pH 5.5–8.0), and biological activity will significantly slow down in conditions outside this pH range. Ammonia causes proteins to break down, which raises pH throughout the composting process. Aerating the drum or pit can raise the pH while lowering the CO₂ level.

The properties of the beginning materials, the ratio in which they are mixed, and the way in which they are processed all play a role in compost quality. Compost stability is a crucial factor in field application, and compost stability and quality are assessed using a variety of quality criteria, including the C/N ratio, CO₂ evolution, humic compounds, water-soluble C, pH, moisture, and germination index. If there is high microbial activity in compost, it indicates that the organic waste is still degrading and that the compost is unstable. This sort of compost cannot be used to amend soil or as a medium for plant growth because it can result in N deficit in rapidly expanding crops. Compost is regarded as stable because, at the conclusion of composting, humus-like substance is produced, which is resistant to microbial activity. Compost phytotoxic behavior is caused by the poor degradation of the organic matter. Therefore, it needs to be examined before being applied to the soil.

The C/N ratio is one of the most important factors that help to determine the extent of composting and compost quality. The initial C/N ratio should be kept 20–40 to produce high-quality processed and stabilized compost. The reduction in C/N ratio of compost indicates conversion of waste organic materials into readily usable products. The C/N ratio of ideal finished compost should be less than 20, and its application to soil can improve soil and plant health and help in maintaining soil sustainability. Zhu (2007) carried out an experiment to examine the impact of low initial C/N ratio on the composting of pig dung using rice straw. They noticed that after 63 d of composting, the C/N ratio dropped from 25 to 14.6. Nitrate grew during composting and reached 33.40 g kg⁻¹ in the finished compost, while ammoniacal N fell to 66.60 g kg⁻¹ in the final compost.

The process of humification converts organic waste material into more stable and straightforward organic material once it has decomposed. Palanivell *et al.* (2013) conducted a study to examine and compare the nutritional values of the empty fruit bunch compost, sawdust, rice straw, and rice husk. They noticed that the compost made from rice straw included more humic acids (10.97%) than that made from rice husk, which contained the least quantity of humic acids (3.13%). Additionally, the composted rice straw included significant nutrient components such as total N (1.85%) and total C (74.00%). Sharma *et al.* (2014) performed rice straw composting and found that the total humus content was 48.2 g kg⁻¹, and after 60 d of composting, the C/N ratio decreased to 15. Zhang *et al.* (2021) showed that chicken manure significantly outperformed urea in reducing crude fiber, polysaccharide, and amino acids in rice straw. Specifically, chicken manure reduced crude fiber by 29.75%, polysaccharides by 53.93%, and amino acids by 73.73%, while urea reduced these components by 14.73%, 28.74%, and 51.92%, respectively. Additionally, the composting process

with chicken manure led to a significant increase (73.05%) in humic substances, whereas the urea treatment showed a 7.51% increase. This comparison highlights the potential of chicken manure as a superior organic amendment in composting processes, particularly for improving soil fertility through both nutrient breakdown and humic substance formation.

Applying unstable compost to the soil has a negative impact on soil fertility and health as well as seed germination and plant growth. Therefore, compost maturity and stability should be evaluated before applied to soils, which is significant for both the compost and the user.

Other strategies

Mulching, or recycling surface residues, is one of the essential elements of conservation agriculture. Despite the little yield boost, mulching reduces salt buildup, inhibits weed development, and conserves water. Rice straw can be used as surface mulch for crops like maize, soybean, potato, sugarcane, sunflower, and chilies to control soil temperature and minimize evaporation (Yadvinder-Singh *et al.*, 2010; Arora *et al.*, 2011). Under mulched soil, as opposed to unmulched soil, soil N mineralization is increased due to the more hospitable soil temperature and higher water content. Straw mulching both avoids soil erosion and adds organic C and N to the soil (Rasmussen and Collins, 1991). Mulching significantly reduces soil loss during the first rainstorm, cutting it to just 25% compared to no mulching (Abrantes *et al.*, 2018). Straw mulch works well to increase soil organic C content, improve soil N, P, and water contents, and increase soil enzyme activities in the 0–10 cm soil layer. Straw mulch also improves water use efficiency and crop productivity (Akhtar *et al.*, 2018). The fact that straw mulch can harbor dangerous diseases and pests that could harm crops is one of the main drawbacks of straw mulch. In addition, the labor-intensive nature of mulching makes it unpopular among farmers.

Mushroom cultivation uses crop waste to produce a nutritious diet that has an amino acid profile similar to milk or meat and contains two to three times as much protein as regular vegetables (Crisan and Sands, 1978). *Agaricus bisporus* (white button mushroom) and *Volvariella volvacea* (straw mushroom), two of the four most widely cultivated fungi, can be successfully grown on wheat and rice straw, respectively. It is possible to produce *Agaricus* using a substrate with extraordinarily high conversion efficiency into fungal bodies when mixed with straw, animal dung, and hay (Maher, 1991). It was discovered that using wheat straw and rice straw as the base substrates for the cultivation of mushrooms was affordable (Yang *et al.*, 2013). Due to its fertile nature and quick 14-d growth cycle, *Volvariella volvacea*, a type of straw mushroom, is frequently cultivated.

Reducing dependency on fossil fuels requires the production of biofuel from crop waste. It is essential to produce alcohol from lignocellulosic biomass because it may be mixed with gasoline and utilized as a fuel extender and octane booster for internal combustion engines. Theoretical estimates suggest that one ton of dry feedstocks, such as corn, wheat, rice, bagasse, and sawdust, could yield 382–471 L ethanol (Bisen and Rahangdale, 2017). India is developing the technology needed to produce ethanol from crop waste. However, there are a few processes that need to be improved in the process of turning crop residues into alcohol (Pandiyan *et al.*, 2019).

Biochar and crop residues have recently drawn much attention as successful soil health preservation strategies. When biomass is slowly roasted without oxygen, a fine-grained, highly C-rich charcoal called biochar is produced. This may significantly impact how long C stays in the soil. Biochar application in agricultural field can improve soil structure, promote N mineralization, increase P availability, and promote growth (Fig. 7). In addition, it can decrease heavy metal bioavailability, reduce greenhouse gas emissions, and increase C sequestration (Spokas *et al.*, 2009; Zhang *et al.*, 2012).

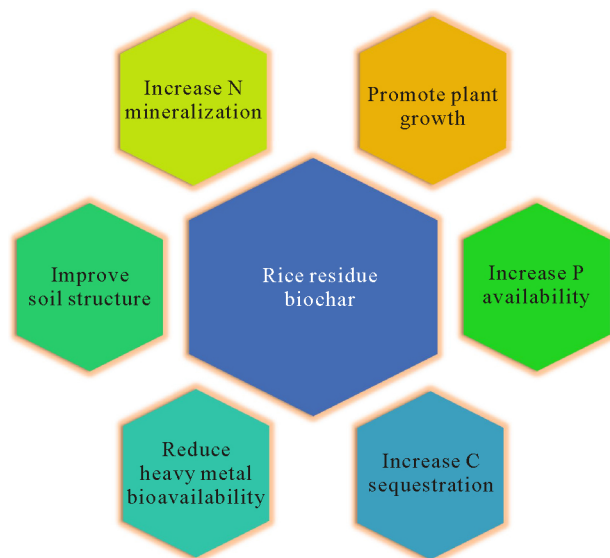


Fig. 7 Beneficial effects of rice residue biochar application in soil.

In biomethanation, microorganisms work in anaerobic environments to transform organic matter into biogas. Any organic material, including rice straw, can be converted into biogas (50%–75% CH₄ + 25%–50% CO₂), which can be used as fuel. For example, one ton of dry rice straw can produce 300 m³ biogas with a CH₄ content of 55%–60% (Gupta and Dadlani, 2012). All necessary plant nutrients, including N, P, and K, are present in the digested bioslurry created as a byproduct of biogas fermentation and can be utilized as a liquid fertilizer.

Poor-quality rice straw should not be fed to cattle. The low C/N ratio, high neutral detergent fiber, and low acid detergent fiber impact its nutritional value. On the other hand, it is thought to be a potential protein and energy-boosting feed supplement. Therefore, a daily intake of 1.0–1.5 kg of rice straw per 100 kg of body weight is advised for ruminants (Drake *et al.*, 2002). By treating the straw with urea, which results in rice straw containing 2%–4% urea, the use and digestibility of rice straw as feed can be improved. Rice residue is less frequently used as animal feed than wheat residue because of its high silica content. The amounts of lignin (6%–7%) and silica (12%–16%) in rice straw reduce its digestibility. In addition, because rice stems have a lower silica content than the leaves, rice stems are more easily absorbed than leaves (Aquino *et al.*, 2020). Therefore, if rice straw is fed to livestock, the rice crop should be cut as near the ground as feasible.

Rice straw is a lignocellulosic material that is profusely available in countries like China, India, and Bangladesh. Therefore, it makes sense that using rice straw as a raw material in the paper and pulp sector benefits farmers and industries (Kaur *et al.*, 2017). The long-term development of such a strategy of making paper from natural resources may be advantageous.

CONCLUSIONS AND RECOMMENDATIONS

The crop that produces the most excellent residues in Asia is rice. In South Asia, it is customary to take rice straw from fields for use as cattle feed and other things. Since the introduction of automated harvesting, farmers have been burning sizable amounts of crop leftovers in the field. This interferes with tillage and subsequent operations for the following crop, resulting in nutrient and soil organic matter losses. The benefits of on-field residue retention include improved soil health, soil water conservation, soil productivity, and environmental protection. However, residue integration has several obstacles, including labor-intensive processes, fallow periods, and N immobilization. There are a number of off-field options for managing rice crop residues, including using rice straw to grow edible mushrooms, using anaerobic digestion to produce biogas from rice straw, using straw to package non-perishable goods for transportation, and providing affordable roof thatch for the rural poor. It is not necessary to mix rice straw into the soil. However, it must be thoroughly examined to guarantee easy disassembly and reduce greenhouse gas emissions. For rice straw to be used sustainably, mechanized collecting using balers is crucial. The key to persuading farmers to refrain from open-field burning and so prevent the detrimental effects on environmental and health issues is to improve the value chain of rice straw byproducts and apply sustainable straw-management strategies.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CONTRIBUTION OF AUTHORS

Jagdish PARSHAD and Ravinder KUMAR contribute equally to this work.

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