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# Enhancing Sustainability in the Indo-Gangetic Plains Through Biochar: A Solution to Stubble Burning

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## ABSTRACT

In the Indo-Gangetic Plains (IGP) of northern India, the prevalent rice-wheat cropping system (RWS) is marked by a continuous cycle of planting wheat from October to April and rice from June to September. However, the transition between these crops necessitates the burning of stubble due to the short time frame available for land preparation before planting wheat. This practice contributes significantly to environmental pollution and poses health risks to both humans and ecosystems. To address this issue, alternative management strategies for crop residue are imperative. Utilizing stubble as fuel, feedstock for biofuels, or raw material for the pulp and paper industry offers promising solutions. Among these, biochar emerges as a particularly effective option. Biochar, derived from the pyrolysis of agricultural waste, not only mitigates environmental pollution but also enhances soil health, crop productivity, and overall agricultural sustainability. Our proposal emphasizes the potential of biochar as a soil conditioner, promoting soil carbon sequestration, improving soil quality, and ultimately enhancing food security.

## INTRODUCTION

The Rice-Wheat Cropping System (RWS) is a highly productive and efficient cropping system that has helped meet the food demands of the growing population in India. Therefore, an enormous quantity of crop residue is expected to be produced as a result of monoculture and intensive farming (Manna et al. 2020). Northwest India produces about 40 metric tons of paddy straw, with Punjab and Haryana contributing the majority of it (Dhanda et al. 2022). Crop residue burning in Haryana, as well as in other parts of India, has been a significant contributor to air pollution and greenhouse gas emissions (Saxena et al. 2021). Burning crop residue releases a variety of hazardous pollutants into the atmosphere, including carbon monoxide (CO), nitrogen oxides ($NO_X$), and particulate matter (PM) (Mor et al. 2022). This practice is frequently used to clean up fields quickly following a harvest. Because so much rice and wheat are farmed there, crop residue burning is particularly common in Haryana and Punjab (Kumar & Singh 2021). According to data from the Indian Council of Agricultural Research, Haryana was responsible for around 14% of India's total crop residue burning in 2018 (Govindaraj et al. 2019). Wheat straw has been used as feed for cattle, and leftover residue is burned every year. According to Chhabra & Mehta (2019), one kilogram of paddy produces one to one and a half kg of straw. Disposing of such a massive amount of crop residue is very difficult. The height of crop stubbles, the low nutritional value of paddy straw, the expense of collecting and transportation, the absence of markets for crop stubbles, and the lack of an effective in situ stubble management system present farmers with several challenges (Kaur et al. 2022). Due to these reasons, open stubble burning is perceived by farmers who are not aware of public health issues as the easiest and most economical way to manage stubble (Abdurrahman et al. 2019). The pollutants released during burning can have significant negative impacts, including respiratory problems and heart disease (Chanana et al. 2023). After being released into the air, these pollutants scatter in the environment, may go through physical and chemical changes, and ultimately have a negative impact on both human health and the environment are shown in Fig. 1. Furthermore, the practice contributes to global warming by releasing significant amounts of greenhouse gases into the atmosphere, including carbon dioxide and methane (Chawala & Sandhu 2020). However, it also poses significant challenges such as soil degradation, and nutrient depletion (Nunes et al. 2020). To overcome these challenges, there is an urgency to implement sustainable and diversified agricultural practices, such as sustainable agriculture, integrated pest management, and crop diversification (Prasad et al. 2020). Biochar made from wheat paddy straw might be a useful tool for managing wheat paddy stubble (Manna et al. 2020). When biomass feedstocks, such as crop leftovers, are pyrolyzed under low oxygen conditions, biochar, a persistent and recalcitrant carbon-rich compound, is produced (Kumar & Bhattacharya 2021). Due to variations in the biomass and pyrolysis temperature, it demonstrates various properties. Biochar has the potential to significantly contribute to the agro-economy's efforts to enhance soil health and improve crop yields (Zhang et al. 2020). When biochar is added to soil, it can enhance the soil's ability to retain water and nutrients, which can lead to improved plant growth and crop yields (Farid et al. 2022). Additionally, biochar can also help the soil's ability to store carbon, which can lessen greenhouse gas emissions and help in the fight against climate change. By employing organic waste as a feedstock, biochar may help lower the quantity of trash produced by agricultural activities (Guo et al. 2020). Overall, using biochar in the agro-economy has the potential to bring about a number of advantages, such as higher crop yields, better soil health, lower greenhouse gas emissions, and less waste (Sessions et al. 2019). However, the effectiveness of biochar will depend on various factors, including the quality of the biochar, the soil type, and the specific crop being grown. Today, biochar is considered a reliable method for mitigating climate change and is predicted to retain carbon and reduce greenhouse gas emissions from crop residue burning (Brassard et al. 2019). Biochar is a useful soil additive for combating climate change because the pyrogenic carbon, also known as carbon black, which is produced when the biochar is partially burned transforms into a long-term carbon sink with a relatively gradual chemical transformation (Luo et al. 2022). Consequently, converting wheat and rice straw into biochar and using it in agriculture could be a current example of a climate-smart approach.

## Rice and Wheat as Feedstocks and Their Physico-chemical Properties

Paddy and wheat straws are agricultural residues that can be used as a potential source of biomass for various applications such as bioenergy, pulp and paper industries, and animal feed (Cao et al. 2018). The physicochemical properties of paddy-wheat straw can provide important insights into its potential applications (Kalkhajeh et al. 2021). Here are some of the physicochemical properties of paddy-wheat straw: The moisture content of paddy-wheat straw can vary from 10% to 20%. High moisture content can affect its handling and storage properties (Iftikhar et al. 2019). According to Manna et al. (2020), the nitrogen content of paddy-wheat straw ranges from 0.5% to 1.5%. The nitrogen content affects the quality of the straw as animal feed. The lignin content of paddy-wheat straw can vary from 15% to 25%. The lignin content affects the quality of the straw as a pulp and paper raw material (Ríos-Badrán et al. 2020). The cellulose content of paddy-wheat straw ranges from 35% to 45%. The cellulose content affects the quality of the straw as a raw material for bioenergy production (Du et al. 2019). The hemicellulose content of paddy-wheat straw ranges from 25% to 35%. The hemicellulose content affects the quality of the straw as a raw material for bioenergy production (Satlewal et al. 2018). In Table 1 the physiochemical properties of rice and wheat straw are described. Parameters include crop management, soil type, agricultural variety, season, and other factors that influence the nutrients in agricultural wastes. Under ongoing fertilization procedures, the continuous removal and burning of crop residues can result in net nitrogen losses, increasing nutrient costs input in the short term and degrading productivity and soil quality (Zhang et al. 2020).

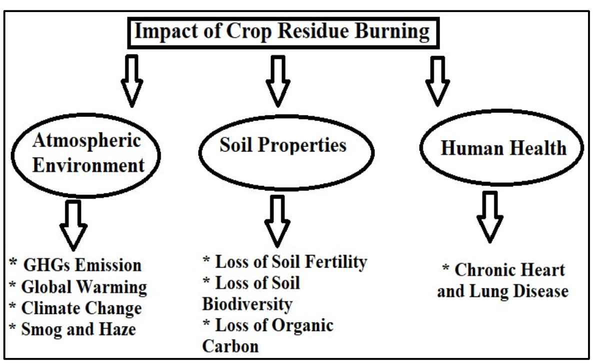


Fig. 1: Impacts of crop residue burning on environment, human health, and soil environment.

Table 1: Physiochemical properties of rice and wheat straw.

| Chemical component | Chemical composition of rice straw (% on dry matter basis) | Chemical composition of wheat straw (% on dry matter basis) |
|---|---|---|
| Total ash | 15.6 | 7.9 |
| Water content | 5.4 | 4.6 |
| Organic matter | 44 | 48 |
| Cellulose | 37 | 43.42 |
| Hemicellulose | 24.5 | 29.48 |
| Lignin | 9 | 15 |
| Silica (Si) | 8 | 5.5 |

## Crop Residue Burning in Haryana and Punjab

Since the beginning of the Green Revolution in the nation, Punjab and the Haryana state have been actively involved in the RWS cropping method (Sarkar et al. 2018). These two small states account for around 69% of the government of India's entire food procurement, including about 54% of the rice and 84% of the wheat, although possessing less than 3% of the country's total land area (Bhuvaneshwari et al. 2019). Experts estimate that 90% of the rice crop is harvested by combine harvesters and leftover residues are burned in the Indian states of Punjab and Haryana, where emissions can substantially affect regional air quality periodically. In 2017, According to Sarkar et al. 2018 India produced 488 Mt of total crop residue, of which 24% was burned in agricultural areas. This led to emissions of 239 Gg of organic carbon (OC), 58 Gg of elemental carbon (EC), and 824 Gg of particulate matter ($PM_{2.5}$). In addition, 211 Tg of greenhouse gases ($CO_2$, $CH_4$, and $N_2O$) comparable to $CO_2$ were released into the atmosphere. Crop residue may also have the potential to generate 120 TWh of electricity when used in biomass power plants, which accounts for 10% of India's total energy output. The inability to store straw, the lack of market demand for its future use, the high cost of labor, and the farmers' need to have their agricultural products transported to grain markets and sold as soon as possible make disposal particularly challenging. Because of this, the agricultural residue is allowed to stay in the open field and is subsequently burned (Kulkarni et al. 2020). This crop-based biomass burning causes a massive cloud of smoke to cover the whole of Haryana and Punjab states (Fig. 2), endangering the quality of the soil, water, air, and environment as well as human health, between October and November.

## Stubble Burning Causes

**Rice-wheat cropping system (RWS):** One of the primary causes of stubble burning in north India is the short period between rice harvesting and wheat sowing. In this region crops are cultivated, wheat is usually sown in November, and rice is often harvested in October (Jat et al. 2019). Farmers now have a limited time to clear their fields from rice straw and get it ready for wheat cultivation. Manual labor or the use of bullock carts are two traditional ways to remove the straw, both of which can be costly and time-consuming (Kumar et al. 2019). Due to this, many farmers use stubble burning as a quick and affordable means of clearing the fields and getting the soil ready for the following crop (Biswakarma et al. 2021).

**Scarcity of labor:** In Punjab and Haryana, where farm sizes are enormous and automated harvesters are frequently used, labor expenses are extremely high (Khedwal et al. 2023). Additionally, both in the states of Punjab and Haryana, there has been a steady and significant rise in the area under paddy cultivation. Therefore, the use of mechanical and electrical power has increased as a result of the fact that human and animal power cannot keep up with the rising demand for labor. Additionally, the issue of stubble burning was exacerbated by rising costs and a shortage of agricultural labor (Shirsath et al. 2020). In the past, the majority of laborers moved to the Haryana Punjab region from the states of Bihar and UP. However, labor migration has decreased over the past few years as a result of the MNREGA program's enormous success. As a result, they are leading to increased dependency on combined harvesters (Dhaliwal et al. 2021).

**Extensive use of heavy machinery:** Due to its low labor and time requirements, the use of combining harvesters has significantly increased over the last few decades. Before now, the waste straw bundles could be collected and removed from the fields more easily thanks to the physical cutting of the standing crop (Yadav et al. 2021). On the other hand, manual paddy harvesting costs approximately three times as much and needs 15–20 persons per acre. The combined harvesters, on the other hand, work quickly and are significantly less expensive, but they have a tendency to scatter the leftover straw around the field (Dhaliwal et al. 2021). This makes collecting it more time-consuming and expensive, which encourages the farmer to burn it instead of collecting it.

**Nutrient content of rice straw:** The poor quality of rice straw is another factor in the burning of crop residue. Due to its poor palatability and low protein content (4%), high lignin, cellulose, and silica content, paddy straw is not as favored as wheat straw which also lowers milk production in dairy animals (Yadav et al. 2022). Additionally, paddy straw has a low dry matter digestibility, ranging from 42 to 48% in various cattle (Yan et al. 2019, Sharma et al. 2020). Additionally, it was noted in a study by Chivenge et al. (2020) that both rice and wheat crops use in-situ burning as a method of soil preparation. In contrast to wheat residues, rice residues are burned on a considerably bigger scale.

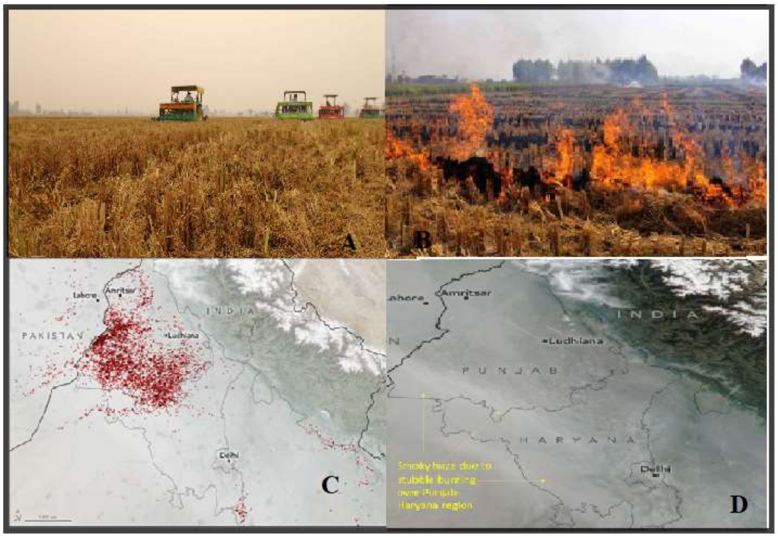


Fig. 2: (A) Use of heavy machinery in fields by the farmers (B) Crop residues burning in open fields (C). Region of Punjab and Haryana burning openly as captured by VIIRS during crop residue burning (D). Burning stubble in the Haryana-Punjab region has caused hazy smoke.

## The Negative Environmental Impacts of Crop Residue Burning

**Depletion of air quality:** The burning of crop residues releases a range of pollutants into the atmosphere, including particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide, and volatile organic compounds. These pollutants can have serious health impacts, particularly for people with respiratory or cardiovascular conditions, and can contribute to the formation of smog and other types of air pollution (Mor et al. 2022). In paddy straw, over 70% of the carbon is emitted as $CO_2$, while 7 % and 0.66% in CO and $CH_4$, respectively. In addition, when straw is burned, 2.09% of the nitrogen is released as $N_2O$ (Satlewal et al. 2018). These gases and aerosols contain carbonaceous material, which could cause acid deposition, an increase in tropospheric ozone, and the thinning of the stratospheric ozone layer in a particular area (Bhuvaneshwari et al. 2019). After carbon dioxide emissions, black carbon emissions are the main cause of the current global warming. Stubble-burning produced particulate matter (PM2.5), which is exceedingly light, may stay in the air for a very long time, cause smog, and move hundreds of miles with the wind (Kulkarni et al. 2020).

Stubble burning contributes to emissions of harmful air pollutants, which can cause severe impacts on human health. For example, shortness of breath, coughing, eye irritation. Old age people, kids, and pregnant women are the main groups affected by irritation, asthma, bronchitis, and other lung problems (Jain et al. 2014). Numerous investigations have also revealed greater dangers for aplastic anemia, blood cancer, bone marrow disorder, pancytopenia, vertigo, nausea, drowsiness, and headache (Von et al. 2020).

The release of carbon dioxide, methane, and other greenhouse gases from burning crop residues contributes to climate change, while the deposition of pollutants onto land and water can damage ecosystems and harm wildlife.

**Deterioration of soil health and fertility:** Crop residue burning can also have a significant negative impact on soil health and fertility. When crop residues are burned, valuable organic matter is lost, which can reduce soil fertility and degrade the overall health of the soil (Dadhich et al. 2021). Organic matter is an essential component of soil health, as it provides nutrients, improves soil structure, and helps to retain moisture. When crop residues are burned, this organic matter is lost, reducing the availability of nutrients for plants and

Table 2: Emission of pollutants from rice and wheat residue burning in India (Gg/year).

| Air Pollutants | Rice | Wheat |
|---|---|---|
| $PM_{2.5}$ | 418 | 264.57 |
| $PM_{10}$ | 458.29 | 175.35 |
| Sulfur dioxide | 9.07 | 12.31 |
| Carbon dioxide | 59275.54 | 54974.27 |
| Carbon monoxide | 4683.64 | 861.38 |
| Nitrous oxide ($N_2O$) | 24.17 | 22.76 |
| Nitrous oxides (NOx) | 114.82 | 52.30 |
| Ammonia ($NH_3$) | 206.48 | 39.99 |
| Organic carbon (OC) | 150.58 | 8.92 |
| Volatile organic compounds (VOC) | 352.53 | 215.34 |
| Elemental carbon (EC) | 25.68 | 4.92 |
| Polycyclic aromatic hydrocarbons (PAH) | 0.026 | 0.04 |

making it more difficult for soil to retain moisture (Bisen et al. 2017). Stubble burning raises the soil temperature (33.8-42.2 °C) up to 1cm, influencing the soil ecology (Rathod et al. 2019). Because of the increased soil temperature, 23–73% of the soil's nitrogen is eliminated in various forms, and the population of helpful microorganisms decreases to a depth of 2.5 cm. Total N and C are decreased in the 0-150 mm soil layer by continuous burning. Burning the residue destroys soil-beneficial micro-flora and fauna and removes a large amount of the organic material, and decreasing the organic matter in the fields (Turmel et al. 2015).

**Loss of nutrients:** When these residues are burned, these nutrients are lost from the soil, reducing soil fertility and the potential yield of future crops. Nitrogen is one of the most important nutrients that can be lost due to stubble burning. When crop residues are burned, nitrogen is released into the atmosphere in the form of nitrogen oxides. This can lead to a significant reduction in the amount of nitrogen available for plant growth in the soil, which can result in reduced crop yields and poorer soil health (Lin & Begho 2022). When rice and wheat straw are burned, the carbon, nitrogen, and sulfur it contains are completely burned off and lost to the atmosphere. One ton of paddy residue contains 6.1 kg N, 0.8 kg P, and 11.4 kg K. Burning of paddy straw causes intact loss of about 79.38 kg $ha^{-1}$ N, 183.71 kg $ha^{-1}$ P and 108.86 kg $ha^{-1}$ K (Dotaniya et al. 2013). The soil would have been greatly improved if the stubble residues had been left in the ground, mostly with organic carbon and nitrogen. These nutrients must subsequently be replaced through expensive organic or inorganic fertilizers.

## Wheat-Paddy Biochar as an Ecological and Economical Solution

Farmers use biochar, a carbon-rich, reliable, and long-lasting substance, to enhance the health and quality of their soil. Crop leftovers are thermally treated to produce biochar. The thermal processes used to produce biochar include pyrolysis, gasification, torrefaction, carbonization, and combustion (Naeem et al. 2017). The most popular method for producing biochar is pyrolysis because it is a quick and efficient process. In a furnace, where oxygen-deficient conditions may be produced, pyrolysis can be accomplished (Manna et al. 2020). The use of biochar has shown promise (Fig. 3) for enhancing soil carbon sequestration, boosting agricultural production, cleaning up contaminated soil and water, reducing greenhouse gas emissions, and minimizing nutrient leaching (Singh et al. 2024).

**A solution to waste management:** The generation of biochar provides us with a fantastic solution to the threat posed by agriculture waste production. The large amounts of rice-wheat stubble produced in the northwest region of India could potentially be pyrolyzed to generate biochar as an effective alternative to burning stubble. This would not only be economical but simultaneously beneficial by making waste profitable. Additionally, biochar has enormous potential for reducing greenhouse gas emissions and mitigating climate change through carbon sequestration, reduced waste biomass burning, clean bioenergy production, and decreased methane and nitrous oxide emissions, enabling the achievement of sustainable development goals.

**Biochar as a soil amendment**: Biochar is a great soil conditioner because it has several advantageous characteristics. The combination of a large surface area, high carbon content, and the capacity to improve soil aeration support and encourage the rhizospheric microbial community to enhance soil fertility and health. The soil ability to retain water is also improved by its application. The use of biochar has also been linked to a decrease in nutrient leaching, according to published research (Yadav et al. 2024). This is a result of the increased soil cation exchange capacity, which has a significant impact on slowing down the leaching of nutrients. Additionally, biochar has an alkaline pH that aids in neutralizing acidic soils and so helps to increase plant yield.

Micronutrients (Cu, Zn, Fe, and Mn) and macronutrients (P, K, N, Ca, and Mg) that are essential for productive agriculture are also added by biochar. It may have a major impact on nutrient retention and be essential for a variety of biogeochemical processes in the soil, particularly nutrient cycling. As a result, it can serve as a soil conditioner to

Table 3: Physiochemical properties of wheat and rice straw biochar.

| Parameters | Wheat straw biochar | Rice straw biochar |
|---|---|---|
| Chemical properties | | |
| pH | 8.1 | 8.7 |
| Electrical Conductivity (dS $m^{-1}$) | 2.56 | 3.23 |
| Cations Exchange Capacity (cmol $kg^{-1}$) | 63 | 56 |
| Nutrient composition | | |
| Organic Carbon (%) | 66 | 63 |
| Nitrogen (g $kg^{-1}$) | 16.2 | 16.6 |
| Phosphorus (g $kg^{-1}$) | 42 | 30 |
| Potassium (g $kg^{-1}$) | 12.6 | 9.2 |
| Iron (mg $kg^{-1}$) | 418 | 348 |
| Calcium (mg $kg^{-1}$) | 11.24 | 8.42 |
| Manganese (mg $kg^{-1}$) | 186.66 | 152.42 |
| Zinc (mg $kg^{-1}$) | 92.48 | 69.5 |
| Magnesium (mg $kg^{-1}$) | 10.8 | 6.84 |

promote plant growth more significantly, storing nutrients as well as by performing other tasks like strengthening the physical and biological characteristics of the soil (Brassard et al. 2019) (Kamali et al. 2022). Due to its slow rate of breakdown, it is also a great soil additive for storing carbon and raising soil organic carbon (SOC) concentration.

**Bioenergy from biochar:** Depending on the temperature at which the biomass is pyrolyzed, a varying amount of biochar, bio-oil, and syngas are produced. Biomass that is pyrolyzed quickly yields more bio-oil and less charcoal (Li et al. 2022). The emissions (air pollutants) that are emitted during the pyrolysis of biomass have the potential to be trapped and condensed into bio-oil, a source of bioenergy. The use of bio-oil as a substitute for fossil fuels would result in decreased carbon emissions. It's interesting to note that some aspects of biochar may be improved to aid in catalysis. Sulfonated biochar is an appropriate catalyst for the production of biodiesel, according to a different study (Lee et al. 2017). Gasification of biomass results in the production of syngas. In such a procedure, tar reduction can improve syngas output. As a result, biochar can be a fantastic tar reduction catalyst. Several studies have employed biochar to support the sulfonated solid acid catalyst in the manufacture of biodiesel. Therefore, the synthesis of biochar could encourage the development of both biofuel and bioenergy (Yadav et al. 2023).

**Biochar as bioremediation technology:** Heavy metal removal with biochar has been recognized as a promising application. Among the aforementioned heavy metal cleanup strategies, it has emerged as an incredibly affordable, enormously potent, and enormously reliable solution (Yi et al. 2020). Applying biochar is a great way to reduce the bioavailability of contaminants in the soil. Even in arid and semi-arid environments, biochar is a highly effective sorbent and an innovative carbonaceous substance for eliminating organic and inorganic pollutants, including heavy metals, from the soil and water. Using maize as a test crop, a study was done to examine the effects of biochar made from wheat straw on the bioavailability of Pb, Cd, and Cr (Xie et al. 2015) (Sizmur et al. 2016). The results showed that when data were averaged over the contamination levels, soil Pb, Cd, and Cr decreased from 15.5, 5.38, and 5.85 mg $kg^{-1}$ in control to 1.34, 0.69, and 0.75 mg $kg^{-1}$, respectively.

In addition, compared to the control, the Pb, Cd, and Cr accumulation in the maize crop also decreased. In general, it was determined that biochar made from wheat straw has a high capacity to immobilize heavy metals in soil and lessen their uptake by crop plants. Similar to that, biochar works well for biologically cleaning up organic pollutants. In one experiment, the effects of applying biochar to paddy straw on the coupled adsorption-biodegradation of the organic pollutant nonylphenol were examined. Biochar derived from rice straw was applied to the soil as the adsorbent. The results showed that when 0.005 g biochar was introduced to 50 mg $L^{-1}$ of nonylphenol, roughly 47.6% of the nonylphenol was biodegraded in two days, which was 125% more than the relative amount biodegraded without biochar. The nonylphenol components resistant to desorption, however, reached 87.1% (Wang et al. 2020, Yang et al. 2021).

### Role of Biochar in Carbon Stabilization

To effectively sequester carbon, biomass must resist chemical oxidation into $CO_2$ or reduction into methane, which results in a decrease in the atmospheric emission of $CO_2$ or methane (Gupta et al. 2017). The partially burned products, pyrogenic carbon/carbon black, have a very gradual chemical change that makes them perfect for soil amendment (Thompson et al. 2016). These partially burned products, also known as pyrogenic carbon or black carbon, may serve as a crucial long-term carbon sink because of how slowly they decompose through microbial action and chemical modification. The process of making carbon molecules resistant to microbial decay, respiration, soil erosion, and leaching is known as carbon stabilization. Biochar made from wheat and paddy straw has high ash content, and an alkaline pH, and nutrients including nitrogen, phosphorus, manganese, iron, and zinc can be found in it (Chagas et al. 2022). Be effectively employed to increase soil C sequestration. Another study (Lee et al. 2017) looked into the effects of rice straw and its biochar on labile soil C and soil organic carbon (SOC). They found that adding straw to soils increased the fraction of labile carbon, whereas adding biochar to soils increased the quantity of stabilized carbon (Aryl C, carboxyl C), indicating the importance of biochar's recalcitrance as a management tool for enhancing soil carbon sink. Biochar have ability to sequester carbon is limited by its recalcitrance, it was revealed in another study (Colomba et al. 2022) that adding biochar encourages the physical stabilization of organic matter of soil through aggregate formation. Biochar production from agricultural waste, such as wheat paddy straw, can be a low-cost alternative to conventional burning for enhancing soil fertility, stabilizing carbon, and eventually reducing GHG emissions (Majumder et al. 2019).

## CONCLUSION AND FUTURE ASPECTS

Despite numerous efforts, the problem of wheat-paddy stubble burning has only somewhat decreased and has not yet decreased to tolerable levels. Due to inadequate farmer education regarding the effects of this practice on soil,

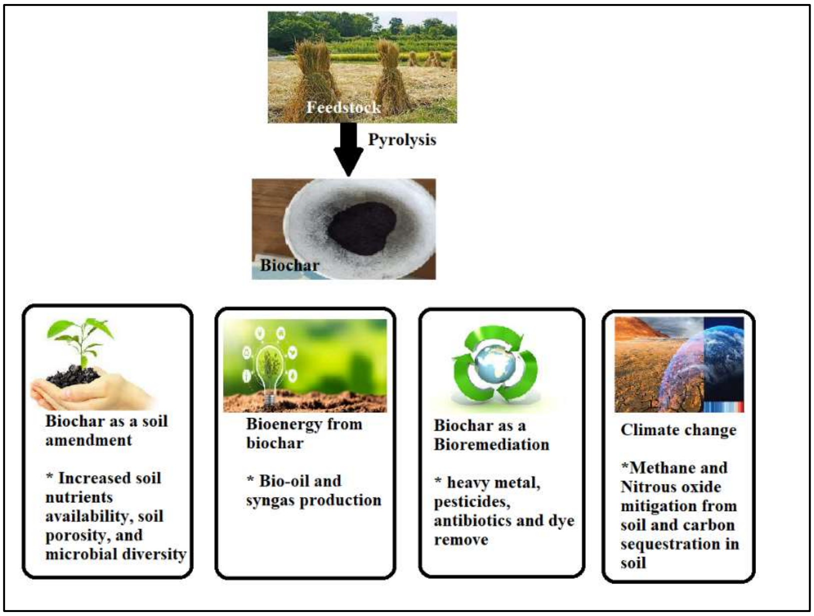


Fig. 3: Environmental and agronomical advantages of biochar.

human, and animal health, it is illegal to burn crop leftovers. Although farmers are aware of the negative effects of burning paddy straw on a farm, they are limited by a lack of equipment that is economically viable, appropriate, and can be used to dispose of rice wastes. Although the government has developed many strategies for the mechanical management of wheat and paddy stubble, the farmers have not effectively adopted them. Therefore, to manage wheat-paddy straw and prevent losses, an appropriate management strategy must be developed. On the other side, it might also be advantageous to the environment. A particularly effective and beneficial method of getting rid of the stubble and using biochar as a soil amendment is the use of biochar as a strategy for the management of crop residues. By educating farmers on how to apply this strategy properly, the government should go in this direction.

Farmers will be encouraged to adopt common farming practices that result in pollution and the waste of potential resources if organic recycling procedures and incentives are promoted. Furthermore, rather than using tough legal enforcement to restrict residue burning, the government should promote and offer need-based support for alternative measures. This is how, via cooperative efforts between farmers and the government, a proper self-sustaining environment may be attained.

## REFERENCES

Abdurrahman, M.I., Chaki, S. and Saini, G., 2020. Stubble burning: Effects on health and environment, regulations and management practices. *Environmental Advances*, 2, p.100011.

Bhuvaneshwari, S., Hettiarachchi, H. and Meegoda, J.N., 2019. Crop residue burning in India: policy challenges and potential solutions. *International Journal of Environmental Research and Public Health*, 16(5), p.832.

Bisen, N. and Rahangdale, C.P., 2017. Crop residues management option for sustainable soil health in the rice-wheat system: A review. *International Journal of Chemical Studies*, 5(4), p.1038-1042.

Biswakarma, N., Pooniya, V., Zhiipao, R.R., Kumar, D., Verma, A.K., Shivay, Y.S., Lama, A., Choudhary, A.K., Meena, M.C., Bana, R.S. and Pal, M., 2021. Five years integrated crop management in direct seeded rice–zero till wheat rotation of north-western India: Effects on soil carbon dynamics, crop yields, water productivity and economic profitability. *Agriculture, Ecosystems & Environment*, 318, p.107492.

Brassard, P., Godbout, S., Lévesque, V., Palacios, J.H., Raghavan, V., Ahmed, A., Hogue, R., Jeanne, T. and Verma, M., 2019. Biochar for soil amendment. In: *Char and Carbon Materials Derived from Biomass*. 1st ed. Elsevier, p.109-146.

Cao, Y., Sun, H., Zhang, J., Chen, G., Zhu, H., Zhou, S. and Xiao, H., 2018. Effects of wheat straw addition on dynamics and the fate of nitrogen applied to paddy soils. *Soil and Tillage Research*, 178, p.92-98.

Chagas, J.K., de Figueiredo, C.C. and Ramos, M.L., 2022. Biochar increases soil carbon pools: Evidence from a global meta-analysis. *Journal of Environmental Management*, 305, p.114403.

Chanana, I., Sharma, A., Kumar, P., Kumar, L., Kulshreshtha, S., Kumar, S. and Patel, S.K., 2023. Combustion and stubble burning: A major concern for the environment and human health. *Fire*, 6(2), p.79.

Chawala, P. and Sandhu, H.A., 2020. Stubble burn area estimation and its impact on ambient air quality of Patiala and Ludhiana district, Punjab, India. *Heliyon*, 6(1), p.1.

Chhabra, V. and Mehta, C.M., 2019. Rice straw management for sustainable agriculture—a review. *Plant Archives*, 19(2), p.47-49.

Chivenge, P., Rubianes, F., Van Chin, D., Van Thach, T., Khang, V.T., Romasanta, R.R., Van Hung, N. and Van Trinh, M., 2020. Rice straw incorporation influences nutrient cycling and soil organic matter. *Sustainable Rice Straw Management*, p.131-144.

Colomba, A., Berruti, F. and Briens, C., 2022. Model for the physical activation of biochar to activated carbon. *Journal of Analytical and Applied Pyrolysis*, 168, p.105769.

Dadhich, S.K., Yadav, G.K., Yadav, K., Kumawat, C. and Munalia, M.K., 2021. Recycling of crop residues for sustainable soil health management: A review. *International Journal of Plant and Soil Science*, p.66-75.

Dhaliwal, S.S., Sharma, S., Shukla, A.K., Sharma, V., Bhullar, M.S., Dhaliwal, T.K., Alorabi, M., Alotaibi, S.S., Gaber, A. and Hossain, A., 2021. Removal of biomass and nutrients by weeds and direct-seeded rice under conservation agriculture in light-textured soils of north-western India. *Plants*, 10(11), p.2431.

Dhanda, S., Yadav, A., Yadav, D.B. and Chauhan, B.S., 2022. Emerging issues and potential opportunities in the rice–wheat cropping system of North-Western India. *Frontiers in Plant Science*, 13, p.832683.

Dotaniya, M.L., Sharma, M.M., Kumar, K. and Singh, P.P., 2013. Impact of crop residue management on nutrient balance in rice-wheat cropping system in an Aquic hapludoll. *Journal of Rural Agricultural Research*, 13(1), p.122-123.

Du, J., Qian, Y., Xi, Y. and Lü, X., 2019. Hydrothermal and alkaline thermal pretreatment at mild temperature in solid state for physicochemical properties and biogas production from anaerobic digestion of rice straw. *Renewable Energy*, 139, p.261-267.

Farid, I.M., Siam, H.S., Abbas, M.H., Mohamed, I., Mahmoud, S.A., Tolba, M., Abbas, H.H., Yang, X., Antoniadis, V., Rinklebe, J. and Shaheen, S.M., 2022. Co-composted biochar derived from rice straw and sugarcane bagasse improved soil properties, carbon balance, and zucchini growth in a sandy soil: A trial for enhancing the health of low fertile arid soils. *Chemosphere*, 292, p.133389.

Govindaraj, G., Hiremath, J., Reddy, G.B., Siju, S.J., Yogishardhaya, R. and Prajapati, A., 2019. *ICAR NIVEDI Annual Report 2018-19*.

Guo, X.X., Liu, H.T. and Zhang, J., 2020. The role of biochar in organic waste composting and soil improvement: A review. *Waste Management*, 102, p.884-899.

Gupta, S. and Kua, H.W., 2017. Factors determining the potential of biochar as a carbon capturing and sequestering construction material: Critical review. *Journal of Materials in Civil Engineering*, 29(9), p.04017086.

Iftikhar, M., Asghar, A., Ramzan, N., Sajjadi, B. and Chen, W.Y., 2019. Biomass densification: Effect of cow dung on the physicochemical properties of wheat straw and rice husk based biomass pellets. *Biomass and Bioenergy*, 122, p.1-6.

Jain, N., Bhatia, A. and Pathak, H., 2014. Emission of air pollutants from crop residue burning in India. *Aerosol and Air Quality Research*, 14(1), p.422-430.

Jat, H.S., Kumar, P., Sutaliya, J.M., Kumar, S., Choudhary, M., Singh, Y. and Jat, M.L., 2019. Conservation agriculture based sustainable intensification of basmati rice-wheat system in North-West India. *Archives of Agronomy and Soil Science*, 65(10), p.1370-1386.

Kalkhajeh, Y.K., He, Z., Yang, X., Lu, Y., Zhou, J., Gao, H. and Ma, C., 2021. Co-application of nitrogen and straw-decomposing microbial inoculant enhanced wheat straw decomposition and rice yield in a paddy soil. *Journal of Agriculture and Food Research*, 4, p.100134.

Kamali, M., Sweygers, N., Al-Salem, S., Appels, L., Aminabhavi, T.M. and Dewil, R., 2022. Biochar for soil applications: Sustainability aspects, challenges and future prospects. *Chemical Engineering Journal*, 428, p.131189.

Kaur, A., Kaur, P. and Kumar, P., 2022. Problems with paddy straw management technologies in South-Western Punjab. *Journal of Community Mobilization and Sustainable Development*, 2, p.335-339.

Khedwal, R.S., Chaudhary, A., Sindhu, V.K., Yadav, D.B., Kumar, N., Chhokar, R.S., Poonia, T.M., Kumar, Y. and Dahiya, S., 2023. Challenges and technological interventions in rice–wheat system for resilient food–water–energy-environment nexus in North-western Indo-Gangetic Plains: A review. *Cereal Research Communications*, 51(1), p.1-23.

Kulkarni, S.H., Ghude, S.D., Jena, C., Karumuri, R.K., Sinha, B., Sinha, V., Kumar, R., Soni, V.K. and Khare, M., 2020. How much does large-scale crop residue burning affect the air quality in Delhi? *Environmental Science & Technology*, 54(8), p.4790-4799.

Kumar, A. and Bhattacharya, T., 2021. Biochar: A sustainable solution. *Environment, Development and Sustainability*, 23, p.6642-6680.

Kumar, P. and Singh, R.K., 2021. Selection of sustainable solutions for crop residue burning: An environmental issue in northwestern states of India. *Environment, Development and Sustainability*, 23, p.3696-3730.

Kumar, S., Sharma, D.K., Singh, D.R., Biswas, H., Praveen, K.V. and Sharma, V., 2019. Estimating loss of ecosystem services due to paddy straw burning in North-west India. *International Journal of Agricultural Sustainability*, 17(2), p.146-157.

Lee, J., Yang, X., Cho, S.H., Kim, J.K., Lee, S.S., Tsang, D.C., Ok, Y.S. and Kwon, E.E., 2017. Pyrolysis process of agricultural waste using CO2 for waste management, energy recovery, and biochar fabrication. *Applied Energy*, 185, p.214-222.

Li, J., Li, L., Suvarna, M., Pan, L., Tabatabaei, M., Ok, Y.S. and Wang, X., 2022. Wet wastes to bioenergy and biochar: A critical review with future perspectives. *Science of the Total Environment*, 817, p.152921.

Lin, M. and Begho, T., 2022. Crop residue burning in South Asia: A review of the scale, effect, and solutions with a focus on reducing reactive nitrogen losses. *Journal of Environmental Management*, 314, p.115104.

Luo, Y., Li, Z., Xu, H., Xu, X., Qiu, H., Cao, X. and Zhao, L., 2022. Development of phosphorus composite biochar for simultaneous enhanced carbon sink and heavy metal immobilization in soil. *Science of the Total Environment*, 831, p.154845.

Majumder, S., Neogi, S., Dutta, T., Powel, M.A. and Banik, P., 2019. The impact of biochar on soil carbon sequestration: Meta-analytical approach to evaluating environmental and economic advantages. *Journal of Environmental Management*, 250, p.109466.

Manna, S., Singh, N., Purakayastha, T.J. and Berns, A.E., 2020. Effect of deashing on physico-chemical properties of wheat and rice straw biochars and potential sorption of pyrazosulfuron-ethyl. *Arabian Journal of Chemistry*, 13(1), p.1247-1258.

Mor, S., Singh, T., Bishnoi, N.R., Bhukal, S. and Ravindra, K., 2022. Understanding seasonal variation in ambient air quality and its relationship with crop residue burning activities in an agrarian state of India. *Environmental Science and Pollution Research*, 29, p.4145-4158.

Naeem, M.A., Khalid, M., Aon, M., Abbas, G., Tahir, M., Amjad, M., Murtaza, B., Yang, A. and Akhtar, S.S., 2017. Effect of wheat and rice straw biochar produced at different temperatures on maize growth and nutrient dynamics of a calcareous soil. *Archives of Agronomy and Soil Science*, 63(14), pp.2048-2061.

Nunes, M.R., Karlen, D.L., Veum, K.S., Moorman, T.B. and Cambardella, C.A., 2020. Biological soil health indicators respond to tillage intensity: A US meta-analysis. *Geoderma*, 369, p.114335.

Prasad, S., Singh, A., Korres, N.E., Rathore, D., Sevda, S. and Pant, D., 2020. Sustainable utilization of crop residues for energy generation: A life cycle assessment (LCA) perspective. *Bioresource Technology*, 303, p.122964.

Rathod, P.H., Bhoyar, S.M., Katkar, R.N., Kadu, P.R., Jadhao, S.D., Konde, N.M., Deshmukh, P.W. and Patle, P.N., 2019. Recycling and management of crop residues for sustainable soil health in climate change scenario with farmer's profit as frontline moto. *Journal of Pharmacognosy and Phytochemistry*, 8(2S), pp.51-55.

Ríos-Badrán, I.M., Luzardo-Ocampo, I., García-Trejo, J.F., Santos-Cruz, J. and Gutiérrez-Antonio, C., 2020. Production and characterization of fuel pellets from rice husk and wheat straw. *Renewable Energy*, 145, pp.500-507.

Sarkar, S., Singh, R.P. and Chauhan, A., 2018. Crop residue burning in northern India: Increasing threat to Greater India. *Journal of Geophysical Research: Atmospheres*, 123(13), pp.6920-6934.

Satlewal, A., Agrawal, R., Bhagia, S., Das, P. and Ragauskas, A.J., 2018. Rice straw as a feedstock for biofuels: Availability, recalcitrance, and chemical properties. *Biofuels, Bioproducts and Biorefining*, 12(1), pp.83-107.

Saxena, P., Sonwani, S., Srivastava, A., Jain, M., Srivastava, A., Bharti, A., Rangra, D., Mongia, N., Tejan, S. and Bhardwaj, S., 2021. Impact of crop residue burning in Haryana on the air quality of Delhi, India. *Heliyon*, 7(5).

Sessions, J., Smith, D., Trippe, K.M., Fried, J.S., Bailey, J.D., Petitmermet, J.H., Hollamon, W., Phillips, C.L. and Campbell, J.D., 2019. Can biochar link forest restoration with commercial agriculture? *Biomass and Bioenergy*, 123, pp.175-185.

Sharma, A., Singh, G. and Arya, S.K., 2020. Biofuel from rice straw. *Journal of Cleaner Production*, 277, p.124101.

Shirsath, P.B., Jat, M.L., McDonald, A.J., Srivastava, A.K., Craufurd, P., Rana, D.S., Singh, A.K., Chaudhari, S.K., Sharma, P.C., Singh, R. and Jat, H.S., 2020. Agricultural labor, COVID-19, and potential implications for food security and air quality in the breadbasket of India. *Agricultural Systems*, 185, p.102954.

Singh, G., Mavi, M.S., Choudhary, O.P., Gupta, N. and Singh, Y., 2021. Rice straw biochar application to soil irrigated with saline water in a cotton-wheat system improves crop performance and soil functionality in north-west India. *Journal of Environmental Management*, 295, p.113277.

Sizmur, T., Quilliam, R., Puga, A.P., Moreno-Jiménez, E., Beesley, L. and Gomez-Eyles, J.L., 2016. Application of biochar for soil remediation. *Agricultural and Environmental Applications of Biochar: Advances and Barriers*, 63, pp.295-324.

Thompson, K.A., Shimabuku, K.K., Kearns, J.P., Knappe, D.R., Summers, R.S. and Cook, S.M., 2016. Environmental comparison of biochar and activated carbon for tertiary wastewater treatment. *Environmental Science & Technology*, 50(20), pp.11253-11262.

Turmel, M.S., Speratti, A., Baudron, F., Verhulst, N. and Govaerts, B., 2015. Crop residue management and soil health: A systems analysis. *Agricultural Systems*, 134, pp.6-16.

Von Schneidemesser, E., Driscoll, C., Rieder, H.E. and Schiferl, L.D., 2020. How will air quality effects on human health, crops and ecosystems change in the future? *Philosophical Transactions of the Royal Society A*, 378(2183), p.20190330.

Wang, Y., Liu, Y., Zhan, W., Zheng, K., Wang, J., Zhang, C. and Chen, R., 2020. Stabilization of heavy metal-contaminated soils by biochar: Challenges and recommendations. *Science of the Total Environment*, 729, p.139060.

Xie, T., Reddy, K.R., Wang, C., Yargicoglu, E. and Spokas, K., 2015. Characteristics and applications of biochar for environmental remediation: a review. *Critical Reviews in Environmental Science and Technology*, 45(9), pp.939-969.

Yadav, D.B., Yadav, A., Vats, A.K., Gill, G. and Malik, R.K., 2021. Direct seeded rice in sequence with zero-tillage wheat in north-western India: addressing system-based sustainability issues. *SN Applied Sciences*, 3, pp.1-7.

Yadav, D.K., Bishnoi, N.R., Bajar, S. and Singh, A., 2022. An in-depth evaluation of feedstock, production process, catalyst for biodiesel production. *Zero Waste Biorefinery*, pp.515-533.

Yadav, D.K., Yadav, M., Mittal, R., Rani, P., Yadav, A., Bishnoi, N.R. and Singh, A., 2023. Impact of silica oxide and functionalized silica oxide nanoparticles on growth of *Chlorella vulgaris* and its physicochemical properties. *Sustainable Chemistry for the Environment*, 3, p.100029.

Yadav, M., Yadav, D. K., and Anuradha, J. 2024. Biochar produced through the pyrolysis of wheat and rice straw: Examining its physiochemical properties. *African Journal of Biomedical Research*, 27, pp.01-07. 10.53555/AJBR.v27i1S.1222.

Yan, C., Yan, S.S., Jia, T.Y., Dong, S.K., Ma, C.M. and Gong, Z.P., 2019. Decomposition characteristics of rice straw returned to the soil in northeast China. *Nutrient Cycling in Agroecosystems*, 114, pp.211-224.

Yang, Y., Ye, S., Zhang, C., Zeng, G., Tan, X., Song, B., Zhang, P., Yang, H., Li, M. and Chen, Q., 2021. Application of biochar for the remediation of polluted sediments. *Journal of Hazardous Materials*, 404, p.124052.

Yi, Y., Huang, Z., Lu, B., Xian, J., Tsang, E.P., Cheng, W., Fang, J. and Fang, Z., 2020. Magnetic biochar for environmental remediation: A review. *Bioresource Technology*, 298, p.122468.

Zhang, X., Zhang, P., Yuan, X., Li, Y. and Han, L., 2020. Effect of pyrolysis temperature and correlation analysis on the yield and physicochemical properties of crop residue biochar. *Bioresource Technology*, 296, p.122318.