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Wheat-Paddy Straw Biochar: An Ecological Solution of Stubble Burning in the Agroecosystems of Punjab and Haryana Region, India, A Synthesis

Diksha Tokas[1], Siril Singh[1,2], Rajni Yadav[1], Pardeep Kumar[1], Sheenu Sharma[1], Anand Narain Singh[1,*]

[1]Soil Ecosystem and Restoration Ecology Lab, Department of Botany, Panjab University, Chandigarh 160014, India
[2]Department of Environment Studies, Panjab University Chandigarh-160014
*Corresponding author: dranand1212@gmail.com; ansingh@pu.ac.in

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Abstract The Rice-Wheat cropping system (RWS) is the predominant agricultural system in northern India, especially in Punjab and Haryana. About 90% of agricultural land in Punjab and Haryana is indulged in the intensive RWS cropping system. The major constraint in this system is the short time interval between rice harvesting and the sowing of wheat. The preparation of the field for the wheat crop requires the removal of stubble, and farmers burn the stubble to get rid of it as there is a lack of any other proper management strategy or alternative use of stubble. Stubble burning is a significant source of pollutants causing severe damage to human health and the environment. The appropriate stubble management could provide immense economic benefits to the farmers and guard the environment against pollution. There is a dire need for alternative solutions to stubble burning. Some alternative management practices include the direct incorporation of the stubble into the soil, stubble as fuel, raw material for pulp and paper industries, or biomass for biofuel production. Since biochar is an effective tool for the utilization of stubble into a carbon-rich source, it can further be utilized in the agroecosystems because of its potential to improve soil fertility, enhance soil carbon, and reduce fertilizer use efficiency and enhance agricultural productivity. Thus, biochar, with its immense benefits, helps in soil conditioning and is an excellent means of carbon stabilization. The stable aromatic structure of carbon is resistant to chemical processes such as oxidation to CO_2 or reduction to methane, making it a suitable means to act as a long-term carbon sink. We infer that biochar as an eco-friendly answer for this issue is an exceptionally viable soil conditioner that directly influences soil carbon, soil quality, crop production and food security, promoting economic and ecological benefits.

Keywords: *biochar, stubble burning, carbon stabilization, agroecosystem*

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1. Introduction

The Rice-Wheat Cropping System (RWS) is one of the extensively performed cropping systems in India. About 90% of the area is concentrated in the Indo-Gangetic Plains (IGP). Therefore, due to monoculture and intensive cultivation, it is expected that a massive volume of crop residue is generated. About 40 Mt of paddy straw is produced in northwest India, of which Punjab and Haryana are the major contributors. Unconcerned about being useful in many ways, wheat paddy stubble has turned out to be trouble, Punjab and Haryana produce19.70Mt and 6.86Mt rice straw per season, respectively. Of the total crop residue generated, paddy endows 154–235.8 Mt followed by wheat (131 Mt) [1,2]. In these states, about 80 % of rice straw is put on fire in the fields and of the overall open field burning, 48% is contributed by Punjab and Haryana individually [3]. National Policy for Management of Crop Residue [4] scrutinized that in Haryana state, the total amount of crop residue production is 27.83Mt. This wheat straw is used for livestock feeding surplus residue (9.08Mt), is being burnt every year. One kilogram of paddy generates 1-1.5 kilogram of straw. The disposal of such a large amount of crop residues is a significant challenge. The crop stubbles that are left in the fields after combine mediated harvesting present striking difficulties to the farmers because of the height of the stubbles, poor nutrient composition of paddy straw, cost engaged with assortment and transportation, lack of stubble buyers and the absence of appropriate *in situ* stubble management. Due to these reasons, farmers who are not aware of the public health issues consider open stubble burning the easiest and most economical option of stubble management [5].

Stubble burning releases many air pollutants, resulting in global warming and severe health hazards. Pollutants released during stubble burning include harmful chemical gases like methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), volatile organic compounds (VOC), suspended particulate matter (SPM) and carcinogenic polycyclic aromatic hydrocarbons. After their release into the atmosphere, these pollutants disperse in the surroundings, may undergo a physical and chemical transformation and eventually adversely affect human health and the environment (Figure 1). Biomass burning is a global phenomenon and can be an essential contributor to poor air quality worldwide. Stubble burning also deteriorates soil health making it less fertile, leading to moisture and soil nutrients. Presently, paddy straw is being utilized as feed for ruminants, raw material for the production of compost, paper pulp, mushrooms, mats, thatching of roofs, as bedding in stud and poultry farms, and as fuel in various industries [6]. However, there are no effective management practices for wheat-paddy straw. Wheat-paddy straw-based biochar can be an effective means for the management of wheat-paddy stubble. Biochar is a stable and recalcitrant carbon-rich substance obtained on pyrolyzing biomass materials such as crop residues under low oxygen conditions [7]. It has different properties as a result of a variation in the biomass and the pyrolysis temperature.

It has a negative surface charge due to which it retains nutrients on the surface and reduces leaching [8]. It also aids in soil quality enhancement, climate change mitigation, waste management, and energy production [9]. Hence, Wheat-paddy straw can be used to produce biochar. The same can be applied in the fields to improve soil water and nutrient retention, soil surface area, earthworm and beneficial micro-organism population [10] and other soil fertility. The unique structure of biochar makes it very beneficial for the soil and the environment in so many ways. It improves Physico-chemical properties and enhances the availability of nutrients in the soil, consequently increasing crop production [11]. Biochar from wheat and rice straw has been previously reported in several studies [12,13]. Biochar is nowadays considered a robust climate change mitigation tool and is expected to sequester carbon and decrease greenhouse gas emissions resulting from stubble burning [14]. As the biochar is produced by partial combustion, it becomes the pyrogenic carbon or the carbon black, which becomes a long-term carbon sink with very slow chemical transformation, making it an ideal soil amendment for climate change mitigation [15]. Thus, utilizing wheat-paddy stubble as biochar and applying the same in agriculture can be a climate-smart approach to deal with the concerned problem.

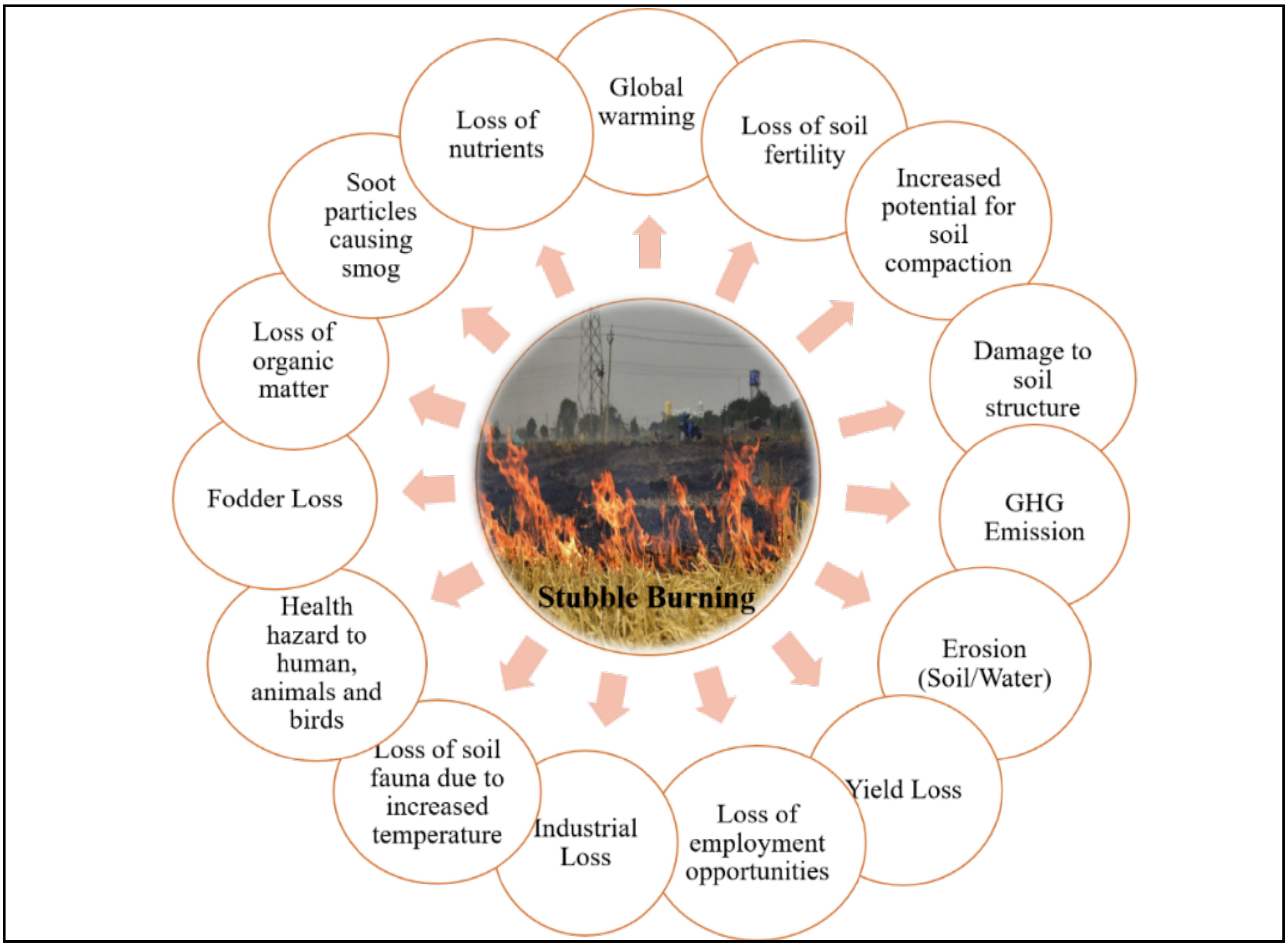

Figure 1. Implications of *in situ* stubble burning on environment and human health

2. Paddy-wheat Straw: Physico-chemical Characterization

Crop residues being excellent sources of nutrients, are the primary source of organic matter (as C constitutes about 40% of the total dry biomass) to the soil and are necessary components for the firmness of the agroecosystems. About 30-35% of the Phosphorus (P), 80-85% of the Potassium (K), 40% of the Nitrogen (N) and 40-50% of the Sulphur (S) absorbed by Rice remain in the vegetative parts at maturity [16]. Similarly, about 35-40% of S, 25-30% of N and P, and 70-75% of K uptake are retained in wheat residue. Typical amounts of nutrients in rice straw at harvest are 5-8 kg N, 12-17 kg K, 0.7-1.2 kg P, 3-4 kg Ca, 0.5-1 kg S, 40-70 kg Si, and 1-3 kg Mg per ton of straw on a dry weight basis [17]. Table 1 summarises the residue to product ratio of Rice and wheat crops. Parameters such as soil type, crop management, crop variety, season, etc., affect the nutrient composition in crop residues. The amount of NPK present in rice and wheat residues generated (197 Mt) is about 4.1x 10^6 Mt in India. Considering 90% of rice straw and 30% of wheat straw are surplus in Punjab, the amount of NPK recycled annually would be about 0.54 Mt. Besides NPK, one ton of rice and wheat residue has about 9-11 kg S, 777 g Fe, 100 g Zn and 745g Mn.

Crop residues still play a crucial role in the cycling of nutrients despite the presiding role of chemical fertilizers in crop production. Continuous removal and burning of crop residues can cause net losses of nutrients under ongoing fertilization practices, leading to escalated nutrient cost input in the short term and deterioration in productivity and soil quality in the long term.

Table 1. Residue to product ratio (RPR)

Crops	Region	RPR ratio / quantity	References
Rice	Gambia (Sahel region)	1.25	[18]
Rice	Uttarakhand, India	1.76	[19]
Rice and Wheat	Punjab, India	1.5:1	[20]
Rice and Wheat	India	1.5:1	[21]
Rice and Wheat	Indo-Gangetic plains, India	6.2-11.8 t/ha and 3.2-5.6 t/ha	[22]

3. Stubble Burning in Punjab and Haryana Region

Both states Haryana and Punjab are intensively engaged in the RWS cropping system since the origin of the Green Revolution in the country. Despite having only less than 3% of the total geographical area of India, these two small states contribute about 69% of the total food procurement by the Government of India (about 54% of the rice and 84% of the wheat) [23]. Researchers estimated that rice residues in 90% of the area harvested by combine harvesters are burned in Punjab and the Haryana state of India, from which emissions can severely degrade regional air quality seasonally [24,25]. The stubble burning is more common in the Kharif season (June to November), which is expected due to a change in the rice-growing period after the enforcement of the "Punjab Sub Soil Water Act-2010" [26]. Further, due to high cropping intensity system (Rice-Wheat) and a short period for land preparation for the next crop, the microbial degradation of rice stubble became limited, which favours the generation of more stubble in open field for burning, a primary reason for air pollution in northern India during October and November month of every year.

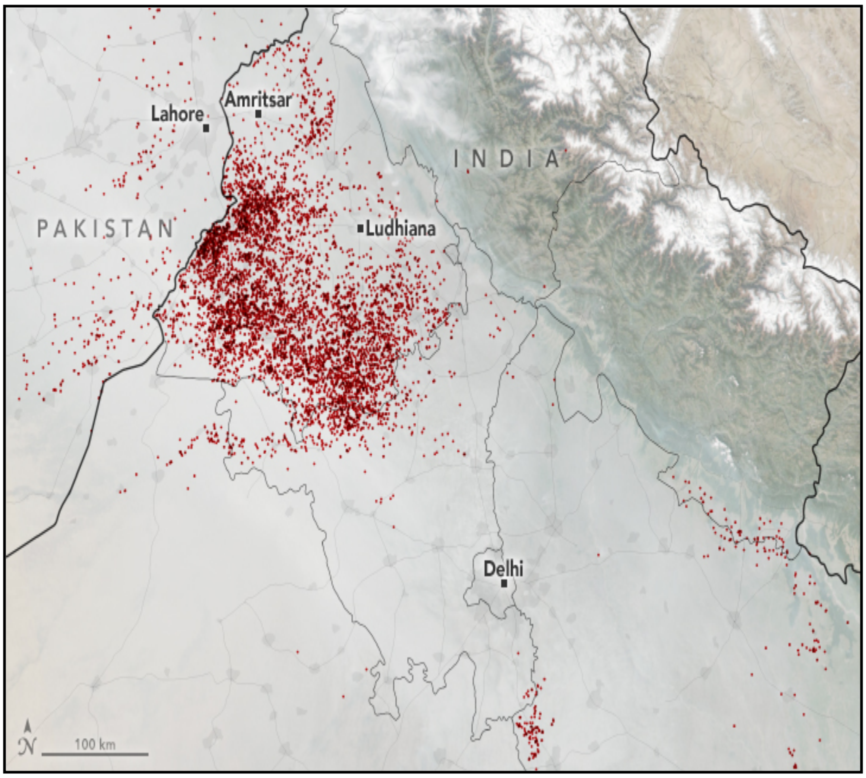

Figure 2. Brazen stubble burning across Punjab-Haryana region (30th Oct-1st Nov 2018) captured by VIIRS [27]

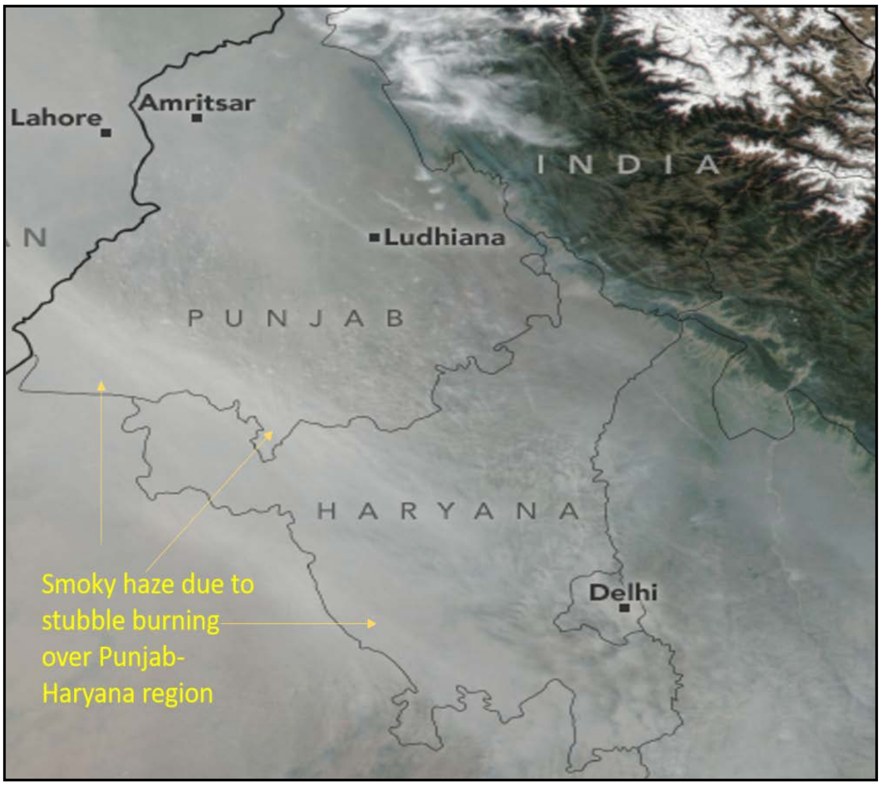

Figure 3. Smoky haze as a result of stubble burning in the Haryana-Punjab region [27]

Lack of storage facility for the straw, insufficient market demand for further use, high labor wages and concern of the farmers to get the crop produce transported to grain markets and sold at the earliest makes the disposal very difficult. As a result, the crop residue gets to remain in the open field and is further subjected to burning [28]. Due to this crop-based biomass burning (Figure 2), a vast cloud of smoke engulfs the whole Haryana and Punjab states (Figure 3) during October–November posing a threat to soil, water, air, environmental quality, and human health [29].

3.1. The Motivation behind Stubble Burning

3.1.1. The Small-time Interval between Rice Harvesting and Wheat Sowing

The government of Punjab implemented "The Punjab Preservation of Sub Soil Water Act" in 2009 [30] to save the groundwater from getting depleted. Simultaneously the State of Haryana had been facing accelerated groundwater depletion as the average groundwater level of the State fell from 12.7 m in 2004 to 15.7 m in 2009 at an average annual rate of 0.36 m. This was attributed to two interrelated factors, one being increased area under tube-well irrigation, which increased from being just 38.9% in 1975–1976 to 61.2% in 2011–2012 and second, rice-wheat cropping system being followed extensively in the State and particularly in the Northern districts of the State [31]. Observing the achievement of the Punjab government, the Haryana government also passed "The Haryana Preservation of Sub Soil Water Act, 2009". This act significantly reduced the groundwater depletion rate [32]. Later on, the governments shifted the date of transplantation to mid-month of June to preserve more groundwater. However, after implementing these laws, farmers were left with a tiny window of 15–20 days to harvest paddy, dispose of the straw, and sow the following wheat crop. Therefore, farmers could not manage the straw during this short period, leaving them no choice but to burn the paddy residue [33].

3.1.2. Extensive Use of Combine Harvester

In the past few decades, combining harvesters has witnessed a significant boom as it requires very little labor and is also less time-consuming. Previously, the manual cutting of the standing crop was highly convenient for the more accessible collection of the waste straw bundles and removing them from the fields. However, Manual harvesting of paddy requires 150–200 people per hectare and costs nearly three times more than combining harvesting. Contrarily, the combined harvesters are fast in working, much cheaper but tend to spread the waste straw randomly all over the field. This makes its collection highly tedious and expensive, motivating the farmer to burn it instead of collecting it [34].

3.1.3. Truncated Nutrition Value of Rice Straw

Another reason for the burning of crop residues is the low quality of rice straw. Paddy straw is less preferred than wheat straw due to poor palatable quality, owing to low protein (4%), high lignin, cellulose, and silica content [35] which reduces milk yield in milch animals [36]. Also, the dry matter digestibility of paddy straw is low, varying from 42 to 48% in different livestock [37]. In a study, it was further [38] reported that the practice of *in-situ* burning as a land preparation measure is present for both rice and wheat crops. However, rice residues are burnt on a much larger scale than wheat residues. Only rice residues from Basmati varieties are used as animal feed. Coarse rice residues are not fed to livestock due to the perceived high silica content and fear of reduced milk yields.

3.1.4. Scarcity of Labor

Labor costs are exceptionally high in Punjab and Haryana, where farm sizes are large and mechanized harvesters are frequent. Moreover, there has been a continuous and a substantial increase in area under paddy cultivation both in Punjab and Haryana states. Therefore, manual and animal power is not enough to live up to the ever-increasing labor requirement, leading to a shift toward mechanical and electrical power. Additionally, increased prices and a reduced supply of agricultural labor augmented the stubble-burning problem. Earlier majority of the laborers migrated from Bihar and UP states to the Haryana Punjab region. However, due to the immense success of the MNREGA scheme, labor migration has reduced in the past few years. As a result, they are leading to increased dependency on combine harvesters.

4. Adverse Effects of Crop Residue Burning on the Environment

In situ stubble burning results in many harmful gases in the atmosphere, like carbon monoxide, N_2O, NO_2, SO_2, CH_4, and particulate matter and hydrocarbons. This practice has become an indispensable source of environmental pollution in the Haryana-Punjab region during harvesting seasons [39]. These trace gases have adverse implications not only in the atmosphere but also on human health, soil health and fertility.

4.1. Depletion of Air Quality

Stubble burning in agroecosystems is a process of uncontrolled combustion, which releases CO_2, CO, CH_4, NO_x, VOCs, SO_2 and other harmful pollutants (Figure 4). About 70% C present in paddy straw is released as CO_2 while 7.00 and 0.66% in CO and CH_4, respectively. At the same time, 2.09% of N in straw is emitted as N_2O upon incineration. These gases and aerosols consist of carbonaceous matter, which may lead to a regional increase in the levels of aerosols, acid deposition, increase in tropospheric ozone and depletion of the stratospheric ozone layer. Black carbon emissions are the second-largest contributor to current global warming, after carbon dioxide emissions. A study led in Punjab state reported that wheat crop stubble burning contributed about 113 Gg of CO, 8.6 Gg of NO_2, 1.33 Gg of CH_4, 13 Gg of PM_{10} and 12 Gg of $PM_{2.5}$ during May 2005 and paddy stubble burning was estimated to contribute 261 Gg of CO, 19.8 Gg of NO_2, 30 Gg of PM10 and 28.3 Gg of $PM_{2.5}$ during October 2005 [22]. Stubble-burning generated particulate matter ($PM_{2.5}$), being incredibly lightweight, can stay in the air for a long time, causes smog and travel hundreds of miles along with wind [30].

4.2. Health Hazards

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, asthma, bronchitis, aggravated chronic heart diseases, and other lung illnesses mainly affects older adults, children, and pregnant women [40]. Various studies have also reported more significant threats for vertigo, nausea, drowsiness, headache, aplastic anaemia, blood cancer, bone marrow disease and pancytopenia [41]. A socioeconomic in the study revealed that the affected members of Punjab State underwent at least half a month from such problems and had to pay Rs. 300–500 per household on medicine as documented in the year 2008-09. In addition, there were few instances where a family member had to be hospitalized for 3–4 days and additional compensation was incurred. Total health cost losses were far higher if expenses on averting events, productivity loss due to illness, the monetary value of uneasiness and usefulness could be calculated. Further, the economic cost of motor vehicle accidents caused by low visibility and blocking or slowing down traffic, especially on countryside roads [42].

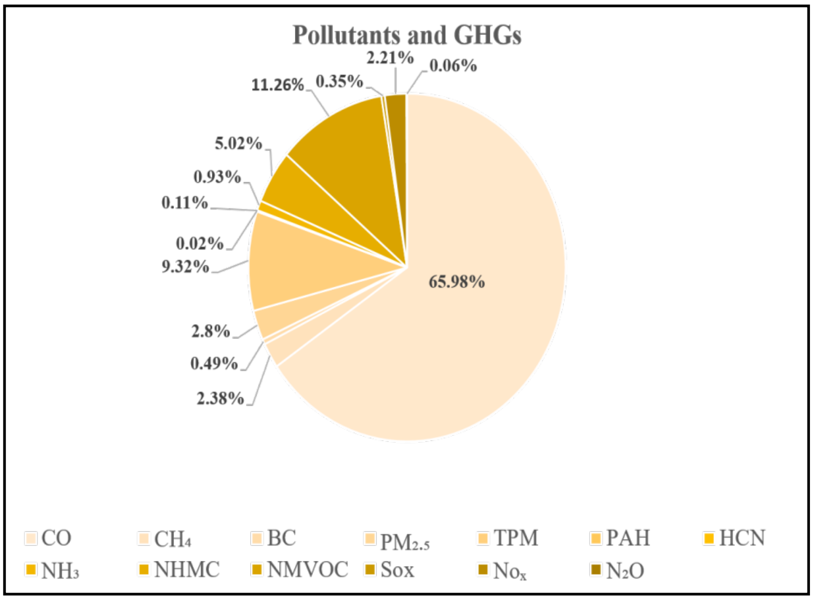

Figure 4. The percentage of air pollutants and GHGs emitted in the environment as a result of stubble burning [40,43,44]

4.3. Deterioration of Soil Health and Fertility

Stubble burning elevates the soil temperature (33.8-42.2°C) up to 1cm, affecting the soil ecology. Because of the elevated soil temperature, 23-73% of the nitrogen in various forms is removed from the soil and the beneficial microbial population also declines to the depth of 2.5cm in the soil [45]. Long-term burning reduces total N and C in the 0-150 mm soil layer. The residue burning kills microflora and fauna beneficial to soil and removes a large portion of the organic material, thereby depleting the organic matter in the fields [28]. Elevated soil temperature affects most soil organisms, thus resulting in the death of beneficial soil micro-organisms and other beneficial organisms such as earthworms involved in maintaining soil fertility.

Table 2. Loss of nutrients due to burning of crop residues (Mt/Year) [42,44]

Crop residues	Nitrogen (N)	Phosphorus (P)	Potassium (K)	Total
Rice	0.236	0.009	0.200	0.45
Wheat	0.079	0.004	0.061	0.14
Total	0.315	0.013	0.261	0.59

4.4. Loss of Nutrients

Stubble burning, carbon, nitrogen and sulfur present in straw are entirely burnt and lost to the atmosphere. One ton of paddy residue contains 6.1 kg N, 0.8 kg P, and 11.4 kg K [46]. 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 [47]. In Punjab state alone, the burning of paddy straw residue causes loss of 3.85 Mt of SOC, 59,000 t N, 20,000t P and 34,000 t K [48]. If retained in the soil, the stubble residues would have enriched the soil, predominantly with organic carbon and nitrogen. These nutrients then have to be replenished through organic or inorganic fertilizers, which come at a cost.

5. Wheat-Paddy Biochar as an Ecological and Economical Solution

Biochar is a carbon-rich, steady, and persistent product utilized by farmers to improve soil health and quality. Biochar is derived from the thermal treatment of crop residues. The thermal treatments involved in biochar generation incorporate carbonization, combustion, torrefaction, gasification and pyrolysis [49]. Pyrolysis is the most favored technique for biochar production because of the simplicity and effectiveness of the process. Pyrolysis can be achieved in a furnace, where oxygen-deficient conditions can be created [50]. The application of biochar has been proven potentially successful (Figure 5) in improving soil carbon sequestration [51], increasing crop productivity [52], remediating contaminated soil and water, mitigating greenhouse gas emissions [53] and reducing leaching of nutrients [54].

5.1. A solution to Waste Management

Biochar production gives us an excellent alternative to overcome the menace of waste generation. The enormous quantities of rice-wheat stubble generated in the Haryana-Punjab region of India could potentially be pyrolyzed to produce biochar as a suitable way to waste management over stubble burning. This would not only be economical but simultaneously beneficial by making waste profitable. Further, biochar has a huge potential for mitigation of climate change by carbon sequestration and reduction in greenhouse gas emissions through reduced waste biomass burning, clean bio-energy production and reduction in methane and nitrous oxide emissions thereby achieving sustainable development goals.

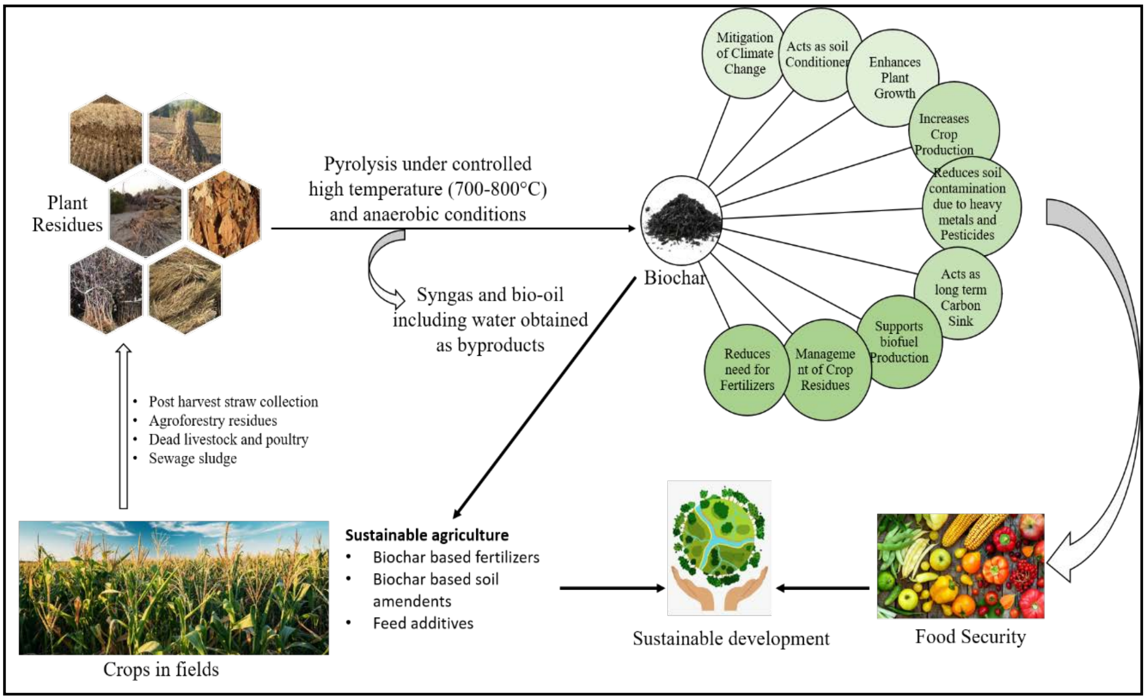

Figure 5. Environmental and agronomical advantages of biochar

5.2. Soil Quality Improvement

Biochar has multiple beneficial properties making it an excellent soil conditioner. The high carbon content, high surface area, and ability to increase soil aeration helps to promote and support the rhizospheric microbial population, thereby improving soil health and fertility. Its application also elevates the soil water retention capacity. A reduction in nutrient leaching by application of biochar has also been reported in the literature. This is an outcome of the increase in soil cation exchange capacity, which has an important effect on fading the nutrient loss by leaching. Further, biochar has an alkaline pH which helps in neutralizing the acidic soils and thereby aids enhancement of plant productivity. Biochar may also serve as a carrier for N fertilizer while potentially reducing the undesired environmental consequences of the inorganic fertilizer, including gas emissions, overland flow and leaching [55]. In an experiment [56] biochar out of peanut hulls was prepared and applied it in a field experiment to explore effects on different soil parameters. The biochar application was also found to increase the pH increase the phosphorus and nitrogen in soil. Furthermore, biochar application is conducive to promoting the rhizosphere biological environment, thus increasing soil enzyme activities and microbial growth [57].

5.3. Climate Change Mitigation

Biochar production has the potential to deal with the menace of climate change. This is done so by the process of carbon sequestration. The carbon, which constitutes the biomass feedstock, gets converted into a more stable form when the biomass is pyrolyzed into the biochar.

Carbon dioxide and other GHGs released during the stubble burning would no longer be released into the atmosphere if the crop residues are pyrolyzed to produce biochar, which shows long-term stability in the soil. The mean residence time of carbon in biochar could be as high as 1600 years [58]. A 2-year field study was conducted to compare the effects of wheat straw, its biochar, and wheat straw plus biochar addition on soil fluxes of CO_2, CH_4, and N_2O during the growing season, and soil properties and crop yield of barley (*Hordeum vulgare* L.). Biochar addition decreased CO_2 and N_2O emissions as compared with both wheat straw applied alone and wheat straw and biochar applied together and resulted in a lower global warming potential, indicating that the biochar is effective in mitigating greenhouse gas (GHG) emission from the agroecosystems [59]. Thus, wheat paddy straw biochar can be an effective management strategy for properly managing crop residues in sustainable agriculture in the Haryana-Punjab region.

5.4. Bioenergy from Biochar

The pyrolysis process produces different amounts of biochar, bio-oil and syngas depending upon the temperature used for pyrolyzing biomass. Fast pyrolysis of biomass produces more bio-oil and less biochar [60]. During the pyrolysis of biomass, the emissions (air pollutants) released could potentially be captured and condensed into bio-oil, a source of bioenergy. Bio-oil would serve as an alternative to fossil fuels and would be associated with lower carbon emissions. Interestingly, a few properties of biochar could be enhanced to assist the catalytic capacity of biochar. In another study, it was [61] reported that sulfonated biochar is a suitable catalyst for producing biodiesel. Syngas is produced via the gasification of biomass. Reducing tar in such a process can enhance syngas production. Therefore, biochar can be an excellent catalyst for tar reduction. Several researchers have used biochar to assist sulfonated solid acid catalyst for biodiesel production. Thus, biochar production could simultaneously promote biofuel and bioenergy generation.

5.5. Biochar as Bioremediation Technology

The application of biochar for heavy metal removal has been acknowledged as a promising area. It has emerged as an exceptionally cheap, immensely potent and tremendously reliable method among the aforementioned heavy metal remediation techniques [62]. The application of biochar is an excellent method to decrease contaminant bioavailability in the soil. Biochar is a highly potent sorbent and an innovative carbonaceous material for removing organic and inorganic contaminants, including heavy metals, from the soil and water, even in arid and semi-arid conditions. A study was conducted to analyse the effects of wheat straw-derived biochar on the bioavailability of Pb, Cd and Cr using Maize as a test crop [63]. The results showed that soil Pb, Cd and Cr reduced 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, with 6% biochar when values were averaged over the contamination levels. Furthermore, the Pb, Cd and Cr accumulation in the Maize crop also decreased compared to the control. Overall, it was estimated that wheat straw-derived biochar has excellent potential to immobilize the heavy metals in soil and reduce their uptake in the crop plants. Similarly, biochar is effective in the bioremediation of organic contaminants. In an experiment, paddy straw biochar was investigated to assess how biochar application affects coupled adsorption-biodegradation of nonylphenol, an organic contaminant. Biochar derived from rice straw was applied to the soil as the adsorbent. The results showed that approximately 47.6% of the nonylphenol was biodegraded in two days when 0.005 g biochar was added to 50 mg/L of nonylphenol, which was 125% higher than the relative quantity biodegraded without biochar. However, the resistant desorption component of nonylphenol reached 87.1% [64].

5.6. Biochar as a Soil Amendment

The addition of biochar can dramatically elevate organic matter in the soil. Several studies have reported that the incorporation of biochar in soils influences soil structure, texture, porosity, particle size distribution, and density. Because of its highly porous structure and large surface area can provide shelter for agriculturally important soil micro-organisms such as mycorrhizae and bacteria and influence the binding of critical nutritive cations and anions. Evidence shows that bioavailability and plant uptake of critical nutrients increases in response to biochar application. Biochar also adds some macro (P, K, N, Ca, and Mg) and micronutrients (Cu, Zn, Fe, and Mn) which are needed for sustainable agriculture. It may significantly affect nutrient retention and play a vital role in a wide range of biogeochemical processes in the soil, especially nutrient cycling. Thus, it can act as a soil conditioner enhancing plant growth by supplying and, more importantly, retaining nutrients and providing other services such as improving soil physical and biological properties [65,66,67]. In addition, it is an excellent soil amendment for sequestering carbon (increasing SOC content) due to its slow decomposition rate.

Table 3. Properties of wheat and rice straw biochar produced at different temperatures (300°C, 400°C and 500°C) Source: [68]

Parameters	Wheat straw			Rice straw		
	Temperature (°C)					
	300	400	500	300	400	500
Ash content (%)	25	36	45	30	39	51
pH	6.74	7.80	8.00	6.98	8.70	9.40
EC (dS $m^{-1)}$	1.78	2.15	2.60	2.35	2.85	3.32
CEC ($Cmol_c$ kg^{-1})	99	83	65	91	73	57
Total C (%)	52	62	66	45	56	63
N (g $kg^{-1)}$	23.8	19.4	18.5	21.5	19.8	18.5
P (g kg^{-1})	3.4	3.8	4.2	1.9	2.0	2.2
K (g kg^{-1})	27	33	41	22	24	30
Ca (mg kg^{-1})	9.5	10.3	13.8	6.9	8.8	9.2
Mg (mg kg^{-1})	7.8	9.6	11.3	4.7	5.7	7.0
Zn (mg kg^{-1})	68	90	99	48	60	71
Mn (mg kg^{-1})	139	167	193	106	117	159
Fe (mg kg^{-1})	185	316	419	147	246	357

6. Role of Biochar in Carbon Stabilization

The carbon sequestration process essentially requires increased residence time and resistance to chemical oxidation of biomass to CO_2 or reduction to methane, which leads to reduction of CO_2 or methane release to the atmosphere [69]. The partially burnt products are pyrogenic carbon/carbon black and become a long-term carbon sink with a very slow chemical transformation, ideal for soil amendment [16,67,70]. Such partially burnt products, more commonly called pyrogenic carbon or black carbon, may act as an essential long-term carbon sink because their microbial decomposition and chemical transformation are probably slow. Carbon stabilization refers to the process where C molecules withstand microbial degradation, respiration, soil erosion and leaching. There are different mechanisms of carbon stabilization in the soil such as (1) physical stabilization, where C molecules are held within soil aggregates which forms a barrier and retard the microbial action; (2) chemical recalcitrance: in this process, an abundance of polychromatic, c-alkyl carbon compounds such as lignin, polyphenols alter the chemical forms which make them less easily accessible to microbial action and their degrading enzymes; (3) mineral complexation: mineral compounds such as clay and silt because of their large surface area absorbs a significant amount of organic matter [71]. A bridge formation between organic anion and polyvalent clay cations resists the organic matter against microbial decomposition. Biochar has been considered as a potential stabilizer of soil organic matter for a longer duration (hundreds to thousands of years) due to its associated intrinsic properties such as (1) abundance of aromatic compounds which render chemical stability and resistance against biotic and abiotic decay, (2) high C content as compared to original feedstock [72]. Soil amendment using Biochar from Wheat and rice residues has been proven to increase soil C pool in different pot experimental studies [73,74,75]. However, there is a discrepancy in the literature regarding the increased stability of C in biochar amended soil. Some studies have observed declining [76] and no effects [77] of biochar on SOC stability. The inconsistent behavior of biochar application in SOC stability could probably be influenced by soil type, climatic conditions [78], raw material used for carbonization, processing conditions and the amount used [79]. Wheat and paddy straw biochar has high ash content, alkaline pH, and nutrient composition such as Nitrogen, Phosphorus, Manganese, Iron, and Zinc [68] can be successfully used to enhance C sequestration in soil. In another study [80] the impact of rice straw and its biochar on labile soil C and SOC was investigated. They observed a higher proportion of labile C under straw added soils whilst a greater amount of stabilized C (Aryl C, carboxyl C) under biochar amended soils, signifying the role of biochar recalcitrance as an efficient management strategy to enhance soil C sink. Apart from the prevailing notion that the C sequestration potential of biochar is due to its recalcitrance nature, in another study [81], it was stated that biochar addition promotes physical stabilization of soil organic matter through the aggregate formation. Rather than the conventional burning, conversion of agricultural waste such as wheat-paddy straw into biochar can genuinely be a low-cost approach to improve soil fertility, C stabilization, and eventually mitigate the emission of GHGs [60,74].

Table 4. Effects of different types of biochar types on different crops under different soil conditions

Biochar type	Soil type	Region /Country	Crop on which applied	Results	References
Waste willow wood (*Salix* spp.)	Dark reddish-brown or red Ferralsol	Tolga, north Queensland, Australia	Maize (*Zea mays*)	Significant increase in crop biomass (10-29%) and grain yield, (9-18%)	[82]
Wood charcoal	Anthrosol and Ferralsol	Manaus, Brazil	Cowpea (*Vigna unguiculata*)	Increase in soil C content, pH value and available P; reduction in leaching of applied fertilizer N, Ca and Mg and lower Al contents.	[66]
Eucalyptus logs, Maize stover	Clay-loam Oxisol silt loam	Cali, Colombia	Common beans (*Phaseolus vulgaris)*	Increase in total N derived from the atmosphere by up to 78%; higher total soil N recovery with biochar addition.	[83]

Charcoal site Soil	Haplic Acrisols	Ejura town, Kumasi, Ghana	Laboratory experiments	Increase in total porosity from 46% to 51% and saturated soil hydraulic conductivity by 88% and reduce bulk density by 9%.	[84]
Peanut hulls, pecan shells, poultry litter	Loamy sand	North and South Carolina, Georgia, and Louisiana	Laboratory experiments	Biochar produced at higher pyrolysis temperature increased soil pH, while biochar made from poultry litter increased available P and Na.	[56]
Wood and peanut shell Chicken manure – Wheat Chaff	Sandy soils	Mingenew, Western Australia	Laboratory experiments	Increase in P availability from 163 to 208%, but decreased mycorrhizal abundances in soils from 43 to 77%.	[85]
Wood and manure-derived Biochar	Different soil types	Technical University, Berlin	Laboratory experiments	Increase the soil's saturated hydraulic conductivity and plant's water accessibility, boost the soil's total N concentration and CEC, improve soil field capacity, and reduce NH4-N leaching.	[86,87]
Manure, corn stover, woods, food waste	Alfisol	Cornell University, USA	Maize (*Zea mays*)	Tissue N concentration and uptake decreased with increasing pyrolysis temperature and application rate but increased K and Na content.	[88]
Different biochar sources	Different soil types	Iowa State University, USA	Laboratory experiments	Increased crop yield, improved microbial habitat and soil microbial biomass, Rhizobia nodulation, plant K tissue concentration, soil pH, soil P, soil K, total soil N, and total soil C compared with control conditions.	[89]
Peanut hull	Ultisols	University of Georgia Tift, Athens	Maize (*Zea mays*)	Increased K, Ca, and Mg in the surface soil (0–15 cm). Increased K was reflected in the plant tissue analysis.	[90]

7. Policy Implications

In recent years, surged concerns for healthy food production and environmental quality and elevated emphasis on sustaining the productive capacity of soils have raised interest in the improvement and maintenance of soil organic matter through appropriate land use and management practices [91,92]. The sustainable management of crop residue has become a pronounced challenge, especially for developing countries like India, with a rising population and production. Crop residues have posed challenges due to their vast volume and lack of proper strategies to manage them. Because rice and wheat usually produce the majority of crop residues being the major staple crops of India. The large-scale cultivation of these crops for feeding an increasing population is undoubtedly the main reason for producing enormous quantities of crop residues. Non-burning of straw will increase the availability of paddy straw at the cheaper rate on the one hand, and the incentivization for not burning on the other hand may also spur the innovation process for finding local solutions for sustainable crop residue management for keeping a clean and safe environment while sustaining soil health. The governments at different levels have attempted to restrict stubble burning through numerous measures and campaigns designed to promote sustainable management methods. India's National Green Tribunal banned stubble burning in 2015, but it had little or no effect in northern states. The charging of monetary penalties from the farmers who burn the stubble and FIRs against them has only politicized the issue rather than putting a brake on it.

The government of India has attempted to curtail this problem through numerous measures and campaigns designed to promote sustainable management methods such as converting crop residue into energy. However, the alarming rise of air pollution levels caused by crop residue burning in Delhi and other northern areas in India observed in recent years, especially during and after the year of 2015, suggests that the issues are not yet under control. The solution to crop residue burning lies in implementing sustainable management practices with Government interventions and policies. Some government interventions, schemes and policies in this approach are:

- Keeping in mind the ill effects of *in situ* burning of crop residues on the environment and human health, the Government of India (GOI) formulated a National Policy for Management of Crop Residue (NPMCR) in November 2014 [93]. Up to November 5, 2016, a total of 1406 violator farmers were fined and a sum of Rs.13.75 lakhs recovered by the Haryana State Pollution Control Board (HSPCB).
- According to Punjab government figures, a total of Rs. 61.47 lakhs were imposed as environmental compensation fine on farmers involved in 10,905 instances of stubble burning during the wheat harvest in 2017 in the State.
- The State of Punjab has distributed 12082 machines to the farmers on an individual ownership basis and has established 3950 Custom Hiring Centres, including Cooperative Societies and Farmers Groups. Total 28609 machines have been distributed in the State during 2018- 2019.
- To prevent the burning of straw, the government invokes Section 144 of the Civil Procedure Code (CPC) to ban the burning of paddy, but it is hardly implemented, and there is little effort to sensitize farmers on the concern.
- Some of the laws in operation pertaining to crop residue burning are The Air Prevention and Control of Pollution Act, 1981; The Environment Protection Act, 1986; The National Tribunal Act, 1995; and The National Environment Appellate Authority Act, 1997.
- Even though residue burning is banned in Punjab state from 2005 and the ban again re-imposed in 2013,

still 32.5% of farmers admitted and justified to opt for residue burning due to the absences of (1) buyers (mainly paddy straw) (2) shortage of labor (3) lack of assistance by the state government (4) shortage of time for sowing next crop (5) non-availability of economically viable machinery.

- The Government of India recently directed the National Thermal Power Corporation (NTPC) to mix crop residue pellets (nearly 10%) with coal for power generation. This helped the farmers with a monetary return of approximately 5500 INR (77 USD) per ton of crop residue. However, these lucrative measures are yet to be in action and the farmers can profitably exploit it.
- The Indian government runs few measures associated with bio-composting. The Rashtriya Krishi Vikas Yojna (RKVY), State Plan Scheme of Additional Central Assistance launched in August 2007, is a government initiative as a part of the 11th Five Year Plan by the Government of India. Under this scheme, eight demonstration and training projects were established in different villages of Azamgarh and Mau districts of eastern Uttar Pradesh. As a result, around 456 farmers were trained for agro-waste bio-conversion and bio-compost production. These large-scale efforts supported farmers in gaining economic advantages.

Educating the farming community is crucially important to bring them out of generational thinking that they are used to that waste management is not their responsibility. Encouragement of crop diversification in Punjab and Haryana can help reduce the area under rice and wheat. It is even more important to empower them with technical assistance. With proper management practices, government and the farmers' collaboration, the adaption of alternative methods crop residue burning issue no more threat to our society. There is a need for deeper understanding through research on economic viabilities and trade-offs of alternative use of crop residues.

8. Conclusion and Future Aspects

Despite innumerable efforts, there has only been a marginal decline in the wheat-paddy stubble burning problem and it has not subsided to manageable levels. Legally inflicting forbidden incineration of crop residues is restricted due to lack of proper education to farmers about its implications on soil, human and animal health. Even though the farmers are aware of the adverse effects of paddy straw burning at the farm level, they are constrained by the lack of economically viable and acceptable machinery and alternatives for the disposal of paddy residues. The government has initiated many approaches for the mechanical management of wheat and paddy stubble but the farmers do not efficiently accept them. Therefore, there is a need to develop a proper management strategy to manage wheat-paddy straw not to suffer any losses. On the other hand, the environment may also benefit from it. The use of biochar as a strategy for the management of crop residues is a very efficient and helpful way to get rid of the stubble on the one hand and using it as a soil amendment on the other hand. Government should look forward in this direction by providing farmers with proper ways to use this approach. Promoting organic recycling practices and incentives to farmers will ensure prevalent sojourn practices leading to pollution and wastage of potential resources. Furthermore, the government should promote and provide need-based support alternative options to stop residue burning instead of strict law enforcement. That is how a proper self-sustained ecosystem may be achieved with the mutual efforts of farmers and the government.

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