

Review

Crop Residue Management in India: Stubble Burning vs. Other Utilizations including Bioenergy

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Abstract: In recent studies, various reports reveal that stubble burning of crop residues in India generates nearly 150 million tons of carbon dioxide (CO₂), more than 9 million tons of carbon monoxide (CO), a quarter-million tons of sulphur oxides (SO_x), 1 million tons of particulate matter and more than half a million tons of black carbon. These contribute directly to environmental pollution, as well as the haze in the Indian capital, New Delhi, and the diminishing glaciers of the Himalayas. Although stubble burning crop residue is a crime under Section 188 of the Indian Penal Code (IPC) and the Air and Pollution Control Act (APCA) of 1981, a lack of implementation of these government acts has been witnessed across the country. Instead of burning, crop residues can be utilized in various alternative ways, including use as cattle feed, compost with manure, rural roofing, bioenergy, beverage production, packaging materials, wood, paper, and bioethanol, etc. This review article aims to present the current status of stubble-burning practices for disposal of crop residues in India and discuss several alternative methods for valorization of crop residues. Overall, this review article offers a solid understanding of the negative impacts of mismanagement of the crop residues via stubble burning in India and the other more promising management approaches including use for bioenergy, which, if widely employed, could not only reduce the environmental impacts of crop residue management, but generate additional value for the agricultural sector globally.

Keywords: agricultural residue; stubble burning; alternative management practices; valorization



Citation: Porichha, G.K.; Hu, Y.; Rao, K.T.V.; Xu, C.C. Crop Residue Management in India: Stubble Burning vs. Other Utilizations including Bioenergy. *Energies* **2021**, *14*, 4281. <https://doi.org/10.3390/en14144281>

Academic Editor: Idiano D'Adamo

Received: 31 May 2021

Accepted: 8 July 2021

Published: 15 July 2021

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1. Introduction

Stubble burning is a practice where fire is purposely put to the stubble which remains after grains, such as paddy, wheat, rice, corn, etc., have been harvested. This represents an important source of atmospheric aerosol and gas emissions, hence having a potential effect on the global air quality and environmental chemistry. Open-field biomass burning is a longstanding method for land clearing and improvements in land use to dispose of living and dead vegetation, used globally. It has been estimated that humans account for nearly 90% of biomass combustion, although only a small portion of natural fires are responsible for the overall amount of vegetation burnt [1]. Over the past few decades, biomass burning has increased worldwide. In India alone, the total amount of crop residue and the burnt was estimated to be 516 million tones and 116 million tonnes (Mt), respectively, in the year of 2017–2018, approximately generating 176.1 Mt CO₂, 10 Mt of CO, 0.31 Mt CH₄, 0.008 Mt N₂O, 0.151 Mt NH₃, 0.814 Mt NMVOC, 0.453 Mt PM_{2.5} (particulate matter) and 0.936 Mt PM₁₀ [2]. Stubble burning has many environmental impacts and consequences, compared with alternatives such as ploughing stubble back in the field or harvesting them for industrial purposes. However, there are inadequate data on the impacts of crop stubble burning. Extrapolation has been commonly used in estimating the pollution factors in the database of farm residues, which may result in high uncertainty in the emission figures. It is well known that, due to agricultural field burning during the harvest season, air quality

is greatly affected. Aerosol and gaseous pollutant source profiles from an agricultural fire are needed to assess their contribution to ambient air quality. As described above, agricultural field burning has created many environmental problems, utilizations of crop residues for such as cattle feed, compost with manure, rural roofing, biomass fuel, beverage production, packaging materials, wood, paper, and bioethanol, etc., should be explored and promoted. In the following sections, the detrimental environmental impacts of open burning of the agricultural residues are discussed in detail and current approaches for managing these crop residues are also presented.

This paper aims to present an overview of the practice of stubble burning of crop residues in India, its effects on the environment and health, and discuss some alternatives to stubble burning for valorization of crop residues.

2. Practices in India

India is a farming nation with many farming practices in step with agro-climatic zones. Rice, paddy and wheat cropping patterns are among the extensive farming practices in the states of Haryana, Punjab, Rajasthan, and western Uttar Pradesh. These regions are also infamous for burning the straw and stubble after the harvesting season. The state Punjab crosses India Pakistani border and is also called a ‘breadbasket’ because it produces two-thirds of India’s food grains. Even though the government increasingly restricted the practice after 1990s, each year in late September and October, farmers from Punjab and Haryana in particular burn an estimation of 35 million tons of crop residue from their paddy fields after harvesting [3]. This practice serves as a low-cost method of getting rid of the straw and reduces the turnaround time between harvesting and sowing for the second (winter) crop. Figure 1 shows the crop-wise distributions of crop production, residue generated, and residue burnt in India for the year of 2018 [4].

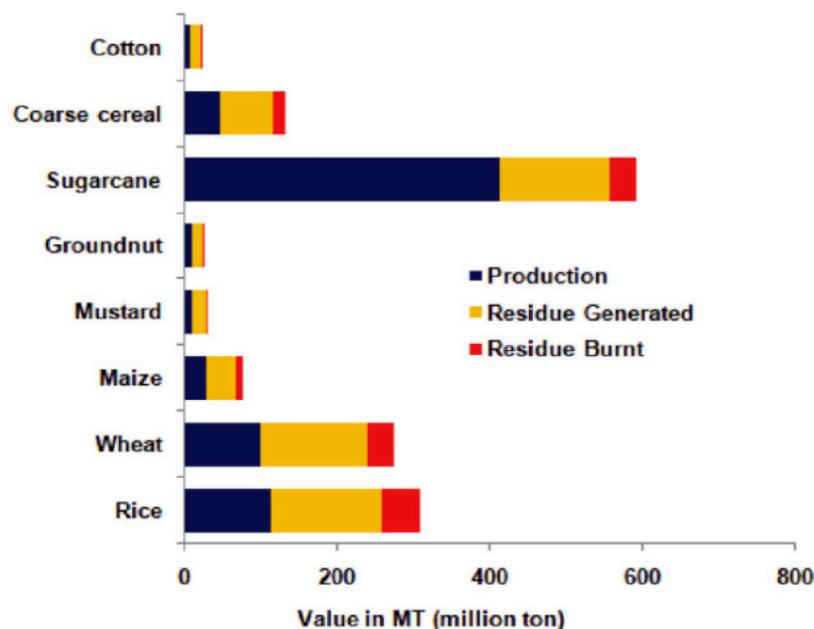


Figure 1. Crop-wise distributions of crop production, residue generated, and residue burnt in India for the year 2018 [4].

Burning the residue leads to the loss of nutrients and resources. Apart from deteriorating the ambient air quality, flaming stubbles causes soil nutrient loss of organic carbon (3850 million kg), nitrogen (59 million kg), phosphorus (20 million kg), and potassium (34 million Kg), and discharges large volumes of various air pollutants such as CO_x, CH₄, NO_x, SO_x, and particulate matters (PM₁₀ and PM_{2.5}) [5]. The burning of straw and stubble is still a major disposal method in India, although the government of India has taken a

few steps to prohibit the practice in recent years. The National Green Tribunal (NGT), located in the capital of India, imposed a ban on the flaming of straw and stubble in the neighbouring four states (Haryana, Rajasthan, Punjab, and Uttar Pradesh) to New Delhi, which contribute the significant air pollution during the early winter [6]. The government encourages farmers to utilize the straw and stubbles for alternative practices like mulching or in situ incorporation rather than burning. This agricultural waste can be used for animal fodder, generation of electricity, growing mushroom, and paper industry.

It has been reported that crop stubble burning contributes to one-quarter of the air pollution that blankets the entire capital city in the winters almost every year. In November 2018, the Delhi pollution index climbed to 12 times higher than the upper limit for healthy air. According to the United States embassy in New Delhi, the air quality in central Delhi in the morning was termed as “unhealthy,” being more than three times the permitted level. The federal government was strongly criticized after the US-based United Airlines suspended flights to New Delhi due to its pollution. Apart from the stubble burning, the entire country celebrates the Diwali festival with fireworks, which also contributes to a lot of air pollution, especially in New Delhi. The Supreme Court of India passed a judgment in early 2019 to regulate the emission of gases from different sources, including the combustion of crop stubble and garbage as well as emissions from motor vehicles. However, most of the farmers in North India, as well as in other parts of the country, are not well educated and they do not become aware of air pollution and its threats to human life and the environment. Thus, the farmers use fire on agricultural waste, not deliberately, as they are the first victims of smoke inhalers. The North Indian farmers, especially from Punjab and Haryana, are in a helpless situation because there are no viable alternatives available to them to clear the fields but burning. All that threatens human health to such an extent is wrong and needs to be prevented. For implementation of the prohibition on the combustion of crop stubbles, a centralized, designated and accountable authority should be established to execute a comprehensive strategy to solve this problem with concrete, time-limited goals.

3. Effects of Stubble Burning

3.1. Environmental Effects

The burning of crop residues generates various environmental issues. The most adverse effects of crop residue burning embody the emission of greenhouse gases (GHGs) that contribute to global climate changes. In addition to that, enhanced levels of PM and other air pollution that cause health hazards, loss of diversity of agricultural land, and the deterioration of soil fertility [7]. The burning of the crop stubble in an open field influences soil fertility, eroding the sum of soil nutrients.

3.1.1. Air Pollution

Crop residue burning produces various air pollutants like GHG emissions, CO, NH₃, NO_x, SO_x, non-methane organic compound (NMHC), volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs) and PM [3], leading to the loss of organic carbon, nitrogen, and alternative nutrients, which otherwise might have preserved in soil. In Punjab, approximately 22 Mt of CO₂, 0.92 Mt of CO, and 0.03 Mt of SO₂ is generated from around 15 Mt of rice residues on an annual basis [8]. Similarly, according to a study by Jain et al., GHG emissions account for 91.6% of total air emissions caused by the burning of 98.4 Mt of crop residue and the remaining 8.4% are CO, NO, NMHCs and SVOCs [3]. Stubble burning also leads to emission of aerosols [9]. As also reported by Gadde et al. [10], the open burning of rice straw in India, Thailand and the Philippines results in severe air emissions of SO₂, NO_x, CO₂, CO, and CH₄.

The major emissions of polluting gases and PM, as well as aerosols and trace gases as a result of crop residue burning, are listed in Tables 1 and 2. The PM released from the burning of crop residues is 17 times higher than that of the emissions from various other sources like motor vehicles, waste incineration, and industrial waste [11]. Intrinsically,

the crop residue burning among the northwest vicinity of the country contributes to a considerable amount of about 200 organic carbon compounds in terms of the national emissions budget [12]. Street et al. [13], have anticipated that about 730 Mt of biomass was burned annually in Asian countries, and among them, India is in 18th position. Crop residue burning will increase the PM within the atmosphere and contribute to temperature change considerably. The fact that the fine black and also brown carbon (primary and secondary) would change sun light absorption and hence contribute to the global climatic change [10,14–16].

Table 1. Major pollutants released into the atmosphere during crop residue burning [8].

Category	Pollutant	Source
Particulate matters	PM _{2.5} and PM ₁₀	Condensation after combustion of gases and incomplete combustion of organic matters
	PM ₁₀₀	Incomplete combustion of in-organic materials, particles on burnt soil
Gases	CO	Incomplete combustion of organic matters
	CH ₄	Incomplete combustion of organic matters
	O ₃	A secondary pollutant formed due to the reaction of nitrogen oxide and hydrocarbon
	NO, NO ₂ N ₂ O	Oxidation of fuel-N or N ₂ in the air at high temperatures
	Polycyclic aromatic hydrocarbons (PAHs)	Incomplete combustion of organic matters

Table 2. Emission levels of air pollutants during harvesting season in Haryana and Punjab (Source: Delhi Pollution Control Committee [DPCC], 2016).

Pollutants	Area in Delhi	Current Level (µg/m ³)	Permissible Limit (µg/m ³)
PM _{2.5}	Punjabi Bagh	650	60–80
PM ₁₀	Punjabi Bagh	1000	60–80
CO	IGI Airport	6.3	2–4
SO ₂	IGI Airport	29.8	60–80
NO _x	Anand Vihar	167	60–80

Usually, PM within the air is classified as PM_{2.5} and PM₁₀ in terms of its particle size (PM_{2.5} is fine particles with a diameter <2.5 µm and PM₁₀ is coarser, with a diameter <10 µm). Lightweight PM materials will remain suspended within the air for an extended time and might travel a prolonged distance with the wind [17,18]. PM pollution worsens under some climatic conditions, when the lightweight particles stay in air for an extended time causing severe air pollution. The annual contribution of PM_{2.5} from the burning of paddy residue within the Patiala district of the geographic region was estimated to be around 60 to 390 mg/m³ [19]. With the onset of cooler weather in November, the smoke, mixed with fog, dust, and industrial pollution, forms a thick haze. In the season if there is a lack of wind, the thick haze would continue for many days, as was the case throughout November 2017. Many major cities, including New Delhi, Lucknow, and Kanpur, faced elevated levels of pollution [20].

According to the United Nations, the permissible levels of PM_{2.5} within the air is 10 µg/m³, while India's National Air Quality commonplace allows the permissible level of PM_{2.5} to be about at 40 µg/m³. However, the capital territory of the urban center recorded a mean of 97 µg/m³, which is double that of any other Indian place and 10 times more than that of the United Nations guidelines [19].

As well known, the emission of toxic gases from burning of the crop residue could lead to coughing asthma, emphysema, bronchitis, irritation of the eye, an opacity of the corneas, and skin disorders. Inhaling of PM can lead to intensifying persistent cardiac and pulmonary ailments and is related to the premature deaths of people who are already suffering from these illnesses [21]. About half of the world's population now lives in urban areas, which facing severe air pollution issues that adversely affects human health through the cardiovascular and respiratory systems [22]. Air pollution results in metabolism diseases like eye irritation, bronchitis, asthma, etc. Increasing individuals' sickness mitigation expenses and, additionally, poignant ones' operating capability. Annually, 3.3 million people are dying prematurely due to air pollution around the world. If air emissions continue to rise, this number will double by 2050 [21]. The Organization for Economic Cooperation and Development (OECD) estimates that in Delhi NCR alone, air pollution contributes to approximately 20,000 premature deaths and this number is expected to increase to 30,000 by 2025 and to 50,000 by 2050 (OECD, 2016). Table 2 shows that current pollutant emission levels in most areas of Delhi are way off the permissible limits.

The burning of crop waste also puts in danger of the survival of animals that produce milk. Air pollution can lead to animal death, as high CO₂ and CO levels in the blood can alter normal haemoglobin leading to death. More than 60,000 people who live in rice-growing areas are vulnerable to air pollution as a result of rice stubble burning, according to Singh et al. [8].

Detrimental compounds such as polyhalogenated organic compounds, namely polychlorinated dibenzodioxins, peroxyacetyl nitrate, polyaromatic hydrocarbons, polychlorinated biphenyls, and polychlorinated dibenzofurans, a family of organic compounds commonly called 'furans', are all classes of chemical emitted from open burning of farm residue [21]. These atmospheric pollutants are potentially toxic, and some are teratogenic, mutagenic, or carcinogenic in nature. The burning of crop straw and stubble has severe negative impacts on health. Pregnant women and infants are most prone to suffer adverse effects due to stubble burning pollutants. Respiratory inhalation of suspended PM_{2.5} prompts asthma and can even worsen symptoms of bronchial attacks [6].

Open burning in the field also affects the lifespan of animals, birds and insects. Burning from time to time also causes poor visibility and increases the impact of road accidents. House surveys show that paddy husk burning causes several other problems as well as increasing health costs in polluted lands. Whether or not households are conscious of the harmful effects of waste burning, the answer would be 'yes' for about 90% of households; however, almost no household would take precautionary action to tackle pollution-related diseases [5].

Eye irritation and congestion within the chest are the two major issues faced by the bulk of people suffering from the stubble burning pollution. Metabolism allergic reaction, asthma attack and cartilaginous tube issues are the smoke connected chronic and non-chronic diseases that affected house members. Within the harvesting season, the affected families have to see doctors or use home medication for temporary relief from irritation/itching in eyes, respiration problems and similar alternative smoke connected issues. Sometimes they need to be hospitalized for 3 to 4 days, with extra expenditure incurred. On average, households spend a lot and suffer a lot from non-chronic metabolism diseases like coughing, a problem in respiration, irregular heartbeat, itchiness in eyes minimized respiratory organ performance, etc., throughout the year in particular during the months of crop husk burning [23]. The state government, from time to time, advises farmers not to set their field blazing. This is publicized in the native newspapers to create individual awareness of the adverse effects of crop husk burning. The administration even makes such announcements by loudspeakers within the villages. However, farmers who store the husk rather than burning it are not given any incentive from the administration, and farmers are not privy to the provision of alternative techniques to burning. The majority of farmers would be interested in adopting other practices if the state government offers enough resources.

In addition to the emission of air pollutants and the associated health effects to living organism, there is a continuous deterioration of soil fertility because of burning, which will be discussed in the following Section 3.1.2.

3.1.2. Soil Fertility

According to the Department of Agriculture, Government of Punjab, the soils of Punjab typically contain low nitrogen content, low to medium phosphorus, and moderate to high potassium. Besides, the organic carbon in the soil has decreased to very low, and insufficient levels and organic manure and crop residue have not been properly applied. Production of 7 t/ha rice and 4 t/ha wheat extract more than 300 kg of nitrogen, 30 kg of phosphorus, and 300 kg of potassium from the soil per hectare. The burning of crop residues contributes to the depletion of soil organic carbon, according to the Department of Soil, Punjab Agricultural University. Moreover, CO₂ and soil nitrogen balance changes quickly, and nitrogen is converted into nitrate, leading to depletion of 0.824 million tons of nitrogen-phosphorus-potassium (NPK) from the soil annually.

In addition, repeated burns can diminish by more than 50% the bacterial population. Long-term burning also reduces the amount of 0–15 cm soil loss along with loss of total nitrogen, biomass, and potentially mineralized nitrogen and organics. The burning of agriculture residues raises the soil temperature and causes depletion of the microorganism and flora population. The residue burning will increase the dirt temperatures to just about 35.8–42.2 °C at 10 mm depth [11], and semi-permanent effects will even reach up to 15 cm of the highest soil. Furthermore, the frequent burning reduces the nitrogen and carbon content in the soil and kills the microflora and fauna, which are useful to the soil, and additionally removes a significant portion of organic matter. With crop residue burning, the carbon-nitrogen equilibrium of the soil can be totally lost [5,24]. According to NPMCR [25], open incineration of 1 tonne of stubble would result in the loss of all organic carbon, 5.5 kg of nitrogen (N), 2.3 kg of phosphorous (P), 25 kg of potassium (K) and 1.2 kg of sulphur (S) in the soil. If the crop residue is kept within the soil itself, it will enrich the soil with C, N, P and K additionally.

Mandal et al.'s study [26] revealed that the burning of rice and wheat residues contributes to a loss of about 80% of nitrogen, 25% of phosphorus, 21% of potassium and 4–60% of soil sulphur, although it does destroy unwanted bugs and diseases borne by the soil.

Crop residue burning also contributes to a depletion in the crop essential nutrients. Around 25% of nitrogen and phosphorus are kept in crop residues, making 50% of sulphur and 75% of cereals potassium intake viable nutrient sources [13]. According to Singh et al. [8], there was a loss of 2400 kg of carbon, 35 kg of nitrogen, 3.2 kg of phosphorus, 21 kg of potassium, and 2.7 kg of sulphur from burning of rice residues in 1 ha in Punjab between 2001 and 2002. As presented in Table 3, burning of rice residue led to almost complete loss of carbon and nitrogen, and about 20–60% loss of P, K and S.

Table 3. Nutrient losses as a result of burning of rice residue in Punjab [8].

Nutrient	Concentration in Straw (g/kg)	Percentage Lost in Burning	Loss (kg/ha)
C	400	100	2400
N	6.5	90	35
P	2.1	25	3.2
K	17.5	20	21
S	0.75	60	2.7

4. Alternative Methods to Open Burning

In order to implement sound selections of alternative crop residue management methods, it is necessary to scientifically perceive the short and temporary effects of various crop residue management practices and to develop new residue management technologies that are cost-efficient and environmentally acceptable.

Crop residue management choices should be measured on the premise of productivity, gain, and environmental impact. These criteria would overlap with those employed in the approach of ecological intensification for intensive crop production systems aiming to fulfill the increasing demand for food, feed, fiber, and fuel, while meeting acceptable standards of environmental quality [27].

4.1. In Situ Incorporation

Although there are different alternatives to stubble burning, currently only two options are available to farmers, either to integrate the remains of crop stubble in situ or to burn it within the field. Farmers do not favour in situ incorporation because the stubble takes a long time to break down into the soil. According to the Department of Agriculture of Punjab, less than 1% of farmers implement in situ incorporation of crop stubble.

As per Singh et al. [28], however, the crop yield was significantly lower if the rice residue was added immediately before seeds are sown due to inorganic nitrogen immobilization and its adverse effect because of nitrogen deficiency. In a few studies, rice stubble was incorporated in the soil during the first 1–3 years, 30 days before wheat planting, and the wheat yield was found to decrease. Yet rice stubble incorporation in later years had no effect on the production of wheat crops.

According to another study by Sidhu and Beri [29], the incorporation of rice residues in the soil could be the best alternative practice (Table 4). A six-year study period showed that the production of subsequent wheat and rice crops was not adversely affected if the rice residue was introduced into the soil between 10 to 40 days before the sowing of the wheat crop. The resulting rice residue had no residual effect on the paddy straw combined with wheat, producing similar yields of rice and wheat with different residual management practices, including burning, elimination and integration [28,30]. Singh et al. [31] reported that paddy straw was introduced to the soil three weeks before wheat sowing and the wheat yield increased significantly in clay loam soil but in sandy loam soil. It was also reported that there was no adverse impact of in situ incorporation of crop stubble on the subsequent grain outputs according to research by Sharma et al. [32,33].

Table 4. Comparison of impacts of different residue management practices on soil properties in Ludhiana, Punjab [29].

Soil Property	Crop Residue Management		
	Incorporated	Removed	Burned
Total P (mg/kg)	612	420	390
Total K (mg/kg)	18.1	15.4	17.1
Olsen P (mg/kg)	20.5	17.2	14.4
Available K (mg/kg)	52	45	58
Available S (mg/kg)	61	55	34

Similar results reported that the incorporation of rice residue 3 weeks prior to sowing the wheat crop increased the amount of wheat only in clay loam soil and not in sandy loam soil [28]. This study also showed that organic carbon increased by 14–29% when the crop residues were incorporated in the soil. Incorporation of rice residue into the soil within 30 days before sowing wheat crops led to lower yields of grape wheat relative to those when the rice residue was burned [34]. Moreover, rice stubble incorporation into the soil has a beneficial effect on physical, chemical, and biological soil properties such as pH, organic carbon, the ability of water retention and bulk soil density. According to Mandal et al. [26], the impacts on the physicochemical properties of the soil over 7 years of various crop residue management practices (incorporated, removed and burned) are comparatively shown in Table 5. Both Tables 4 and 5 clearly show that methods of handling the rice residue for soil nutrient conservation are in the following order: in situ incorporation > removal of the rice residue from the land > stubble burning.

Table 5. Impacts of different residue management practices on soil properties [26].

Physiochemical Properties of the Soil	Crop Residue Management		
	Incorporated	Removed	Burned
pH	7.7	7.6	7.6
EC (dSM ⁻¹)	0.18	0.13	0.13
Organic C (%)	0.75	0.59	0.69
Available N (kg/ha)	154	139	143
Available P (kg/ha)	45	38	32
Available K (kg/ha)	85	56	77
Total N (kg/ha)	2501	2002	1725
Total P (kg/ha)	1346	924	858
Total K (kg/ha)	40480	34540	38280

4.2. Mulching

Mulching is the protective covering of the soil using sawdust, compost, or paper to reduce evaporation, prevent erosion, control the weeds, enrich the soil, or cleanse fruit. Mulching usually requires biomass transfer from the field before the soil is puddled, and then the biomass returns once the soil is prepared [35]. After harvesting the rice in India, some farmers do not drain their land on early rice crop and keep the field flooded during a short transition to the late rice crop transplant. Placing straw from early rice as mulch in lengths along the transplanting path for late rice ensures that the soil is moist enough to allow late rice transplants, controls the growth of weed and prevents rice rotting, while other Indian rice farmers have attempted to avoid flooded rice systems that allow crop residue to be retained on the surface [36]. Farmers either throw rice seedlings or seed germinated rice directly in many northern states such as Uttar Pradesh. Residues of crops are maintained on the soil surface in these systems. During plant establishment, the soil is saturated or flooded and weeds are managed by herbicides. Some farmers use relay crops to sow rice in wheat fields before mixing harvests. During the rice crop, the standing wheat stubble gradually decays. In order to save water and enhance N performance, a rice system for rice production (GCRPS) covers the soil under non-flooded conditions with soil covered by rice straw paw during development, but the yield of grain was often lower than in flooded rice [37].

A reduced or no-tillage system (Figure 2) makes it fairly easy to preserve the residue on the soil like a mulch by merely holding it onto the field during harvesting, when the residue does not need to be removed and added until tillage.



Figure 2. No-tillage farming (<https://smallfarms.cornell.edu/2016/01/no-till-permanent-beds/> (accessed on 8 July 2021)).

Farmers in rice-based cultivation systems in India typically practice no sowing of winter crops, including wheat, barley, and rapeseed. Surface seeding of wheat is performed in ~60% of the rice-wheat system in Southern India by making a little hole in the earth (dibbling) followed by mulching with rice residue (4–6 t/ha). As the time span between maize harvest and the wheat crop sowing is relatively short (20 to 45 days) in India, it is difficult to enforce activity to manage weeds and to minimize evaporation in the fallow while not flooding the next crop [38]. Maize residue is spread to the mulch immediately following the harvest. For farmers who grow rice rather than wheat after rice, this technique is attractive. Farmers in the Indo-Gangetic Plains in north-western India have been gradually using reduced and no-tillage for wheat since the end of the 1990s and it results in substantial cost savings by reducing the fuel and labour use. Early seeding, particularly after the late rice harvest, also makes it easier in the eastern part of the Indo-Gangetic Plain to achieve potential yield advantages. Since the end of the 1990s, the region of reduced and non-smoking wheat has grown exponentially in the Indo-Ganges plain to an estimated 20% to 30% or 2–3 million hectares in 2006. However, the non-sowing of weeds after combine-harvesting of rice encounters some difficulties, e.g., accumulation of residues in the furrow openers, problems with the friction of the driving wheel of the drill, difficulties with loose straw fertilizer metering systems and uniform sowing depth due to frequent leaving of the drill to clear blockages [39]. Many methods for direct sowing into rice residue are being tested to address the problem of clogging and ‘hair pinning’ when the straw bends but is not cut and buried, which leaves the seed on the surface. These include the double and three-disk systems [40], the paw thrower and stubble chopper, although, to date, none has been successfully implemented.

Tillage mulching is a method to retain enough residue remains on the surface of the soil to significantly reduce erosion. It is used in low-soil lands. The residue can also be used as mucus to the following non-flooded crop (Figure 3). This method is not used by many farmers because it requires that the residue be partially removed from the field and returned after planting [41]. For farmers with limited land holdings and ample labour, however, this approach can be easier. In conventionally tilled fields in the rice-wheat system in South Asia, rice residue mulching is carried out only occasionally [42].



Figure 3. Tillage method of mulching (www.livinghistoryfarm.org (accessed on 8 July 2021)).

4.3. Composting

Composting is a biological process where organic waste is converted into compost that can be used as a fertilizer by microorganisms under controlled aerobic conditions [43]. A composting technique is usually used for the management of off-field residues where the compost generated is not returned to the field, while it can also be implemented in fields (in situ composting) [44].

In situ, rice straw is stacked up at threshing locations [45] as an instance of composting, where the straw decomposes gradually, mostly aerobically, and then at the beginning of the next season the compost can be dispersed into the soil as a fertilizer. The drawbacks of this operation include the establishment of suitable habitat for rodent pests and the

undesirable presence of immobilized residual N. In China, another form of in situ composting is practiced in which wheat or barley residue is buried in ditches parallel to the rice transplant [46]. Crop residue can be composted alone or with other organic materials such as animal manure. The resulting compost can then be collected and added to the soil as a fertilizer. It is an appealing alternative to stubble burning owing to its ability to turn waste in a farm into a valuable fertilizer product by simply packing crop residues into piles or pits for a long time [47]. The composting method used in Indian rural areas often employs a passive aeration system with aeration holes and the treatment time is commonly within two to three months. Composting technology requires the input of the labour force but does not entail capital investment nor advanced machinery and infrastructure, which can be particularly attractive to small farms with sufficient labour resources.

4.4. Happy Seeder Machines

Although crop residue retained in the field plays a positive role in recovering soil quality and reducing environmental pollution caused by stubble burning, seeding of wheat in the field with rice residue retained was a challenge until the development of a happy seeder machine recently. The 'Happy Seeder', incorporating mulching and drilling of stubble in a single unit, is a promising new method [48], where the stubble is cut and gathered before seeding, and the cut stubble is then deposited as a mulch behind the seed sower.

The technology evolution has led to invention of a device known as the Combo Happy Seeder equipment (Figure 4) [49]. Several Happy Seeder machines have been built including the nine-row Turbo Happy Seeder (v.2). The 9-row Turbo Happy Seeder (vers.2) with a weight of 506 kg can be driven by a 33.6 kW tractor, and it has a working capacity of 0.3 ha h^{-1} for seeding wheat in the field with rice residue retained [50]. The adoption of happy seeder machine is facing some constraints including its low machine operating window (25 days a year), limited machine efficiency, inability for wet straw operation, and the lack of spreaders on a combined harvester. According to the National Academy of Agricultural Sciences (2017), rice residue can be managed by concurrent use of a super straw management system (SMS) fitted combines and turbo happy seeder. More importantly, profit analysis showed that Happy Seeder systems are more profitable than other alternatives for crop residue management [51]. Sowing wheat with the combination of happy seeders has an operating cost 50–60% lower than that with a traditional seeder [8].



Figure 4. Happy seeder equipment [49].

4.5. Bioenergy

Another promising residue management method is the production of bioenergy from crop residues. For example, crop residues can be used for liquid biofuel production, i.e., conversion of biomass to biopower or electricity or liquid fuel [52,53]. The most common biofuel produced from crop residues is cellulose-based ethanol, and the production in-

volves enzymatically breaking down the polysaccharide within the straw into its element sugars, which will then be fermented into ethyl alcohol. Biopower is generated by direct combustion of straw alone (direct firing), or together with another fuel (co-firing) [54]. Another alternative method to direct combustion is through gasification, in which straw is gasified by air or steam to generate a fuel-gas mixture of N_2 , H_2 , CO , and CO_2 followed by combustion of fuel-gas mixture to generate electricity.

Bioenergy can also be generated from crop residues via anaerobic digestion to produce biogas mainly CH_4 , which is collected and combusted to generate electricity [55]. For example, Gross et al. [56] applied cattle and buffalo manure and crop residues as the feedstock to produce biogas by anaerobic digestion, which was accompanied by the production of organic fertilizer. In another study, Abdelsalam et al. [57] produced biogas from the mixture of agricultural waste (e.g., potato peels, lettuce leaves, and peas peels) and livestock manure by co-digestion, and it was observed that the highest CH_4 and biogas production yield of 6610.2 and 1,23,55 mL, respectively, were achieved using the co-feedstock of manure and lettuce leaves.

A state-wise surplus crop residue biomass potential in India is illustrated in Figure 5 [58]. As shown in the Figure, Uttar Pradesh produces the largest amount of surplus residues (40 MT) followed by Maharashtra (31 MT) and Punjab (28 MT), which can be used for bioenergy production. As suggested by the previous literature, the state ranking ranges from the lowest in western Bengal (679 MJ) to the highest in Punjab (16,840 MJ) [58].

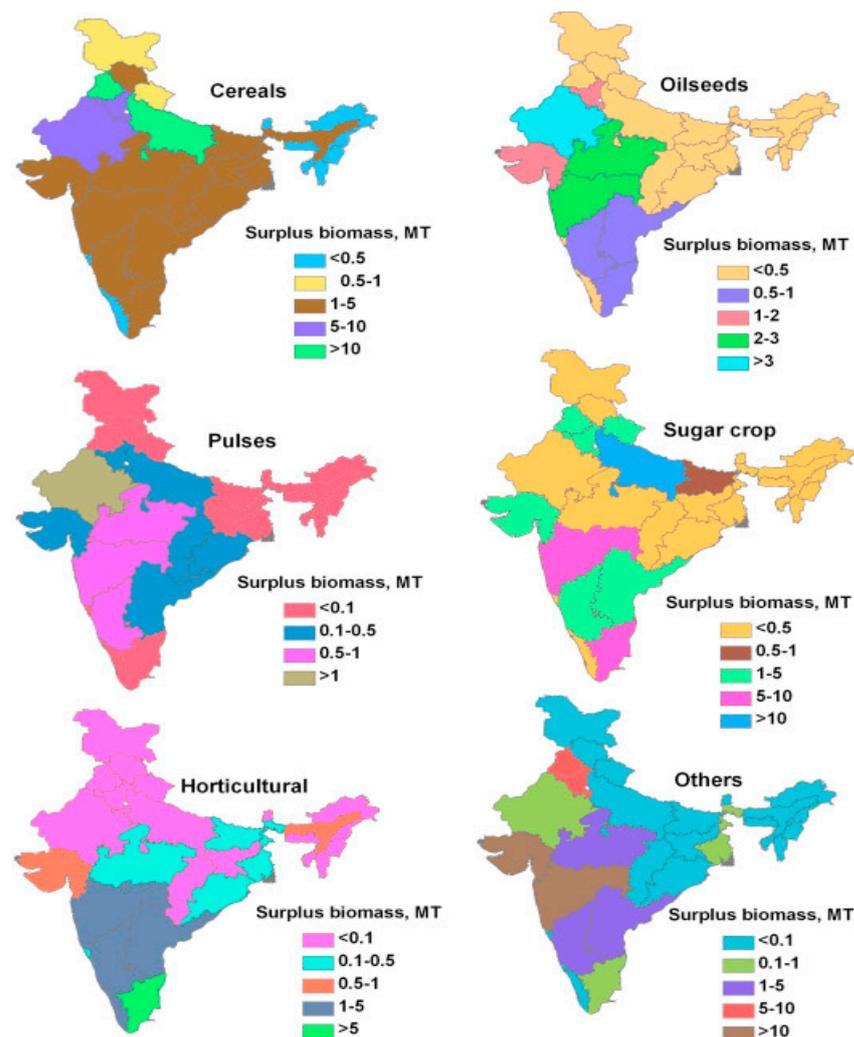


Figure 5. State-wise surplus crop residue biomass potential in India [58].

4.5.1. Case Study of Generation of Electricity from Agricultural Residues

The Jalkheri, Fatehgarh Sahib District thermal plant is the first plant in India using bioenergy sourced from agricultural and forestry residues [5]. The plant uses rice husk, wood chips, and stalks from different crops, such as paddy, wheat, etc. In June 1992, Bharat Heavy Electricals Limited (BHEL) commissioned this plant to use rice straw at the cost of Rs. 47.2 crores from Punjab State Electricity Board (PSEB). Originally, some of the teething problems were investigated by small-scale experiments, and a process of 10 MW was realized by modifications of an existing boiler to accept biological feedstocks like rice husk, wood chips, etc. The plant was leased and run on a sustainable basis in its full capacity of 10 MW. The Punjab Biomass Power, Bermaco Energy, Archean Granites and Gammon Infrastructure Projects Limited in Punjab have also built another 10–15 MW agricultural waste power plant. The plant uses local farm wastes, including rice paw and sugar cane bagasse. The annual total biomass consumption is approximately 120,000 tonnes of biomass obtained from that region. Punjab annually produces approximately 20–25 million tonnes of rice straw, conventionally disposed of by burning. As the technology is developed, this straw waste can now be used to generate electricity. The plant will provide 15,000 farmers with additional income from supplying agricultural waste. The development of this plant will be an important milestone for protecting the environment and creating new jobs and revenues by turning farm waste into bioenergy or green electricity.

In contrast to other biomass to produce bioenergy, using crop residues for large-scale production of bioenergy, there are several challenges to address with respect to both efficiency and economy. For instance, crop residues commonly contain a high content of alkaline ash which would pose operating issues (corrosion and deposition) in boilers for electricity generation. Cost-wise, since the crop residues are bulky, so the feedstock transportation and processing (crushing/pelletizing) costs would be high for centralized large-scale power plants. While it might not make it profitable for large bioenergy plants fuelled by crop residue, it can be adopted as small-scale energy suppliers for households and smaller communities. For instance, digestive biogas can be easily used as a bioenergy source for households.

4.5.2. Shortcomings and Ways to Overcome Them

Although there is a rapidly increasing trend to use wheat, rice husk for energy [59], biomass transport is among the main costs for energy use due to its bulky nature. To address this shortcoming, decentralized energy systems could offer a chance to use biomass to meet local demands for heat and electricity. For instance, rice husk can be used within the rice mill to some extent for energy, thereby reducing the total energy consumption of the entire plant. Rice millers may preferably sell the husk to a power plant operator. Energy suppliers may manage their own rice millers to supply the husk for power generation. A new trend can be that the rice millers themselves produce electricity and then sell electricity to a grid.

As mentioned previously, crop residue's transport costs are a significant constraint in its use as a source of bioenergy. Transport distances farer than 25–50 km are usually not cost-effective, depending on the local infrastructure. For large scale applications, straw can be packed in the field into bales or briquettes, making transportation more viable to the power generation site. The logistics of a supply chain for straw, although complicated, should be established for large-scale applications of crop residues for bioenergy generation.

5. Government Support and Policies

India is a country rich in legislation concerning pollution. Scientists, engineers, environmentalists, and government officials are also aware of the harmful consequences of the practice of stubble burning of agricultural residues on human health, soil, soil fertility and the environment. There are 11 major pollution control laws in India and many different regulations for implementation of these laws [60]. However, in order to avoid the burning of the straw, Section 144 of the Code is called upon by the Government to prohibit paddy burning but is difficult to implement, likely due to insufficient efforts having been made

to increase the awareness of farmers about the serious impacts of stubble burning practices [19]. Nevertheless, the government must play more active roles in implementing all measures or practices planned or suggested by the various government or non-government groups, environmental scientists, and activists at the ground level in order to put an end to this damaging activity of stubble burning.

5.1. Steps Were Taken by the Government

Instead of working on solutions, the government has not even come out with the final version of its much-touted National Clean Air Plan (NCLAP) yet. The present Prime Minister of India, Narendra Modi and his cabinet ministers signed off on the plan in early 2018. The expenditure is far less than the \$600 million per year that National Institution for Transforming India (NITI Aayog), a government policy advisory group, had initially proposed to the government. As per the proposed plan, money will be given to growers in three states bordering Delhi–Punjab, Haryana, and Uttar Pradesh to subsidize 80% of the cost of machinery for extracting crop residues from the fields, so as to avoid burning. Farmers are welcoming the plan since most of them cannot afford the machinery on their own. While this is an important step, it will depend on how quickly the scheme is rolled out at a scale that can make a difference. Other proposals put forward to deal with the stubble include purchasing crop residue by the state electricity company NTPC as a fuel in its coal-fired power stations.

5.2. Potential Future Strategies

- (1) Providing farmers with incentives not to burn crop residue outdoors.
- (2) Facilitation of maximum land cover using agricultural conservation practices.
- (3) Promoting the sustainable, environmentally friendly, and cost-effective use of surplus crop residues for generating bioenergy in power plants.
- (4) Crop residues should be classed as recycled fertilizers, and their use as fertilizers or amendments should receive government support.
- (5) Increasing subsidy rates for farmers who retain and utilize their crop residues.
- (6) There should not be free power as the same policy has resulted in the installation of high-powered tube wells that draw water from deep within the earth.
- (7) Promoting in situ management of crop residues by fast decay by chemical or biological means and mulching by mechanical means.
- (8) Promoting the use of machines such as double disks, zero tillage and happy seeders.
- (9) Valorization of crop residues for useful products, for example, compost, organic manure and biochar as a renewable fuel for power generation or as a soil amendment to improve soil health and fertility.
- (10) Increasing the awareness of farmers on the serious impacts of the open field burning practice.

6. Discussion

Considering the detrimental influence of the lack of proper management practice, the Indian Government should advise farmers on alternative solutions to open field burning of crop residues, in order to reduce the toxic clouds over Delhi at the very least. For instance, to stop burning stubble altogether, many farmers from Punjab are pleased with the Happy Seeder, a system that can seed crops while minimizing stubble burning.

In fact, none of the alternative methods to open burning are perfect, but it is still noteworthy to implement them in a proper way considering geographic location, transportation, economic feasibility, etc.

When used as feedstock for livestock, bioenergy, and industrial raw materials, crop residues will be a bioresource of a higher economic value. However, in some regions complications in crop residue management remain diverse. The government should promote and provide alternatives in order to stop stubble burning, but simply legally prohibiting incineration of crop residues may not be successful because farmers do not have proper

information about its consequences on soil, human, and animal health. Although farmers are aware of the adverse effects of paddy straw on the farm, these are limited by the lack of economically viable and acceptable machinery and options for paddy residue disposal. Nevertheless, alternatives should be promoted, such as gasification of crop residues for fueling boilers, transformation into briquettes, etc. Other alternative management methods such as using Happy Seeder, zero-till machine, dual disc coulters, straw choppers, and agricultural conservation activities are also promising, as they could reduce the stubble burning in the rotation of rice-wheat. Encouraging organic recycling practices will reduce air pollution and convert wastes into resources, while machinery availability is currently the major obstacle for this management method and the other obstacle is lack of crop residue-fueled power plants.

Very recently, D'Adamo et al. [61,62] compared the status and performance of the EU countries in the bio-economy and circular economy and assessed them using a new socio-economic indicator for the bio-economy (SEIB), and performed a techno-economic analysis on integration of an effective management of renewable energy and municipal organic wastes. They demonstrated that the transformation of municipal organic waste into clean bio-energy, particularly through the generation of bio-methane, would close the loop and help societies make progress toward becoming circular economies, which can contribute to decarbonizing the transport sector. We believe that the results of their analyses may be applicable not only for utilization of municipal organic wastes but also agricultural wastes that are currently under-utilized but being disposed of by stubble burning in India as well as in many other Asian countries.

Although many alternative treatment methods have been developed and proven to be helpful for preventing the mismanagement of crop residues to some extent, the following practices are still recommended: (i) social awareness needs to be strengthened regarding the detrimental effects of open burning of agricultural residue; (ii) conservation agriculture techniques to maximize land cover need to be implemented; (iii) the conversion of crop residue into biofuels, thereby enhancing air and soil quality and halting greenhouse gas emissions, needs to be promoted; (iv) methods of in situ decomposition of crop residue by using chemical, biological, and mechanical approaches should be developed.

7. Conclusions

Undoubtedly, the lack of proper management of abundant crop residue has had an adverse influence on the environment and human health not only in India but also in the world. Agricultural field burning has created many environmental problems, particularly causing a threat to the soil fertility and the emission of toxic gases such as CO₂, CO, SO₂, PM_{2.5} and PM₁₀. Consequently, a variety of alternative approaches should be considered as substitutes for open field burning, e.g., in situ incorporation, mulching, composting, Happy Seeder machines, and bioenergy use. In conclusion, this article provides an overall understanding of the adverse impacts of open burning of crop residues in terms of ecology and environment and more promising alternative management practices for the crop residues, which, if widely employed, could not only reduce the environmental impacts of crop residue management, but generate additional value for the agricultural sector globally.

Author Contributions: Conceptualization, G.K.P. and C.C.X.; formal analysis, G.K.P.; investigation, G.K.P.; resources, G.K.P. and C.C.X.; writing—original draft preparation G.K.P.; writing—review and editing, C.C.X., K.T.V.R., Y.H.; supervision, C.C.X.; project administration, C.C.X.; funding acquisition, C.C.X. All authors have read and agreed to the published version of the manuscript.

Funding: Natural Sciences and Engineering Research Council of Canada (NSERC), DG Grant.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: This work was supported through the Biomass Canada Cluster (BMC) that is funded through Agriculture and Agri-Food Canada's AgriScience Program and industry partners. The authors also acknowledge the financial support from Natural Sciences and Engineering Research Council of Canada (NSERC) through the Discovery Grant awarded to C. Xu.

Conflicts of Interest: The authors declare no conflict of interest.

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