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TOPICAL REVIEW

Rice residue burning in Northern India: an assessment of environmental concerns and potential solutions – a review

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Abstract

Environmental alarms like climate change and rising air pollution levels in north India, particularly in the Delhi National Capital Region (NCR), draw attention to the severe issue of Rice straw burning. Straw burning is the common practice in Punjab and Haryana's Indo-Gangetic plains. Large-scale burning of residues (straw and stubble) is a severe problem that emits Green House Gases (GHGs) while polluting the air, posing health problems, and eliminating micronutrients from burned-out field. Residue management has been a problem for the paddy farmers and as time changes, it is necessary to update their practices. For the disposal of rice residue, farmers are constrained by an insufficient technology base and a lack of viable economic solutions. Technical solutions are available, classified mainly as on-site (*in situ*) and off-site (*ex situ*) solutions, the *in situ* solution includes a variety of machines that can be used to incorporate or mulch residue efficiently. While *ex situ* management allow collecting the residue from field for various applications such as energy production, briquetting, composting, paper and cardboard making, and for mushroom cultivation. Farmers in North India are not aware of the prolific alternatives for managing stubble and, therefore, consider burning as the best option. Therefore, extensive awareness programs are needed to inform farmers about economic options and the effects of stubble burning. Zero till drill, happy seeder and super Straw Management System (SMS) are recommended for the farmers, and need to be supplied in sufficient quantity to evade residue burning in these regions. Meanwhile, alternative technology for straw management constitutes an active area of research, area-specific and crop-specific applications need to be evolved. All stakeholders i.e., farmers, researchers, extension agents and policy makers need to be engaged in understanding and harnessing the full potential of using crop residues with conservation agriculture for sustainability and resilience of Indian agriculture.

1. Introduction

Rice is the world's major crop and a staple diet for more than 50% of the population. Globally, rice is cultivated over 158 million hectares (Mha) with an annual yield of around 700 million tonnes (Mt) to meet the grain demand (Papademetriou 2000). In Asia, 640 Mt of rice is produced from 143 Mha of land, accounting for over 90% of global rice production (Ministry of Agriculture and Framers Welfare 2021). India represents the largest area (44.6 Mha) under rice cultivation and is second in rice production succeeding China. Rice is the essential diet of 65% of the total population in India. It constitutes 52% of the food grain production and 55% of the total cereal production (Hira 2015). However, after 1960, the acreage was significantly increased and a rice-wheat farming system was introduced in the semi-arid climatic conditions of the North West Indo-Gangetic plains, primarily in Haryana and Punjab. In the last four decades, these states have contributed about 40% and 30% of

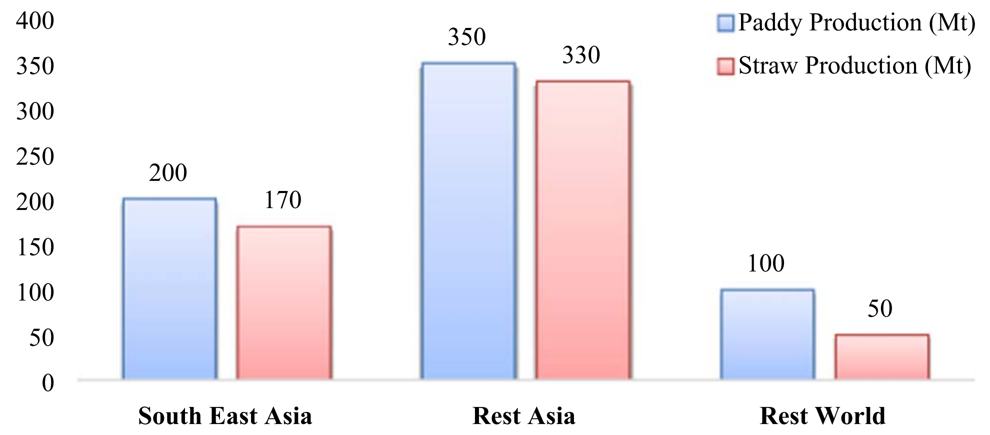

Figure 1. Status of rice and straw production in the south east Asia (SAE), rest Asia and world (2019). Adapted from [Van Hung 2020] with permission from Springer Nature, 2020.

Table 1. Grain, residue and surplus residue production from major crops (India 2017–18).

Major crop	Annual production (Mt)	Gross residue generation (Mt)
Rice	112.91	191.94
Wheat	99.7	179.46
Sugarcane	353.22	141.28
Maize	26	59.8
Cotton	34.32	130.43
Jute & Mesta	10.5	21
Pulses	25.32	50.46

Courtesy (SAARC 2019).

the central stock of wheat and rice, respectively, becoming the most predominant contributors to the nation's food security (Chauhan *et al* 2012, Lohan *et al* 2015). In 2014-15, the total food grain outputs of Punjab and Haryana increased to 37.46 Mt and 16.75 Mt, respectively, with productivities of 4.1 t ha^{-1} and 3.7 t ha^{-1}, respectively (Lohan *et al* 2017).

Every year, around 800 Mt of rice straw and residue is produced in Asian fields (Sarkar and Aikat 2013). India contributes 25% of total rice straw produced in Asia (Bhuvaneshwari *et al* 2019), figure 1 represents the status of rice and straw production in Asia and the world. The annual gross crop residue production of India is 371 Mt, wherein wheat and rice residues constitute 27%–36% and 51%–57%, respectively (Lohan *et al* 2017, Venkatramanan *et al* 2021) (table 1). Generally, rice is harvested using combine harvesters, which leave a trail of loose residues and straw that interferes with the land preparation and sowing/planting of the next crop. This loose residue and straw is considered to be a poor feed for cattle owing to its high silica content. The removal and processing of rice straw should be ideally accomplished within the 10–15 days that are available between rice harvesting and sowing of next crop (Thakur *et al* 2018). Hence, the management of straw and residue is a significant challenge for farmers (Gupta 2019). To circumvent this issue, farmers consequently tend to burn the rice residue, which not only leads to a loss of biomass, but also causes environmental pollution (Thakur *et al* 2018, Van Hung 2020).

Almost 80% of the rice crop has mechanised harvesting in North-West (NW) India (Abdurrahman *et al* 2020). Straw burning releases particulate pollutants and greenhouse gases, substantially contributing to air pollution and posing as a severe human health and environmental hazard (Awasthi *et al* 2010). In megacities, the substantial consumption of energy in various forms (e.g. fossil fuels and biofuels) contributes to high levels of air pollution (Butler *et al* 2008, Ravindra *et al* 2015). After industrial and vehicular emissions, straw burning is the third most significant source of air pollution in many parts of the world (Gurjar *et al* 2016). As a result, the residing population of Southeast Asia is exposed to excessive levels of air pollution. According to the latest reports (World Air Quality Report 2020), of the top 40 most polluted cities in the world, 37 belong to South Asia. Owing to the lack of alternative residue management practices, around 70%–80% of the crop residue is burnt in the open fields, causing greenhouse gas (GHG) emissions and air pollution, which is detrimental to humans,

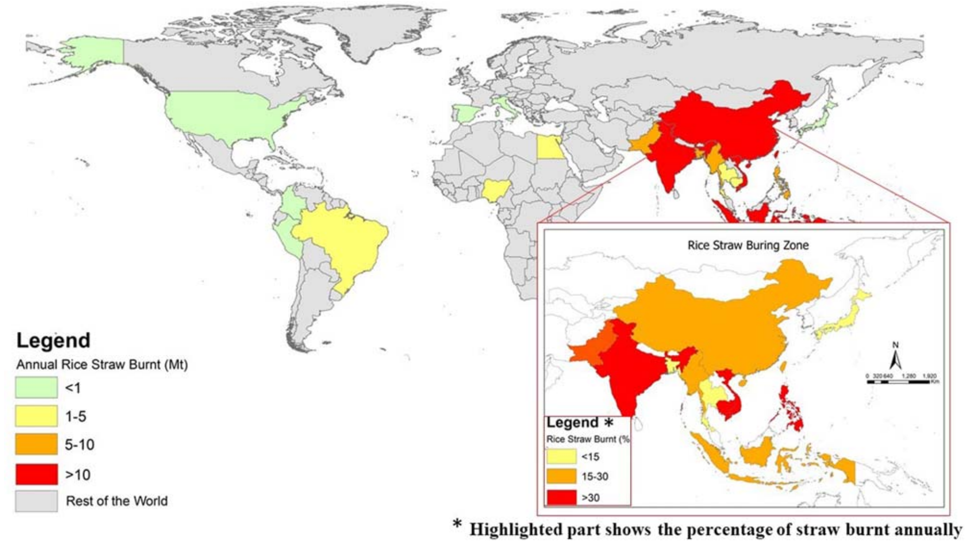

Figure 2. Status of rice straw burning in the world (*Source:* Singh *et al* 2021).

Table 2. Major crop residue burnt (Mt) in south Asian countries.

Crop	India	Pakistan	Bangladesh	Shri Lanka	Nepal
Rice	23630.74	1521.05	6262.27	578.27	749.6
Wheat	12092	3657.23	178	3657.23	298.32
Sugarcane	3217.5	735.03	63.93	10.88	52.6
Maize	10200	1334	334.97	72.39	891.58
Total	49140.23	7247.32	6839.18	661.55	1992.17

Courtesy (SAARC 2019).

animals, and the environment (Lohan *et al* 2017, Chaudhary *et al* 2019, Kumar *et al* 2019, Abdurrahman *et al* 2020). Asian countries including China, India, Indonesia, Bangladesh, Vietnam, Thailand, and Myanmar, conjointly contribute 80% of the global rice production. Figure 2 represents the major rice-producing countries across the world, and highlights the estimated quantity of straw burnt in each country annually. Various countries including China are now identifying and demarcating residue-burning areas using modern technologies such as remote sensing. Since no compiled global data is available, this approach has provided an approximate estimate based on independent studies conducted by researchers, scientists, and academicians (Singh *et al* 2020). Further, majority of the straw burning takes place in Asian countries like China, India, Vietnam, Pakistan, and Indonesia (figure 2: inset). Nevertheless, the extent and severity of burning activities in the other continents are far from negligible, and the problem is persistent, as apparent every year during the rice harvest period. Thus, rice straw management is a serious global issue that is not limited to Asian countries (Singh *et al* 2018).

The northern states of India, such as Punjab, Haryana, and New Delhi are severely afflicted with this problem. Table 2 shows the status of major crop residues burnt in South Asian countries during the year 2016.

In the Indian subcontinent, rice straw burning is mostly performed between October to November, which coincides with the beginning of winter every year. This period often displays the occurrence of dense fog, which combines with the high amounts of smoke generated from straw burning and results in smog. Consequently, the northern states witness a dense layer of haze during this period (Singh and Kaskaouits 2014). The NASA satellite images clearly reveal the burning fields and smog in Punjab, Haryana, Delhi, and several regions of Pakistan and Nepal (figure 3). In a recent study, the atmospheric particulate matter levels in Delhi have been found to have increased 20 fold compared to the levels recommended as safe by the World Health Organization (Manisalidis *et al* 2020). Consequently, air pollution arising from the burning of crop residue in Northern India is causing severe health hazards to the residents.

Several studies have been carried out by different researchers on emissions and air quality through rice straw burning in NW India. The number of such publications is increasing because of the increased interest of the scientific community in environment-related problems (Chakrabarti *et al* 2019, Abdurrahman *et al* 2020). There

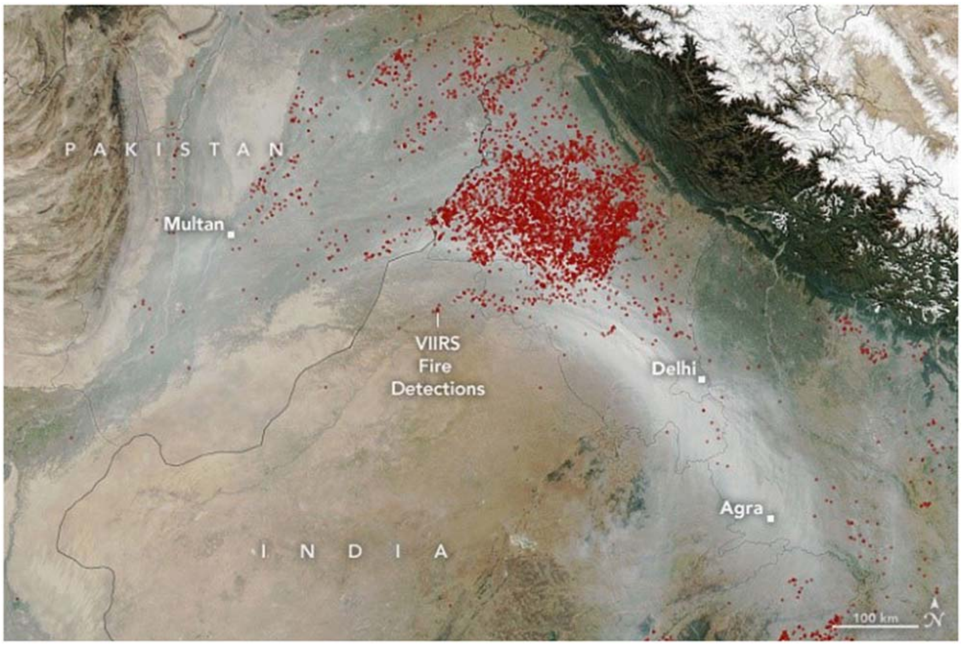

Figure 3. Crop residue burning image captured by NASA satellite *(Courtesy: NASA 2021)*. Satellite image published on the website of NASA Earth observatory on Nov 11, 2021.

Table 3. Rice straw burning in Northern region of India.

Particular	Punjab	Haryana	Western UP	Total
The rice cultivation zone (Mha)	2.9	1	1.3	5.2
Area sown in rice wheat system (Mha)	2.6	1.3	0.7	4.6
Generation of rice straw (Mt)	22	7.5	4.4	33.9
Burning of rice residue (Mt)	18.7	3	1.3	23

(Source: NAAS 2017).

are several studies, which focus on rice straw burning (Mishra *et al* 2021, Venkatramanan *et al* 2021) but there is a need to critically review and analyse the current state of understanding of the straw burning problem and their potential solutions in NW India. To identify the research needs and data gap, the present study appraises the current rice residue disposal methods, the effect of burning, and available machinery for residue management in India. The assessment is exercised using scientific data available in various journal articles, reports, and online sources.

In this paper, an attempt has been made to discuss the implications of stubble burning in NW states of India and methods to mitigate these practices. This review comprehensively covers the current status of stubble burning in India, including; (1) the generation and burning of crop residue (2) consequences of rice stubble burning (3) various aspects of managing stubble (4) available machinery for managing rice residue and (5) the alternative techniques for managing crop stubbles.

2. Prevalent methods of crop residue disposal

The highly mechanized rice-wheat cropping system prevalent in Northern India leads to a large amount of straw left over in the field after harvesting. Hence farmer opts burning as a convenient disposal method of the rice straw. According to a report (table 3) western Uttar Pradesh produces 4.4 Mt of unused rice residue from an area of 1.3 Mha, Haryana produces 7.5 Mt from 1 Mha area, and Punjab produces 22 Mt from 2.9 Mha area, which is intended for burning by the farmers to vacate the field (NAAS 2017, Pathak *et al* 2021).

Farmers generally rely on various techniques for disposing off crop residues, which includes using straw as cattle bedding, animal fodder, thatching for rural home roofs, soil mulching, incorporation, fuel for domestic and industrial use (figure 4). It is important to note that wheat straw may be utilized to feed domestic animals and does not require any specific disposal method, while rice straw is a poor feed for livestock due to its high

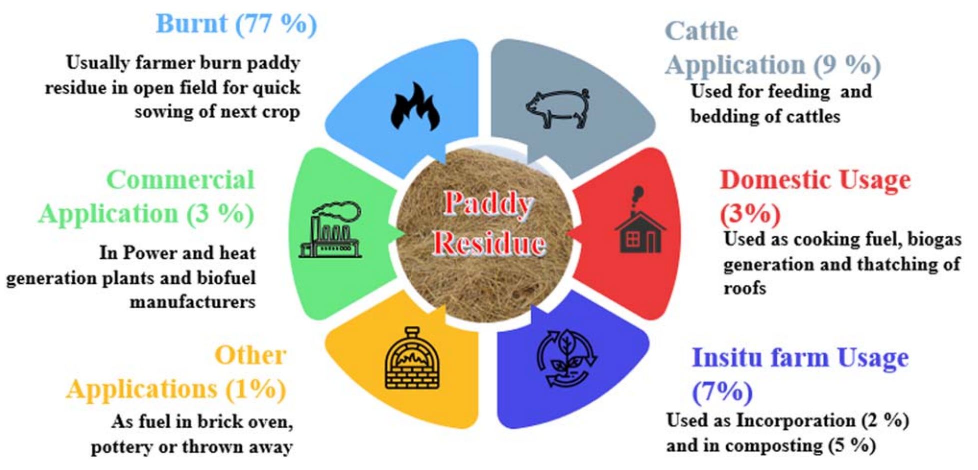

Figure 4. Prevalent methods of crop residue disposal (*Courtesy:* SAARC 2019).

silica content, and requires various management/disposal methods (Thakur *et al* 2018). However, the limited period between rice harvesting and wheat sowing usually hampers the implementation of the aforementioned straw disposal strategies. To overcome this issue, novel methods are being adopted for the utilization and disposal of residues, such as converting into biofuel or natural fertilizers (through composting), and using for mushroom production in tropical areas. Additionally, the residues can be used in the fields to enhance the biological and chemical properties of the soil (Hanafi *et al* 2018, Sayara *et al* 2020). However, these methods are still being optimized and have been implemented at a small scale only.

Rice straw burning is most common in combine-harvested fields, because loose straw and standing stubbles (25–30 cm height) remain in the field after the operation of the harvester. Burning of straw is assumed to be a simple, inexpensive, and speedy technique for residue management, which is regularly adopted by farmers to clear the field for the sowing of next crop (Singh *et al* 2014). Additionally, burning rice residue can reduce the number of soil-borne pathogens and insect pests, as inoculum from rice straw biomass reduces reinfection (Kaur *et al* 2022). Burning also helps to reduce nitrogen (N) tie-up, as microbes decompose the straw residue, which results in nutrient release from the combusting straw. Further, burning can result in loss of most of the N and sulphur (S) content in the residue. However, the most important reason behind stubble burning is the economic benefit (Pathak *et al* 2014). In recent years, there have been improvements in pest management options, so residue burning is no longer necessary for this purpose.

3. Effects of rice straw burning

3.1. Effects of rice straw burning on environment

Approximately 17.6% of rice straw is burnt within three to four weeks during October and November each year in NW India (Yadav 2019). Rice straw burning is a predominant source of aerosol particles, including the coarse dust particles (PM_{10}) and fine particles ($PM_{2.5}$), affecting the regional air quality and overall radiation budget of the Earth (Sahai *et al* 2011). It is estimated that the burning of crop residues releases about 627 kilotonnes (Kt) of PM_{10} and 4677 Kt of carbon monoxide to the atmosphere annually in India (Datta *et al* 2020). Moreover, the burning of crop residues emits 26.1 Mt of carbon and 0.35 Mt of nitrogen each year (Sahai *et al* 2011). According to previous studies, large volumes of farm residue are burned *in situ*, posing a substantial detrimental impact on the local air quality (Bhuvaneshwari *et al* 2019, Saxena *et al* 2021). The rice straw burning causes environmental pollution through the discharge of many gases such as CO_2 (70%), CH_4 (0.66%), CO (7%), N_2O (2.09%), and ash (Pathak *et al* 2021). Due to this, in the National Capital Region (NCR) the air quality index(AQI) often reaches severe levels due to harsh pollution. Figure 5 showing some major cities of the India and there respective air quality index in the November 2019.

3.2. Effects of rice straw burning on human health

The burning of straw in open fields releases a range of air pollutants known to impact the human health negatively (Sharma *et al* 2010, Ghosh *et al* 2019). The crucial pollutant from a human health perspective is particulate matter (coarse particles 2.5–10 microns and fine particles < 2.5 microns in size), the impacts of which are mainly local and depend on concentration, population density, extent of exposure, and weather (Saggu *et al* 2018). The amount of particulate matter emitted from burning the crop residues in and around

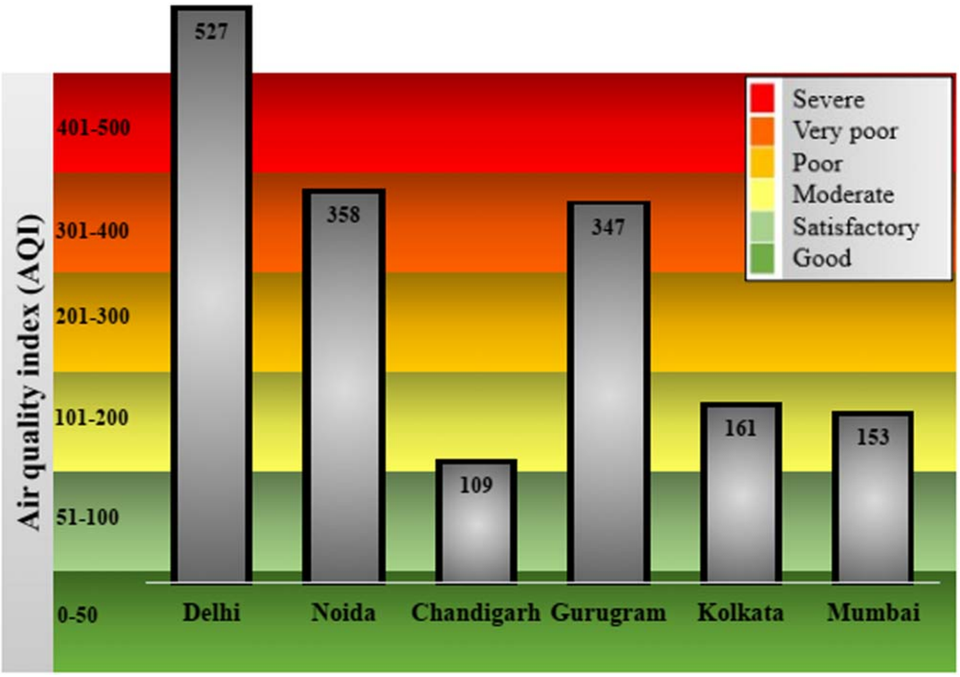

Figure 5. Air Quality Index (AQI) of different cities in India (Source: SAARC 2019).

Delhi is 17 times higher than that from all other sources such as vehicle emissions and garbage-burning industries (Bhuvaneshwari *et al* 2019). Females, infants, and individuals with serious diseases are particularly affected by the harmful implications of stubble-burning pollution. Local air pollutants that result from biomass burning include carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NOx), ammonia (NH_3), sulphur dioxide (SO_2), carcinogens such as polycyclic aromatic hydrocarbons (PAHs), and several other toxic compounds (Gheorghe and Ion 2011). Additional adverse health consequences of straw burning are eye irritation, corneal opacity, and skin illnesses that occur off-site (Singh 2018). Among various sources of outdoor air pollution, crop residue burning is estimated to be responsible for approximately 66200 deaths in 2015 in India (Chakrabarti *et al* 2019, Kant *et al* 2022). Burning residue also enhances ozone pollution in the troposphere (Kumar *et al* 2015).

3.3. Effects of rice straw burning on soil health

Rice straw burning negatively impacts soil health by deteriorating the soil properties. Agricultural residue burning has been reported to pose detrimental effects on plant and soil ecology. Rice residue burning increases the soil temperature considerably. An increase in soil temperature to 33.8 °C–42.2 °C was noted at the soil depth of approximately 1 cm (Gupta *et al* 2011). The increased temperature of soil removes 23%–73% of the nitrogen in different forms from the soil, resulting in rapid changes in the C:N ratio in the topmost layers of soil (Singh *et al* 2010, Kumar *et al* 2015). At the same time, carbon is emitted into the atmosphere in the form of CO_2, whereas nitrogen is transformed into nitrate. These processes eliminate around 824 thousand metric tonnes of nitrogen, phosphorous, and potassium (NPK) elements from the soil (Gupta *et al* 2004). According to Jat *et al* 2013, rice straw burning leads to a cumulative loss of 80 kg ha^{-1} nitrogen, 184 kg ha^{-1} phosphorus, and 109 kg ha^{-1} potassium. The incineration of crop residues resulted in a loss of 3.85 Mt soil organic carbon, 59 Kt nitrogen, 20 Kt phosphorus, and 34 Kt potassium specifically in Punjab (Gupta *et al* 2004, Kumar *et al* 2015). Consequently, rice waste burning in the field leads to poor soil health, resulting in lower yields (El-Sobky 2017, Abdurrahman *et al* 2020).

Burning also destroys the microflora and fauna of the soil, resulting in the loss of microbial biodiversity (Mehta *et al* 2013). The beneficial microbial population of the soil declines till a depth of 2.5 cm (Gupta *et al* 2004, Singh *et al* 2010) after residue burning. Figure 6 represents the major adverse effects of straw burning.

3.4. Effects of rice straw burning on agricultural productivity

Convincing empirical evidence reveals that air pollution caused by rice residue burning substantially affects food production (Abdurrahman *et al* 2020). According to a recent independent study, stubble burning in Punjab and Haryana has contributed to a decline in agricultural productivity (Abdurrahman *et al* 2020). The study illustrates

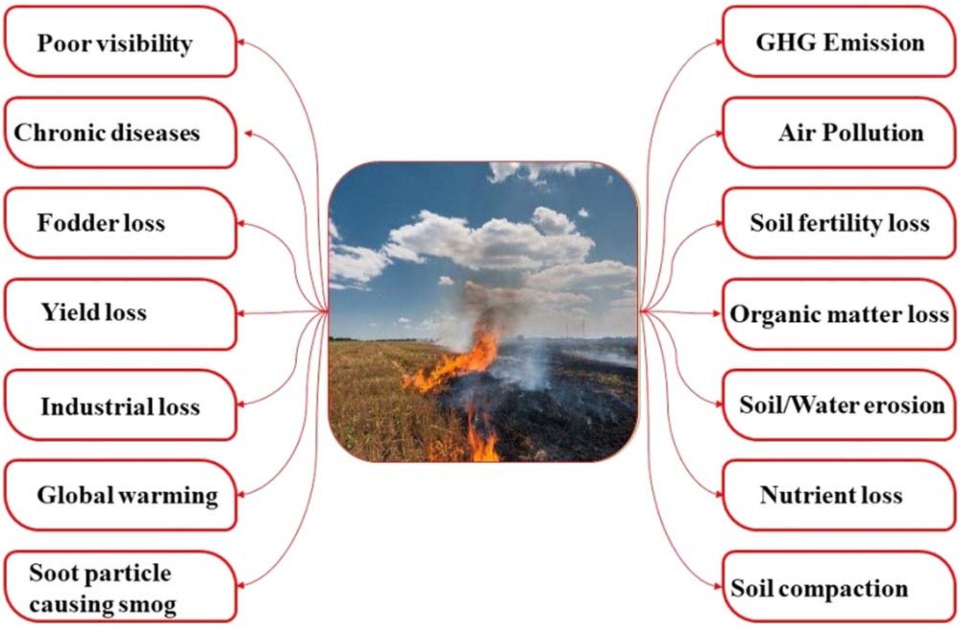

Figure 6. Adverse effects of straw burning in open field.

elevated levels of fine particulate matter and NO_2 at the end of the Kharif season (monsoon) in Punjab and Haryana due to extensive rice biomass burning.

Air pollution through rice residue burning may pose direct or indirect effects on agricultural productivity. Direct effects entail injury to foliage and grains, or assimilation of toxic heavy metals in biomass. In addition, exposure to excess nitrogen oxides (NO_x) can damage the tissue of plants and cause discoloration, while SO_2 emissions results in acid rain, which have severe detrimental effects on soil and causes lower productivity (Augustaitis *et al* 2010). Prolonged exposure of plants to particulate pollutants may lead to chlorosis or bifacial necrosis (Ghosh *et al* 2019). On the other hand, some studies indicate that indirect effects of air pollution caused by stubble burning include the emergence of favourable conditions for the growth of pests and pathogens. For example, the growth of aphid pests is facilitated by high concentrations of SO_2 and O_2 (Ghosh *et al* 2019). Furthermore, elevated surface levels of ozone are also considered a major cause of declined crop productivity for wheat, rice, cotton, and soybeans in India. The volatile organic compounds (VOCs) and NO_x released from stubble burning react in the presence of solar radiation to form ground level ozone. Ground level ozone penetrates the plants, destroys their leaves, and disrupts their metabolism. Ozone has been shown to cause serious negative effects on crops in the northern parts of India, particularly in context of the performance of wheat and soy (Sharma *et al* 2019). Hence, stubble burning negatively impacts agricultural productivity; and appropriate measures are required to overcome its effects, which would improve the agricultural productivity necessary to meet the increasing food demand.

4. Farmer's opinion on rice straw burning

Farmers adopt crop residue burning because of two main reasons: low calorific value of straw and shortage of labour. In addition to being an inexpensive strategy, residue burning serves as a suitable pest management procedure (Dobermann and Witt 2000) and facilitates the reduction of insects resulting from inoculum reinjection into the straw biomass (Haysa *et al* 2005). Thus, burning provides an efficient alternative to control weeds, insects, diseases, and pests, both by direct elimination or by modifying their habitat. Some farmers have expressed that poor storage facilities and lack of market utilities of rice residue motivates them to burn the stubble in the field (Lohan *et al* 2017). Others state that *in situ* burning of straw saves the tractor fuel cost incurred when stubble remnants are processed mechanically. Burning offers a time-saving approach to clear the field and accelerates seed bed preparation for sowing of the successive crop. On the other hand, collection of straw or incorporation within soil is perceived to be a highly time consuming and expensive alternative. Moreover, farmers face significant challenges in obtaining cheap labour during peak harvesting seasons (Kumar *et al* 2019) for these practices. During this period, there is minimal opportunity for efficient harvesting and the hourly charges of local labour are very high due to the high demand. These reasons compel the farmers to burn the residue and avoid high expenditure for labour or rentals for mechanized straw management options.

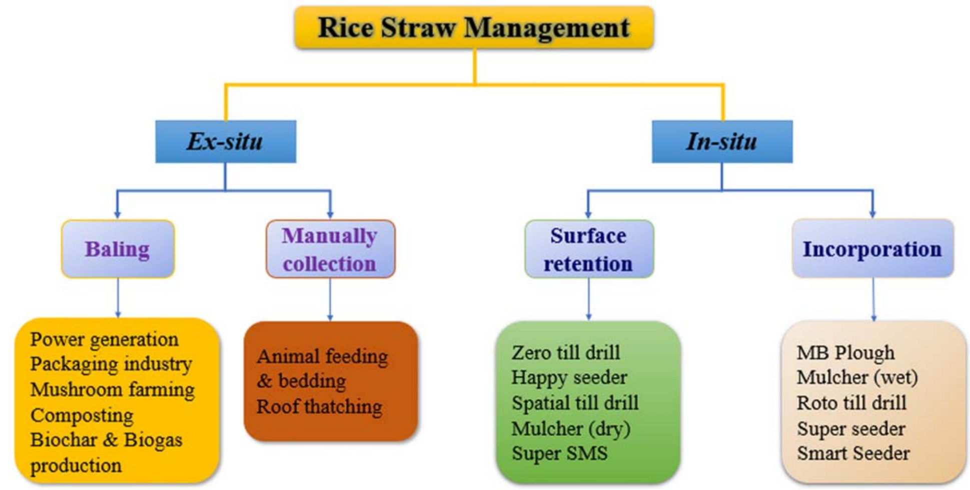

Figure 7. Rice straw management techniques.

5. Rice straw management techniques

It is essential to restrict the open field burning of rice residue and employ alternative management strategies in time to ensure sowing of the subsequent crop. In order to select and implement a suitable rice residue management method, it is necessary to understand the temporary and permanent impact of various practices, and to develop advanced, cost-efficient, and sustainable residue management technologies (Porichha *et al* 2021). The suitability of crop residue management method should be evaluated based on productivity and environmental impact. The best management approach is to address the problem at a fundamental level by adopting precautionary and preventive techniques. About 10–15 days are available between rice harvesting and sowing of wheat, which coincide with the period of manual labour shortage, exacerbating the issue. Therefore, a mechanized solution may be adopted by farmers for managing the rice residue effectively and preparing the field for successive crops (Bhatt *et al* 2016). Using various available technologies (figure 7), rice straw can be managed off-field (*ex situ*) or in the field (*in situ*). Different factors are taken into consideration when farmers choose their residue management method, such as the economics, availability of implements, and requisite implementation time.

5.1. *Ex-situ* management

Ex-situ management of crop residue involves the off-field solutions for removing or utilizing rice straw, such as by packing them into bales, and using them as a raw material for energy generation; packaging material for fruit, vegetables, and glassware; for mushroom cultivation, and as bedding for cattle. This approach aims to remove crop residue and prepare the field for another crop. Ex-situ management increases the efficient utilization and value addition of rural biomass wastes, including derivation of biomass-based energy, and use for feedstock supply (Lee *et al* 2019, Kasinath *et al* 2021). Such operations at the farm level can also generate rural employment opportunities and provide additional income to the farming community. In particular, the custom hiring of the tractor-operated baler and rake machines has a substantial potential to encourage on-farm employment and rural income (Maski 2019).

5.1.1. Benefits of ex situ *management*

Globally, an overall increase has been recorded in farmer income after the adaptation of excess residue removal and its utilization as feedstock for power generation (Suardi *et al* 2019). The Indian government has been recommending various technologies for the *ex situ* utilization of crop residues packaged as briquettes or pellets via pyrolysis (biochar), bio-methanation (biogas), conversion to biofuels such as bio-compressed natural gas and bio-diesel (CII and NITI Aayog 2018). Based on a recent report, rice residue may be utilized for power generation as a fuel combination consisting of a mixture of coal and 7% biomass pellets, as shown by the National Thermal Power Corporation Limited (NTPC). This strategy has been adopted by many countries for electricity generation and other heating requirements across various industries, due to the associated economic and environmental advantages (Demirbas 2003, Hansson *et al* 2009, Sullivan and Meijer 2010). The following section tries to caver the machinery and application of *ex situ* rice straw management.

5.1.2. Rakers and balers

Ex-situ management of straw primarily involves the use of two machineries: rakers and balers. Rakers are used for making windrows of harvested stubbles. Straw baler collects the straw and compress into bales. To increase the capacity of the straw baler, raker is operated to arrange the residue in the form of rows after the operation of shrub master. This reduces the number of passes for which the baler has to be operated to collect the straw for baling, thus increasing its field capacity (Singh *et al* 2017). With the help of balers, rice straw can be bundled in bales of different sizes and shapes. Rice straw collected using the straw baler is easily transported to far-off areas where it may be used in boilers, for manufacturing packaging material and cardboards, and for energy generation in the form of biogas and electricity (Mangaraj and Kulkarni 2011). Promoting the use of straw balers may facilitate the establishment of fodder banks at a large scale, which may be used for feeding animal population during wheat straw shortage, such as in case of natural extremities i.e. flood or drought. Even though rice straw is a poor source of nutrition, it is shown to be palatable after different processing methods (Insightsias 2021), such as treating rice straw bales with urea or molasses. The potential value of rice straw as fodder is currently being explored by government ventures (The Tribune 2021, and Insightsias 2021), and warrants further investigation. In addition, the activity of balers improves the soil and environmental health by means of avoiding its burning (Balingbing *et al* 2020). A 45 fold reduction in gaseous emissions is estimated with the use of baler to collect rice straw, instead of burning (Pal *et al* 2019). Hence, straw baling in the combine harvested rice field is considered a technically and economically viable, and environment-friendly option for sustainable management of straw for animal feed, biofuel and other industrial uses.

5.1.3. Briquetting and pelleting

Briquetting increases the density of the loose agricultural waste into a compact form. During the briquetting process, the bulk density of rice residue may increase 4–10 times using a hydraulic piston or screw mechanism. Studies indicate that the calorific value of rice straw in this form ranges from 3400 to 3600 Kcal kg^{-1} (Pachpor *et al* 2019). Therefore, it may be used for boilers, furnaces, and other domestic purposes like heating and cooking. Pellets are preferred in thermal power plants because of their small size and higher binding strength as compare to briquettes. Furthermore, they are easily combustible along with coal, the common fuel in power plants. Pellets are available in several types and grades, i.e. as fuels for electric power plants, other industrial uses, homes, and other applications.

5.1.4. Energy generation

The use of agricultural residues as feedstock for biomass-based energy generation has been gaining popularity in many countries. Several studies have been undertaken in many parts of India, which focus on agricultural wastes such as rice straw as a possible feedstock for biomass based energy (Moazzem *et al* 2012, Allen *et al* 2020). Due to such a substantial crop production, agricultural residues could be a significant biomass-based energy source in countries like India (Popp *et al* 2014, Mohammed *et al* 2018). Although electricity generation with biomass sources is desirable, seven biomass power stations have been built in Punjab so far, while additional six are underway. However, these biomass power sources can cumulatively absorb only around 10% of the state's rice waste. A rice residue based power plant of 12 MW capacities that utilizes about 0.12 Mt of residue per year requires an ample dumping space (NAAS 2017). Furthermore, these biomass power stations generate a large volume of slag, giving rise to a significant challenge of the disposal. Currently, the generated waste is being disposed of in landfills or depressions formed by brick kilns, and further research is needed to provide suitable alternatives. However, rice residues can serve as potential fuel in power plants, which would minimize the air pollution resulting from in-field crop residue burning as well as the carbon footprint compared to coal-based power plants.

5.1.5. Biogas production

Since rice straw is a cheap and renewable resource, it can be efficiently used as a feedstock for biogas generation (Saini *et al* 2015, Abdurrahman *et al* 2020). Rice straw is majorly composed of lignocellulose and is therefore rich in organic matter, constituting cellulose (25.4%–35.5%), hemi-cellulose (32.3%–37.1%), and lignin (6.4%–10.4%) (Jin and Chen 2006, Kaur and Phutela 2016). Recent studies have reported biogas production can be achieved by co-digestion of animal wastes with rice straw. Biogas production is one of the key technologies for sustainable utilization of rice straw as a renewable energy source (Lei *et al* 2010). However, anaerobic digestion of rice straw cannot be achieved via conventional processes involved in biogas production owing to the floating characteristics of straw in water. The Punjab Agricultural University, Ludhiana has developed a batch-type biogas system that can utilize agricultural residue and cow manure as feed. This plant can run for 3–4 months, circumventing the time-consuming process of a regular addition of cow manure (Singh *et al* 2020). This technology may be a potential alternative of open environment straw burning for individual or a group of farmers, or even beneficial as a community based biogas plant for power needs at village level.

5.1.6. Straw as biochar

Biochar is produced by burning organic substances like rice residue with no or very little oxygen, in a process similar to charcoal production. Biochar can be used as fuel source and fertilizer. When rice straw is burned in open air, a large amount of oxygen is consumed, whereas a large amount of carbon dioxide is released. However, the carbon content of biomass is unaffected by its combustion in the absence of oxygen. As a result, converting straw to biochar instead of ash reduces the number and quantity of greenhouse gases emitted into the atmosphere, and the preserved carbon is expected to last for several years in the soil (Wu *et al* 2012). Biochar has gained widespread popularity because of its potential use for soil amendment to improve the nutritional quality of soil (Silber *et al* 2010) by sequestering carbon (Lal 2004) and enhancing the immobilization of potentially hazardous chemicals (Borchard *et al* 2012). Biochar has a strong sorption capacity to many contaminants (including organics and inorganics) (Liang *et al* 2021). Therefore, application of rice straw based biochar could be a potential management strategy for utilizing rice residue and treating contaminated soil to achieve agricultural sustainability.

5.1.7. Mushroom production

Mushroom cultivation is a viable agribusiness venture extracting nourishment from wheat and rice crop residues, while providing an environmentally sustainable alternative for agricultural waste management. Rice straw can be effectively used to cultivate mushrooms (*Volvariella volvacea*) due to a short incubation period and convenient application. Rice straw can support the production of 50–100 kg mushrooms per tonne of rice biomass. The additional advantages of mushroom cultivation with rice straw are shorter life cycle, high growth rate, ease of cultivation, superior texture and aroma, and high acceptability at the consumer level (Ahlavat and Arora 2016). This application further provides a sustainable option for avoiding rice straw incineration in the field by enhancing the value of rice cultivation and reducing environmental damage (Ngan *et al* 2020).

5.1.8. Problems associated with ex situ *management*

Currently, the *ex situ* management practices consume less than 15% of the total rice straw generated in northern India (Kurinji and Kumar 2021). A major reason behind this disparity is that collecting and transporting straw from the field is both time and effort intensive, causing delay in field preparation. Considering the huge amounts and seasonal availability of the rice residue, its handling and timely delivery for various applications is a significant issue, since it requires substantial workforce, heavy vehicles for logistics, and extensive storage infrastructure. In addition, the rice residue cannot be transported over long distances because of its low bulk density and high transportation costs (Singh *et al* 2010). To enable the utilization of rice straw residue as biomass, an intricate network of collection centres and well-regulated supply chain management (SCM) is required. However, insufficiency of such facilities and substantial transportation costs prevent the scale up of these *ex situ* management options (Singh *et al* 2010).

The Punjab government reported that 12.85 Mt of rice was burnt within the state in 2018 (Ministry of Agriculture & Farmers Welfare 2018). The collection, transportation, and storage of such huge amount of rice straw would require about 37,000 tractor-trailers running per day across the villages of Punjab for 20 days during the kharif harvesting season. This approach is not viable, since such high volume of traffic may lead to the congestion of the village roads due to the lack of suitable infrastructure (Kurinji and Kumar 2021). Also, during the harvesting season in Punjab, the high dew content in the atmosphere increases the moisture content in rice residue. The residue is generally Sun dried to bring down the moisture content up to 10%. This process often needs to be assisted with drying equipment, which entails additional expenditure.

Besides, compared to other prevalent power generation technologies, biomass based projects need a very high amount of water (Chen *et al* 2021). Therefore, establishment of new biomass plants for power generation would certainly strain the already depleting water reserves of the state. In addition, lack of an assured supply of biomass in adequate hampers the endeavours of private firms to set up biomass plants due to reduced economic viability of investing INR 4.45 to 6 crore per MW (Central Electricity Regulatory Commission 2019). Hence, it may be concluded that the *ex situ* straw management options are more capital intensive and would require significant subsidy amounts for farmers and industry to remain sustainable.

5.2. ***In-situ*** management

Several approaches for the in-field management of crop residues have been recommended due to their high efficiency, low environmental strain, and cost-effectiveness. *In-situ* rice straw management practices are performed in two ways, i.e. mulching, which involves retaining the straw as a surface layer, and incorporation, which allows mixing of straw into the soil. In mulching method, the residue is allowed to decompose in the field, whereas in the incorporation method, the crop residue is chopped and buried in the soil with specially designed implements . Technically, both methods of the *in situ* management help to improve the organic contents in the soil by retaining the crop residue in the field. Mulching of rice straw allows the retention of moisture and reduces weed emergence by utilizing rice straw as surface cover in the field for the succeeding crop (Chaudhary *et al* 2019, Kaur *et al* 2021). In contrast, the incorporation technique entails the mixing of the residue into the soil and prepares the field for next crop with the assistance of various machines. Thus, these methods enhance the nutrient value and fertility of the soil (Bandyopadhyay *et al* 2009, Goswami *et al* 2020). In-field utilization is not only environmentally friendly, but it also saves the farmers' time in the field after rice harvesting by consuming only about 4–10 days, depending on the method.

5.2.1. Advantages of in situ management

In situ management of straw has several benefits, including reduced water pollution and soil erosion, improved soil characteristics, increased crop productivity, and Soil Organic Carbon (SOC) sequestration for global warming mitigation (Blanco-Canqui and Lal 2009). These advantages have been explained as follows:

5.2.2. Improvement in soil health

Partial or complete surface retention of the residues is possibly the most desirable alternative in many cases. The mulching of rice straw enhances the soil carbon content and plays a dynamic role in nitrogen management. Rice residue slowly decomposes on the surface, increasing the organic carbon and total nitrogen levels in the topmost 5–15 cm of the soil. Nitrogen is generally applied in the form of urea during field preparation, which is likely to decompose and ensures a fast delivery of nitrogen to the soil. The use of crop residues as surface cover enhances the C:N proportion, which influences the balance of nitrogen conversion and storage. According to a study, at least 30% of the soil surface should be covered with previous crop residues at the emergence stage when crop residues are used as mulch (Erenstein 2002).

Moreover, the incorporation of the straw in the soil has a favourable effect on the physical, chemical, and biological properties of the soil such as pH, organic carbon content, water holding capacity, and bulk density of the soil (Singh *et al* 1996 and Zhao *et al* 2019). It has been observed over a long period that straw increases micronutrients viz., zinc, copper, iron, and manganese in the soil and also prevents the leaching of nitrates. By increasing organic carbon, the decomposing straw increases bacterial and fungal population in the soil. In a rice-wheat rotation, Beri *et al* (1995) and Sidhu *et al* (1995) observed that soil treated with crop residues was capable of sustaining 5–10 times more aerobic bacteria and 1.5–11 times more fungi than the soil subjected to the removal or burning of residues. Due to the increase in microbial population, the activity of soil enzymes responsible for conversion of nutrients from their unavailable to available forms also increases. The incorporation of rice residue before sowing of the wheat crop increases the grain yield. Further it was observed that incorporation of crop residues increases organic carbon by 14%–29% (Singh *et al* 1996). Overall, mulching and incorporation is beneficial in terms of enhancing the nutrient properties of soil and grain productivity. However, further research is needed to elaborate the effects of mulching on different kinds of soils and different crops.

5.2.3. Moisture conservation

Increasing the quantity of crop residue on the soil surface limits evaporation (Bussiere and Cellier 1994, Gill and Jalota 1996). Rice straw mulch has been shown to lower the crop water use by 3%–11% and enhance the water use efficiency by 25%, as compared to the crops grown without mulch (Chakraborty *et al* 2010). Mulch retains soil moisture at more profound levels, resulting in 40% higher root length densities than no mulch (Singh *et al* 2015). Rice straw provided as surface mulch can reduce greenhouse gas emissions by roughly 13 t ha^{-1} (Mandal *et al* 2004) and regulate the canopy temperature during the grain-filling stage (Mandal *et al* 2004, Jat *et al* 2009, Gupta *et al* 2010). Rice residue mulch treatments were found to allow higher retention of water than other methods including burning (Freebairn *et al* 1986, Chaudhary *et al* 2019). It has been estimated that use of residue as mulch in 5 Mha would lead to a saving of 5 billion cubic meter of water each year (Bijarniya *et al* 2020). Overall, rice residue mulching can be save a significant amount of moisture in the field that maintains the optimum soil temperature and favourable conditions for growing crop.

5.2.4. Impact of crop residues on pests

Incorporation of crop residues in soil affects the pests both directly and indirectly. The direct impact of straw incorporation on pests includes the detrimental effect on the egg laying of beetles and cutworms. However, decrease in temperature and increase in moisture content of the soil under residues also facilitates pest infestation in the imminent crops. Furthermore, straw biomass supports diversification among insects, by allowing the proliferation of both harmful and beneficial arthropods, thus decreasing the overall pest pressure (El-Shafie *et al* 2019). On the other hand, incorporated residues indirectly influence the propagation of insects and natural enemies of the crops by altering the type and density of weeds (Gupta and Dadlani 2012). The decomposition of residues leads to a chemical change in soil which may affect the host's sensitivity to pests. In addition, the decomposition of crop residues may produce phytotoxic substances, particularly during early stages of decomposition (Aktar *et al* 2009). However, residue cover provides shelter to some insects and pests in short term but incorporation of residue helps to reduce the harmful insects in the soil.

5.2.5. Reduced weed emergence

Residue retention on the surface has a significant impact on weed dynamics. By reducing the exposure of weed seedlings to Sunlight through mechanical impedance, the retained residue assists in suppressing weed emergence (Malik *et al* 2002). Residue from a previously combine harvested crop can be preserved on the field by uniform scattering on the surface, or by slicing and spreading a combination of standing stubble and loose straw. Physical resistance and the presence of several neurotoxic compounds in rice straw contributed to the restriction of weed propagation after mulching. Use of rice straw has the potential for a sustainable and cost effective management of the weeds. A combined application of multiple weed control approaches, including both chemical (Tribenuron-methyl, florasulam) and nonchemical practices (retention or incorporation) can aid in the effective management of weeds in wheat fields (Kaur *et al* 2021). Khankhane *et al* (2009) found that rice residue incorporation has reduced the weed density by 32.6% and the weed biomass by 31.3%, as compared to its removal from field. Moreover, Singh *et al* (2013) found that weed density was lowered by 18.9% with incorporation of rice residue compared to that achieved by straw removal. However, some study depict that no or negative effect of residue incorporation was observed on weed population. In contrast Jat *et al* (2003), found that weed biomass in residue incorporated fields was increased by 6%–12% as compared to straw removal or burning. The effect of rice straw incorporation may depend on the amount of residue incorporated and the succeeding crop. Nevertheless, rice residue retention and incorporation creates unfavourable condition for weed by means of mechanical impedance and competition for Sunlight leads to slow growth. On the other hand decomposition of rice residue helps to boost the growth on crop which also suppresses the weed population.

5.2.6. Enhanced crop production

Residue retention and incorporation improve soil health in various ways, which promotes crop development and production. However, in case of wheat sowing, since the rice residue is present above the level of the seed in the soil, a short delay in plant emergence is observed. This can be explained by the physical impedance in lateral root growth (Hiel *et al* 2018, Kaur *et al* 2021). Surprisingly, this adversity has not been found to affect the overall yield of wheat crop. Moreover, a succeeding rice crop has also been shown to remain unaffected by the incorporation of rice residue in wheat field (Sidhu and Beri 2005). Several reports show a similar maintenance of rice and wheat yields under different residual management practices such as burning, removal, or incorporation (Walia *et al* 1995, Singh *et al* 1996, Singh and Singh 2001). In fact, residues have been demonstrated to improve yields following decomposition, with a 14.8%–18.6% higher productivity observed in wheat with residue retention compared to when the residue was burnt or removed (Ladha *et al* 2011). Wheat yields under zero tillage with residue retention were 26.7% and 12.8% higher, respectively, than that of traditionally sown wheat crops (Kaur *et al* 2021). Even maize, soybean and sugarcane crops have displayed improved yields after mulching of rice straw (Kumar *et al* 2015 and Akhtar *et al* 2019).

6. Machinery for *in situ* management of crop residues

The use of the combine harvester for rice crop harvesting exacerbated the problem of residue management. A limited period between rice harvesting and wheat sowing encourages consideration about mechanical solution of the problem. The major challenge in mechanization of straw management is the limited use and higher cost of residue handling machines (Kumar *et al* 2021) Conventional farm machineries are unable to perform satisfactorily in the heavy residue conditions because of their own limitations. Straw management machinery should provide better straw handling, straw cutting or chopping ability and good soil penetration in straw load conditions. On the other hand machinery should be energy efficient, less expensive and highly productive in single operation. Collection of the residues and subsequent application as mulch in the following crop could be a sustainable solution. In case of rice straw incorporation energy efficiency and cost of machine could be a challenge which increases the cost of operation of the machine. Several options are available for management of rice residue and are popular among the farmers.

6.1. Machinery for rice straw mulching

6.1.1. Super SMS

Straw Management System (SMS) was developed by Punjab Agricultural University (PAU), Ludhiana for the uniform spreading of rice straw while harvesting by combine harvesters (The Tribune 2020). Straw spreader is attached to the rear side of combine harvester below the straw walkers behind the chaffer sieves (figure 8(A)).

Figure 8. Different rice straw management machineries (A. Super SMS System, B. Straw Chopper-cum-Spreader, C. Mulcher, D. Zero-till-drill, E. Spatial till drill, F. Happy seeder).

The spinning discs behind the harvester facilitate the spreading of loose residues falling from the harvester straw walker. Later, these spinning discs were modified and Super SMS was developed in 2015–16 (Singh *et al* 2019a). The combine with Supers SMS attachment requires an engine power of 110 hp for its functioning. The straw coming out of straw walkers of the combine harvester undergoes the Super SMS attachment as input from one side of the unit and scatter discharged from the outlet of the housing. The chopped material is expelled tangentially from outlet and deflected using a deflector for uniform spreading of the residues across the entire width of the combine harvester. These fine particles of rice residue made sowing easier in the rice stubble field. This reduces the choking and straw accumulation in furrow openers of seed drill up to some extent. Compared to traditional wheat sowing, the use of super SMS increased wheat crop productivity by 2%–4% (Manes *et al* 2017). It consumes about 2.5 to 3 l h^{-1} fuel and increases the field capacity of the happy seeder by 20%.

6.1.2. Straw chopper cum spreader

The tractor mounted straw chopper cum spreader allows the harvesting of the stubble remaining in the field after combine harvesting and chops them into smaller size. Thereafter, the chopped straw is evenly distributed in the field in a single operation (Singh *et al* 2011). The machine consists of a rotary shaft equipped with four rows of flail blades which harvest and cut rice stubble. Machine is operated by Power take-off (PTO) of tractor through the universal shaft. This machine is capable of chopping rice straw into 7–10 cm size (figure 8(B)). This machine has an average field capacity of 0.33–0.46 ha h^{-1} over varying forward speeds. Straw chopper cum spreader may be operated by a 45 hp tractor with fuel consumption of 6 to 6.5 l h^{-1}. Once the loose and standing stubbles have been chopped, effective wheat sowing may be accomplished with no-till drill without clogging and straw accumulation. Moreover, yield and yield attributes obtained using this machine have been shown to be similar to the conventional no-till drills operated in a stubble free field (Singh *et al* 2014). On the other hand, after straw chopper cum spreader wheat may be seeded with a standard seed drill depending on the kind of soil and straw load in the field.

6.1.3. Mulcher

Rice and wheat straw are the most commonly used mulching materials used for fruit and vegetable production. After decomposition, straw enhances the fertility of soil (Rajan *et al* 2017). For this purpose, mulcher has been developed as a tractor-driven post-harvest tool, which enables removal of the harvested plant remnants. Mulcher performs multiple tasks simultaneously, including cutting and chopping of straw, combination of chopped straw with soil, and clearing the field for preparation of the subsequent crop. Mulcher chops the straw into smaller pieces, which are then pressed by a roller attached to the rear. This process compresses the straw, thus creating a mulch layer over the topsoil. The tractor-operated rice straw mulcher has a field capacity of 0.32 ha h^{-1} (figure 8(C)). The mulcher is capable of slicing the residue up to 10 cm size, with a fuel consumption rate of 5.88 l h^{-1}. Subsequently, other equipment such as happy seeder or reversible mould board plough (MB plough) can be employed for wheat sowing or to revert the straw back into the soil, respectively (Verma *et al*

2016). However, mulching has not been adopted sufficiently across farming communities, most likely due to high expenditure and lack of awareness about its positive impact on crop yield.

6.1.4. Zero-till-drill

In various parts of India, zero-tillage with bed planting practices has become extremely popular, and the zero-till drill has become an indispensable element of agricultural farm machinery. This equipment enables the farmers to achieve precise sowing of a crop in a rice field with limited soil disturbance (figure 8(D)). The functioning of this machine involves drilling of wheat seeds directly into the standing rice stubbles. The best results of this approach have been observed with the cultivation of basmati, which is manually harvested, and short anchored stubbles remain in the field (Mishra *et al* 2021). Zero-till-drill minimizes the time and energy consumed by the conventional tillage operations, thus reducing the overall cultivation costs and the risk of *Phalaris minor* in wheat. In addition, it improves crop yields and enhances the farmers' profit. It has a field capacity of 0.24–0.4 ha h^{-1} and may be easily operated with a tractor having 45 horsepower (Malik *et al* 2005, Dhillon 2020).

6.1.5. Spatial no-till drill

The spatial no-till drill has been designed to sow wheat after a chopper or baler operation in the rice stubble field. This approach eliminates the requirement of rice straw incorporation for the sowing of wheat. This machine consists of three-member frames, which provide vertical clearance to the tynes, thus enabling the drilling of wheat seeds under loose straw intermingled with a high amount of anchored stubbles (figure 8(E)). In this drill, the spacing between the adjacent tynes is fixed at 60 cm in each frame to minimize the dragging of loose straw along with tynes (Singh *et al* 2014). Spatial no-till drill permits the utilization of crop residues as mulch, and has displayed promising results in terms of wheat production and profitability (Ladha *et al* 2003). This machine shows a field capacity of 0.24–0.4 ha h^{-1} and can be operated by a 45 HP tractor. Regular use of this machine with at least 30% coverage of the soil surface containing residue from the previous crop will allow realization of its complete potential.

6.1.6. Happy seeder

Happy seeder is used to perform the sowing of wheat in combine-harvested rice fields, after standing stubbles are chopped and distributed using a straw chopper. Happy seeder ensures compression of chopped rice straw in the form of mulch and its uniform distribution in the inter-row space. This equipment is usually operated using a 45 hp tractor, and has a field capacity of 1.6 ha h^{-1} (figure 8(F)). Happy seeder has been shown to enhance the wheat production by approximately 0.5 t ha^{-1}, reduce the fertilizer cost, and decrease other expenditures, in addition to allowing a timely completion of wheat sowing. Owing to the economic, environmental, and agricultural benefits of happy seeder, the administration has adopted the initiative and supports happy seeder by providing 50%–80% subsidy (Dhillon 2020). It has been observed that using the happy seeder with the SMS attached combine harvester, crop growth and grain size were higher than conventional practice.

6.2. Machinery for rice straw incorporation

The technique of rice straw incorporation as an alternative to burning has gained immense popularity among farmers. The incorporation of straw, instead of removal or burning, enhances soil organic matter and the N, P, and K content. Some studies concluded that wheat yield was decreased during the first three years after rice straw incorporation 30 days before to wheat sowing due to soil nitrogen immobilization in the availability of rice residues with a good C:N ratio, however straw incorporation had no significant effect on wheat yield in subsequent years (Mandal *et al* 2004). Rice residue can be fully incorporated in the soil after harvesting, and also after partial burning. Reportedly, very few farmers ($<1\%$) adopted the practice of incorporation of rice straw, most likely due to the increased requirement of subsequent tillage operations, compared to burning (Singh *et al* 2008). Fortunately, the scenario has now significantly improved due to the rapid mechanization of agricultural practices and enhanced awareness among the farmers regarding the disadvantages of burning and additional benefits of rice straw incorporation.

6.2.1. Reversible MB plough

Ploughing is the most effective way of incorporating residues. The reversible MB plough allows efficient management of rice residue by reversing the stubble and loose straw under the soil cover (figure 9(A)). In addition, MB plough may be employed to operate on the chopped rice field, followed by seedbed preparation with a secondary tillage implement such as rotavator. This approach is particularly beneficial for crops such as potato and sugarcane, which require proper seedbed preparation for adequate vegetative growth. Rice residue management using MB plough enhances soil characteristics and fertility. It can be operated using a power engine of 45 hp or higher, and displays a field capacity of 0.25 ha h^{-1}. The fuel consumption associated with straw

Figure 9. Different rice straw management machineries. (A). MB Plough, (B). Roto-till-drill, (C). Super seeder, (D). Smart seeder).

incorporation using the reversible MB plough depends upon the size of the mouldboard and tractor. According to studies the impact of rice residue management on wheat yield is visible after the fourth year of continued practice (Singh *et al* 2005, Gupta *et al* 2010). However, the lack of awareness about this equipment and the potential advantages severely limits its popularity in the farming community.

6.2.2. Rotary-till-drill

The rotary till-drill is another machine designed for efficient incorporation rice residue while sowing the succeeding crop. This machine mainly chops and mix the residue in the field with the help of rotavator blades (figure 9(B)). With this approach, wheat sowing and residue incorporation may be accomplished in a single operation, leading to substantial reduction of fuel and time, as compared to the conventional field preparation. This method involves dropping of wheat seeds in plastic tubes using a fluted roller mechanism in front of the machine, which are then integrated in the soil with the help of the rotavator. Therefore, seeds are sown at different depths randomly in the field. Additionally, rotary till drill may be employed for puddling operation in rice cultivation (Sharma *et al* 2008). This approach expedites the sowing of the subsequent crop, leading to higher profits associated with an early harvest (Dixit *et al* 2014). The field capacity of this machine is 0.3–0.4 ha.h^{-1}, and it can be operated by a 45–50 hp tractor.

6.2.3. Super seeder

After rice harvesting with a combine harvester attached with super SMS, super seeder is predominantly used for incorporation of anchored rice stubble in soil and simultaneous sowing of wheat in multiple rows. Super seeder can be operated with a 50 hp tractor, depending upon the width of machine. It consists of a rotary unit, seed box, PTO gear box, seed and fertilizer box, ground wheel, and furrow opening mechanism(figure 9(C)). The rotary unit carries out the chopping and mixing of the stubble and loose straw in the soil. Thereafter, the furrow opening mechanism slits the soil and places the seed and fertilizer on their respective places in rows. Next, the seed covering roller ensures the compression of the sown seed and incorporation of residue in the soil. The field capacity of super seeder is 0.35 ha h^{-1} and fuel consumption 6.7 l h^{-1} (Devgan *et al* 2020).

6.2.4. Smart seeder

The machine represents a 9 row seed-cum-fertilizer drill, comprising a rotor designed for rice residue incorporation and a strip till mechanism for simultaneously sowing of wheat. The rotor blades perform the tillage of narrow strips and incorporate the anchored stubble/loose straw that appear in the furrow during operation (figure 9(D)). Seeds and fertilizer are dropped directly through plastic tubes with the help of a set of

Table 4. Availability of straw management machinery in different states.

Name of machine/ Equipment	Number of machines/ Equipment			
	Punjab	Haryana	Uttar Pradesh[a]	Total
SMS	3634	909	8	4552
Happy seeder	9758	2376	24	12158
Reversible MB plough	3034	1159	232	4425
Shrub master/ Cutter cum spreader	86	216	14	316
Straw chopper/ Shredder/ Mulcher	4486	1581	96	6163
Rotary slasher	484	265	11	760
Zero till drill	3437	2527	906	6870
Rotavator	3690	1714	15115	20519
Total	**28609**	**10747**	**16406**	**55762**

[a] The data regarding Uttar Pradesh relates to machinery possessed by individual farmers only. (Courtesy: GOI 2019).

paired fixed disc furrow openers. In addition, a set of furrow closing rollers are present behind the furrow openers for immediate covering of seeds and fertilizer, thus enhancing the seed-soil contact for efficient germination of the crop. Strip tillage seeding technique is considered a superior *in situ* straw management technique, which offers combined benefits of residue mulching and incorporation. It operates with a field capacity 0.4 $\mathrm{ha\ h^{-1}}$ with a fuel consumption rate of 5.7 $\mathrm{l\ h^{-1}}$ (Chaleka 2018).

6.3. Problems associated with *in situ* management

Even though the approaches for *in situ* management of crop residues are far more advantageous than *ex situ* management, several issues remain unaddressed. For instance, direct drilling involves the retention of unincorporated straw from the previous crop remains that were also not mulched. These remnants on the soil surface often obstruct the direct drilling of subsequent crops, frequently causing mechanical failures and inefficient sowing. Furthermore, residue retention is not a prevalent approach due to the challenges such as increased chances of insect infestations and dependence on high power tractors (Singh *et al* 2019b), in addition to high cost and requirement of energy intensive machinery (Kaur *et al* 2021). These issues are further complicated with technical challenges regarding straw incorporation. For instance, increased soil complexity, along with variable straw properties necessitate the fine tuning of rotary tillers to optimize a practical and energy-efficient straw incorporation. Owing to these problems, sets of agronomic practices specifically defined for independent operational domains are non-existent, despite the availability of a wide array of machines for the rice straw management (Chaudhary *et al* 2019).

7. Government interventions to prevent rice straw burning

The government of India and several state governments have taken various initiatives to curb rice residue burning. Government policies are mainly aimed at restricting the on-site burning of rice residue by providing the necessary financial support to the farmers for renting or purchasing the machinery associated with straw management (table 4). In this regard, the Hon. Supreme court had ruled to provide incentives amounting to Rs 100 per quintal of rice residue for small and marginal farmers in Punjab, Haryana, and Uttar Pradesh to compensate for stubble management without burning (Pandey 2019).

The states of Punjab, Haryana, and Uttar Pradesh have 2,108; 1,725 and 2,559 Custom Hiring Centres (CHCs), respectively, which are administered by various NGOs, government agencies, and independent entrepreneurs (Pandey 2019). Various efficient approaches to minimize stubble burning have been popularized in these states. In addition, the Union Ministry of Agriculture, Govt. of India has launched the CHC Farm Machinery mobile application to facilitate the connection of small and marginal farmers in these states to the local CHCs, where they may avail the required agricultural machinery on a rental basis. Machines that facilitate stubble management as an alternative to burning, such as happy seeder, reversible MB plough, and rice straw mulcher are available at the CHCs via the mobile application (Pandey 2019). However, this facility aimed to assist in rice residue management has received a lukewarm response from the farmers so far.

Considering the limited use of the various options related to rice straw management, the Indian government launched a scheme 'Promotion of Agricultural Mechanization for *in situ* management of crop residue in the States of Punjab, Haryana, Uttar Pradesh, and Delhi' in 2018, offering a substantial grant to the farmers for purchasing a variety of machines for *in situ* crop residue management. Under this scheme, farmers received a 50% subsidy on machine costs, while cooperative societies, farmers' interest groups, and other collectives of

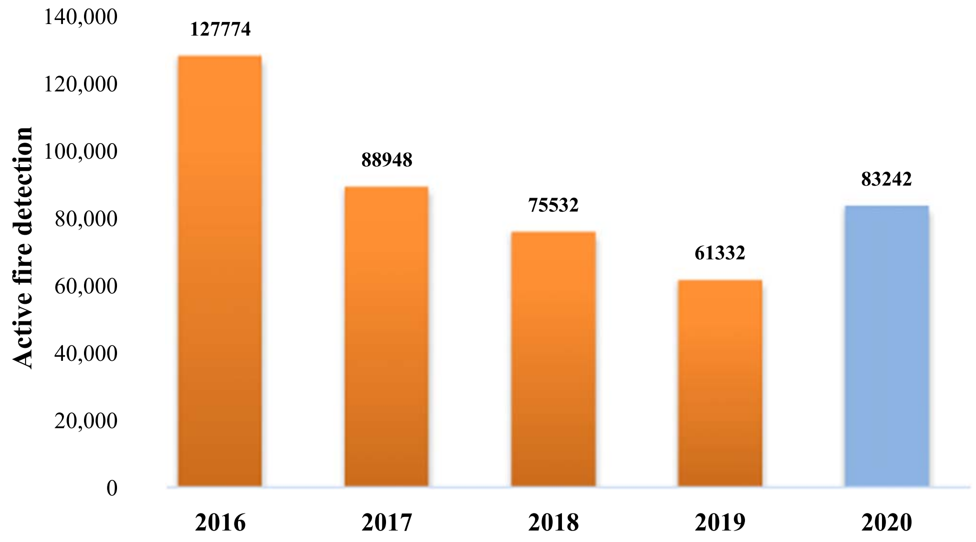

Figure 10. Reduced active fire detection in northern India (Chhabra *et al* 2019, ICAR 2020).

farmers received an 80% subsidy (Ministry of Agriculture and Farmers Welfare 2018). The plan also ensured a consistent market for these machines, encouraging the manufacturers to expand their manufacturing capacities. According to satellite data it was seen that the active fire detection has reduced in the northern India, this may be due to joint effort of administration and farmers. (figure 10). A rise in residue incineration has been observed following the Covid pandemic outbreak in 2020.

In addition to these initiatives, alternative use of rice straw has also been promoted by the government for industrial purposes such as cardboard manufacturing, fodder applications, mushroom cultivation, and as packaging material for fruit and vegetable exports. Moreover, Punjab has 11 operational biomass-based power plants with an aggregate capacity of 97.5 MW, in which 0.88 Mt of rice straw is consumed annually (Chaba 2020). In 2018, the central government reported that 1.1 Mt of rice residue (5.5% of total residue generated) was subjected to various *ex situ* managements methods, including its application in paper/cardboard mills and biomass power projects (Ministry of Agriculture and Farmers Welfare 2018).

In 2017, the Government of India also mandated the largest thermal utility, National Thermal Power Corporation (NTPC), to integrate 10% crop residue with coal as an attempt to prevent residue burning. Under this *ex situ* management program, NTPC aims at purchasing the crop residue from farmers and manufacturing biomass pellets for incineration along with coal at all NTPC plants across India (The Hindu 2017). Furthermore, the Government of India has set an ambitious goal to increase the renewable energy capacity to 175 GW by the year 2022, of which 10 GW is to be contributed by biomass-based power. Since December 2016, when the plan was announced, an increase from 7.8 GW to 9.2 GW has been recorded in the capacity addition under biomass derived power till July 2019 (Ministry of New and Renewable Energy 2018). The government has provided the necessary impetus and support in the form of an increased budg *et al* located to The Ministry of New and Renewable Energy (MNRE), which is the nodal agency for matters relating to new and renewable energy, in addition to curtailing the import duties on biogas plant components. The implementation of *ex situ* treatment strategies for crop residue management, such as setting up of decentralized power generation plants, palletization and briquetting plants, and biogas plants, requires high capital investment. Therefore, while state governments have initiated the Viability Gap Funding to ensure financial assistance, state grants as investments up to 25% of the capital cost of industrial plants have been provided. However, the accessibility of such grants is limited, depending on the priority, feasibility, and availability. Overall, even though government is actively encouraging the adaptation of residue management alternatives, there is a long way to go until the straw burning practice is entirely eliminated.

8. Discussion

In India, the intense rice-wheat cropping pattern leads to enormous amount of straw generation in farms. While wheat straw is utilized as animal feed, rice straw is not palatable for animals due to its high silica content. Since there is no potential use of rice straw for the farmers and the equipment designed for straw management is expensive, farmers burn the straw in field as a cheap and quick solution. Even though several farmers are aware that burning of rice straw is harmful for humans, animals, and the environment, they still adopt this practice to ensure a timely preparation of the field for the next crop. The detrimental impact of residue burning on the nutrient budget of the soil, and the consequent resource loss necessitates the advancement in harvesting technology and solutions for long-term management of the rice-wheat system.

In order to avoid straw burning and its detrimental effects, various strategies of straw management have been developed and recommended. These approaches are broadly categorized as *ex situ* and *in situ* management methods, depending on whether rice straw is managed by removing it from the field, or within field. Under *ex situ* approaches, straw can be collected and transported in the form of bales or pellets, and utilized for various purposes such as in biogas plants, industrial purposes and cardboard industry. However, these methods are energy-intensive, and lack the requisite infrastructure support. Alternatively, rice straw management via *in situ* methods provide a superior substitute for residue burning, since these methods allow the retention of the organic biomass within the field, which is highly beneficial for soil health and environment. These positive effects further translate into timely sowing of subsequent crops, increased nutrient availability, improved pest and weed control, and higher yield. Currently, various *in situ* rice straw management technologies are available, in which happy seeder, zero till drill, and super seeder are the most effective and popular among the farmers. Moreover, transplanting of rice should be scheduled so that after SMS-based combine harvesting, sowing of wheat can be performed with happy seeder, zero till drill, and rotary till drill on residual soil moisture without pre-sowing irrigation.

A major reason for the reluctance of farmers to use these methods is the higher power requirement (over 45 HP) of these machines, which causes increased burden on farmers in terms of the cost of fuel and time. To overcome such economic issues, realization of the complete potential of rice residues is necessary in the context of conservation and sustainable agriculture, which can be achieved with an active involvement of all stakeholders i.e., farmers, researchers, extension agents, civil servants, policy makers, supply and value chain service providers, and consumers. Furthermore, the concerned government agencies should ensure the availability of relevant machines to agricultural cooperative societies and farmers on subsidized rates. Simultaneously, adequate promotion of these technologies through diverse extension strategies such as demonstrations, field days, and exposure visits is essential to increase awareness among farmers regarding the associated financial advantages. Farmers should also be educated to enhance their ecological consciousness towards capacity building for a cost-effective use of the available machines. Farmers' fairs, exhibitions, seminars, demonstrations, and the use of communications technology, electronic, social, and print media, among other things, should be initiated and supervised for their adequacy in light of current technology acceptance and integration at different phases of the cultivation period.

9. Conclusion

Stubble burning has been a persistent issue in north India for several decades, leading to extensive environmental pollution. Due to a lesser window period during sowing of wheat and harvesting of rice crop, farmers choose to burn the rice residue in the field. Rice residue collection and transportation makes *ex situ* residue management economically unfeasible. For *in situ* management it is essential to have is affordable and readily available machinery. Hence, a synergistic approach is required to eliminate the straw burning practice. Ex-situ options are also being promoted for rice residue management, such as gasification as a boiler fuel, briquetting, pelleting and cardboard making. Utilization of rice straw as animal feed and application in mushroom cultivation are the most prominently used techniques, due to their economic benefits. However, lack of an intricate network of biomass supply chain facilities in northern India is posing challenges to the popularization and expansion of *ex situ* management strategies. Happy seeder, super seeder and zero till drill like machines has been recognized as economical *in situ* rice straw management choices. In addition, a logical blend of *in situ* and *ex situ* options should be adopted, not solely relying on the *in situ* residue management approach. As a result, farmers will not only be able to prevent straw burning, but also enjoy improved soil and environmental conditions, which will increase their profitability.

Furthermore, the concerned government agencies should ensure the availability of relevant machines to agricultural cooperative societies and farmers on subsidized rates. Simultaneously, adequate promotion of these technologies through diverse extension strategies such as demonstrations, field days, and exposure visits is essential to increase awareness among farmers regarding the associated financial advantages. Farmers should also be educated to enhance their ecological consciousness towards capacity building for a cost-effective use of the available resources. The government and policy makers should also ensure development of stringent guidelines and law enforcement against rice straw burning, through both incentives as well as penalization.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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