INTEGRATED STRAW MANAGEMENT IN INDIA

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Foreword

The Development Papers Series of the Economic and Social Commission for Asia and the Pacific, Subregional Office for South and South-West Asia (ESCAP-SSWA) promotes and disseminates policy-relevant research on the development challenges facing South and South-West Asia. It features policy research conducted at ESCAP-SSWA as well as by outside experts from within the subregion and beyond. The objective is to foster an informed debate on development policy challenges facing the subregion and sharing of development experiences and best practices.

This paper by C.R. Mehta, Uday R. Badegaonkar, P.L. Singh, and Kanchan K. Singh is one of four national studies commissioned by ESCAP SSWA and carried out in collaboration with the Centre for Sustainable Agricultural Mechanization (CSAM), to better understand the status of crop residues management in South Asia. This paper examines the case of India. The burning of crop residues is a major reason for creating air pollution in the Indo-Gangetic plain region. Crop residue or straw burning increases the concentration of particulate matter and black carbon in the air, adversely affecting the health of both rural and urban populations. This burning negatively degrades soil fertility that needs to be compensated by greater use of fertilisers and can reduce agricultural productivity in the long run. Greenhouse gases emitted from burning also contribute to global warming and climate change. All of these factors adversely affect the achievement of the Sustainable Development Goals as crop residue burning harms our health and wellbeing (SDG 3), has implications on food security (SDG 2), affects the air quality of city inhabitants (SDG 11) and contributes to climate change (SDG 13).

It is hoped that the findings from this study highlighting issues faced by farmers in India to sustainably manage crop residues is useful to identify opportunities to improve the existing situation as well as enable the policy makers to make relavant policy interventions. The study also collects good practices and technologies for managing straw (with particular emphasis on mechanization-based solutions) and proposes an action plan for interventions at the national level.

The findings from this study also contributes to a sub-regional report which summarizes the findings from the four national studies, explores key actions and the possibility of having a sub-regional framework for cooperation to promote sustainable and integrated management of straw residues.

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Integrated Straw Management in India

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Abstract

The burning of crop residue generates severe air pollution in the Indo-Gangetic plain area of South Asia. It affects people's health, impacts agricultural production and food security by deteriorating soil health and contributes to climate change with the emission of greenhouse gases. Crop straw yield has kept growing and maintained a high level with increase in agriculture production in South Asia. The lack of suitable agricultural technology and machinery to sustainably utilize the straw or promote its recycled usage has led to their burning and caused a high level of air pollution, including through transboundary sources.

This paper takes stock of the residues generated by various crops in India, how crop residues are used by farmers and factors influencing decisions to burn residues. The adverse economic, health and environmental impacts of crop residue burning are also examined to better understand the problems that crop residue burning has on sustainable development. Various in-situ and ex-situ methods for managing crop residues as well as the agricultural machinery and equipment used in India are documented. Government policies and efforts to promote better management of crop residues and reduce the level of burning are also examined.

Based on this background information, the paper analyses various problems and gaps that exist to ensure a more sustainable management of straw. Recommendations are made on actions that can be taken to improve the functionality and use of agriculture machinery by farmers to manage crop residues, proposes laws and legislation to ensure more sustainable management of crop residues as well as other interventions that can provide and promote alternative uses for crop residues.

JEL Codes(s): O13, Q16, Q53, Q55

Key words: crop residues management, straw burning, agriculture technology and machinery, air pollution

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1. Introduction

The agriculture sector in India has experienced buoyant growth during 2020-21 and 2021-22. The sector, which is the largest employer of workforce, accounted for a sizeable 18.8 % (2021-22) in Gross Value Added (GVA) of the country, registering a growth of 3.6 % in 2020-21 and 3.9 % in 2021-22. Growth in allied sectors, including livestock, dairying, and fisheries, have been the major drivers of overall growth in the sector.

India accounts for about 2.4 % of the world's geographical area and 4.2 % of its water resources but supports about 17.6 % of its population. The phenomenal growth in Indian agriculture in terms of total food-grains production from 51 million tonnes in 1950–51 to 316 million tonnes in 2021–22 was due to the development of high yielding varieties and hybrids, increase in cropping intensity, increase in irrigated area, lab to land programmes, farm mechanization and technology transfer. The need to provide food-grains for a growing population while sustaining the natural resource base has emerged as one of India's main challenges. Agricultural growth has caused enormous pressure on environmental health.

The new paradigm of Climate Smart Agriculture recognizes the need for productive and remunerative agriculture, which while increasing profitability, also conserves and enhances the natural resource base and environment. Climate Smart Agriculture not only reduces the impact of climate change on crop production, but also mitigates the factors that cause climate change by reducing emissions and by contributing to carbon sequestration into the soil to improve soil fertility.

The fertility of the soil is highly dependent on soil organic matter. Intensive cropping and tillage system have led to a substantial decrease in soil organic matter levels of Indian soil and thereby a decline in soil fertility and crop production. Technological advances and the use of machinery for crop harvesting leave behind large quantities of crop residues, which has further worsened the problem. The leftover residue is burned by farmers as a cheap and the easiest method with the misconception that burning of crop residues enhances soil fertility and helps in controlling weeds, insects and pests. However, it is widely accepted that high soil organic matter means high potential productivity and health of the soil. Soil organic matter may in fact be maintained by the addition of crop residues. Therefore, crop residue management (CRM) becomes very important for soil health and crop production.

2. Crop Residues Generation in India

Harvesting of various crops generates a large volume of on and off farm residues. A large variability exists in the estimates of generation, utilization and on-farm burning of crop residues. Pathak (2004) estimated that annually 523 Mt of crop residues were generated in India, out of which 127 Mt was surplus. According to IARI (2012), the Ministry of New and Renewable Energy estimated the amount of crop residues generated in 2009 was 500 Mt and surplus was 140 Mt. The majority of crop residue is used as fodder for animals and fuel for other domestic and industrial purposes. There is still a surplus of 140 Mt out of which 92 Mt is burned each year (MoA, 2014; Bhuvaneshwari *et al*., 2019). Out of various crops grown, rice, wheat, maize and sugarcane are prone to crop residue burning.

Jain *et al*. (2014) estimated the total amount of dry crop residue generated from nine major crops as 620.43 Mt (Table 1). According to them, there was a large variation in crop residues generation across different states of India depending on the crops grown in the states, their cropping intensity, and productivity. Generation of cereal crop residues was the highest in the states of Uttar Pradesh (72 Mt), followed by Punjab (45.6 Mt), West Bengal (37.3 Mt), Andhra Pradesh (33 Mt) and Haryana (24.7 Mt). Uttar Pradesh had the maximum contribution to the generation of the sugarcane residue (44.2 Mt), while residue from fibre crops was dominant in Gujarat (28.6 Mt) followed by West Bengal (24.4 Mt) and Maharashtra (19.5 Mt). Rajasthan and Gujarat generated about 9.26 and 5.1 Mt residues, respectively, from oilseed crops (Table 1). Among different crop categories, 361.85 Mt of residue was generated from cereal crops, followed by fibre crops (122.4 Mt) and sugarcane (107.5 Mt) (Table 1).

Cereal crops generated 58 % of residue of which rice crop alone contributed 53 % and wheat ranked second with 33 % (Figure 1). Fibre crops contributed to 20% of residues generated with cotton rank first (90.86 Mt) with 74 % of fibre crop residues. Sugarcane residue contributed to 17% of total crop residues. The oilseed crops generated 28.72 Mt of residue annually (Figure 1). Their estimates are in line with other studies (Pathak *et al.*, 2006; IARI, 2012; Pathak *et al.*, 2010).

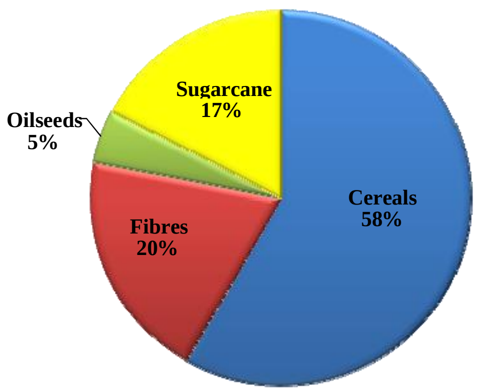
Table 1: Crop-wise residue generated in various states of India

States	Crop residue generated (Mt/year)			
	Cereal crops	Fibre crops	Oilseed crops	Sugarcane
Andhra Pradesh	33.07	16.07	2.50	5.80
Arunachal Pradesh	0.56	0.00	0.06	0.01
Assam	8.15	2.01	0.29	0.41
Bihar	19.87	3.27	0.20	1.87
Chhattisgarh	8.87	0.01	0.11	0.01
Goa	0.24	0.00	0.01	0.02
Gujarat	8.18	28.62	5.06	5.85
Haryana	24.73	7.58	2.15	1.93
Himachal Pradesh	1.95	0.00	0.01	0.02
Jammu & Kashmir	2.76	0.00	0.11	0.00
Jharkhand	7.34	0.00	0.09	0.13
Karnataka	11.73	3.55	0.81	8.80
Kerala	1.14	0.01	0.00	0.10
Madhya Pradesh	16.05	3.51	2.13	1.12
Maharashtra	8.75	19.51	0.57	22.87
Manipur	0.78	0.00	0.00	0.01
Meghalaya	0.44	0.13	0.01	0.00
Mizoram	0.10	0.00	0.00	0.01
Nagaland	0.89	0.01	0.06	0.07
Orissa	13.38	0.56	0.16	0.24

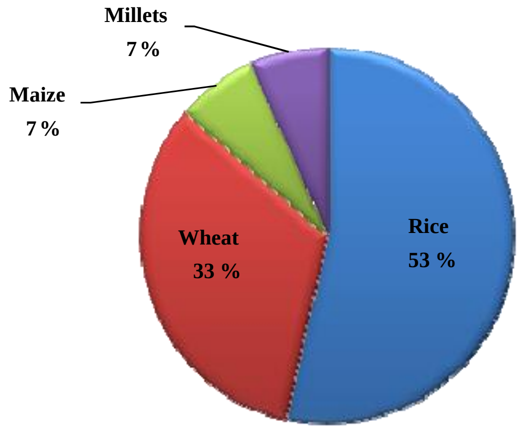
States	Crop residue generated (Mt/year)			
	Cereal crops	Fibre crops	Oilseed crops	Sugarcane
Punjab	45.58	9.32	0.08	1.76
Rajasthan	22.19	2.96	9.26	0.15
Sikkim	0.14	0.00	0.01	0.00
Tamil Nadu	11.69	0.78	1.56	12.37
Tripura	1.22	0.02	0.00	0.02
Uttar Pradesh	72.02	0.04	2.49	41.13
Uttarakhand	2.40	0.00	0.03	2.11
West Bengal	37.26	24.43	0.95	0.62
A & N Islands	0.04	0.00	0.00	0.00
D & N Haveli	0.05	0.00	0.00	0.00
Delhi	0.17	0.00	0.00	0.00
Daman & Diu	0.01	0.00	0.00	0.00
Pondicherry	0.10	0.00	0.00	0.06
All India	**361.85**	**122.37**	**28.72**	**107.50**

Source: Jain et al. (2014)

Figure 1: (a) Contribution of different crops in residue generation, (b) Contribution of different cereal crops in residue generation



(a)



(b)

Source: Jain et al. (2014)

TIFAC and IARI (2018) selected eleven crops, namely rice, wheat, maize, sugarcane, cotton, pulses (Gram and Tur) and oilseeds (groundnut, mustard, soybean and castor) for assessment of surplus crop biomass generation. The crops were selected based on their acreage and total production across the country. The study was carried out for the whole of India, comprising of 662 districts. The assessment methodology involved (1) compilation of area and production statistics of selected crops, (2) estimation of dry biomass generation, and (3) development of surplus factors and quantification of surplus biomass generation. The crop biomass usage pattern by farmers for their own use as well as the biomass sold to others for industrial or any other usage was compiled to estimate the factors for surplus crop biomass generation. The crop biomass generated from each crop was estimated on a dry weight basis. The crop-wise and season-wise area estimated total dry biomass and surplus biomass of selected crops in India are reported in Table 2.

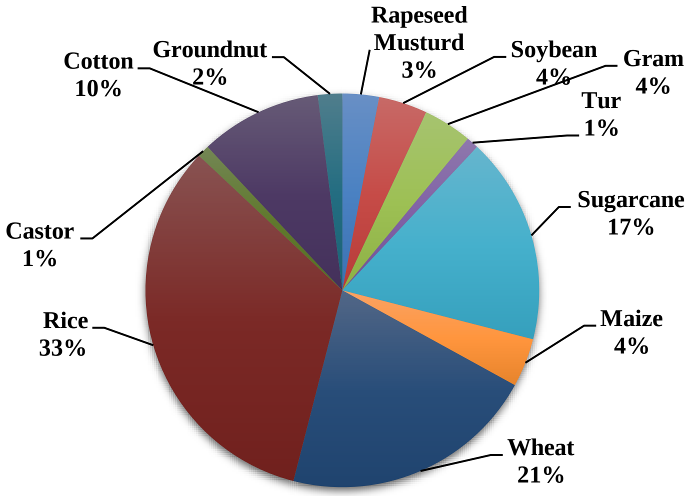
Table 2: Crop wise and season wise area, total dry biomass and surplus biomass of selected crops in India

Crop	Season	Area (Mha)	Dry Biomass (Mt)	Surplus Biomass (Mt)	Bio-ethanol Potential (billion litre)
Rice	Kharif	28.597	142.761	35.993	9.862
	Rabi	13.334	66.997	7.267	1.991
	Summer	2.429	15.728	0.596	0.163
	Sub Total	**44.360**	**225.487**	**43.856**	**12.017**
Wheat	Rabi	30.838	145.449	25.070	6.919
Maize	Kharif	7.591	21.491	4.979	1.110
	Rabi	1.190	6.389	1.057	0.236
	Sub Total	**8.781**	**27.880**	**6.036**	**1.346**
Sugarcane	Kharif	5.037	119.169	41.559	14.629
Gram	Rabi	8.484	26.515	8.724	2.172
Tur	Kharif	4.040	8.942	1.704	0.433
	Rabi	0.073	0.225	0.051	0.013
	Sub Total	**4.113**	**9.167**	**1.755**	**0.446**
Soybean	Kharif	10.694	27.779	9.950	2.935
Rapeseed and Mustard	Rabi	5.869	17.085	5.157	1.495
Cotton	Kharif	12.039	66.086	29.555	7.359
	Rabi	0.116	0.480	0.178	0.044
	Summer	0.003	0.017	0.007	0.002
	Sub Total	**12.158**	**66.583**	**29.470**	**7.405**
Groundnut	Kharif	4.399	9.449	2.648	0.580
	Rabi	0.593	2.145	0.961	0.211
	Summer	0.483	1.305	0.263	0.058
	Sub Total	**5.474**	**12.900**	**3.873**	**0.848**
Castor	Kharif	1.176	4.589	3.013	1.133
	Rabi	0.009	0.016	0.005	0.002
	Sub Total	**1.185**	**4.604**	**3.017**	**1.134**
All Crops across all seasons	**Grand Total**	**136.994**	**682.618**	**178.738**	**51.348**

Source: TIFAC and IARI (2018)

The findings of TIFAC and IARI study indicated that about 683 million tonnes (Mt) of total dry biomass were generated in three crop growing seasons. Out of this total 683 Mt of annual crop biomass, the maximum biomass was generated from rice crop (225.49 Mt), and the minimum was from castor crop (4.60 Mt). The highest share of biomass generation was of rice crop (33 %), followed by wheat (21 %), sugarcane (17 %) and cotton (10 %). The remaining 19 % of biomass was generated from maize, tur, gram, soybean, rapeseed-mustard, groundnut and castor crops (Figure 2). About 59 % biomass was generated during the kharif season (June-Oct) and 39 % during the rabi season (Nov-April). The remaining about 2 % was generated during the summer season. The total annual surplus crop biomass was estimated at 178 Mt which is about 26 % of the total dry biomass generated. The season-wise surplus biomass was the highest in the kharif season (72 %) and the major crops contributing to surplus biomass are rice, sugarcane, cotton and soybean. In rabi season, wheat, gram, rice and mustard were the crops contributing to the surplus crop biomass. The surplus biomass generated during summer season was negligible.

Figure 2: Share of crop in total dry biomass generated for selected crops



Source: TIFAC and IARI (2018)

3. Utilisation of Crop Residues

Across India, crop residues are being utilized differently depending on the region and its socio-economic status, type of cultivated crop, number of crops per year, etc. Traditionally, crop residues have numerous competing uses such as for animal feed, fodder, fuel, roof thatching, packaging and composting. Cereal residues are mainly used as cattle feed. Rice straw and husk are used as domestic fuel or in boilers for parboiling rice in West Bengal State. Farmers use residue either themselves or sell it to other landless households or intermediaries, who in turn sell the residue to industries. The remaining residues are left unused or burned in field.

In states like Punjab and Haryana where rice residues are not used as cattle feed, a large amount of rice straw is burned in the field. In southern India, rice stubble is used for domestic fuel or in boilers for parboiling rice. Sugarcane tops in most of the areas are either used for feeding dairy animals or burned in fields for ratoon crop. Residues of groundnut are burned as fuel in brick kilns and lime kilns. Cotton, pulses, oilseed crops, chillies, coconut shells, rapeseed and mustard stalks, sunflower, and jute residues are mainly used as fuel for household needs (Pathak *et al*., 2010). Coconut generates about 3 Mt of husk annually and about 1.2 Mt is utilized for making coir, and 1 Mt is burned as fuel.

Wheat is the second most consumed crop after rice. A large amount of wheat straw (residue) is used for cattle feeding, domestic fuel, paper board making and oil extraction (TIFAC, 1991). However, in areas of the Indo-Gangetic plains (IGP) such as Punjab, Haryana, Uttaranchal and Uttar Pradesh where an intense cropping system is adopted, the straw is burned as it is the easiest and most economical option to get rid of it in the short period available between two crops. Unlike wheat, corn straw and millet stalks are relatively hard, and therefore used less for fodder. However, they are either left in the field as compost or used for cattle feed (TIFAC, 1991; Meshram, 2002). Similarly, mustard stalks are widely burned or used for domestic fuel. Sugarcane is a relatively long duration crop and its residue is disposed of quickly to catch up for the sowing of the follow-up crop. Sugarcane residue includes trash, tops and bagasse. Trash is used as fuel for jaggery extraction, cattle feed or burned on-site (Tyagi, 1989; Meshram, 2002). Similarly, peanut stems and shells are used for domestic and industrial fuel, respectively (Tyagi, 1989; TIFAC, 1991; Meshram, 2002).

The use of crop residues as a feedstock for producing renewable energy and other valuable products has received considerable attention in recent years. However, these uses must be balanced against the long-term benefits of maintaining and improving the productivity of the soils.

With the increased incidence of the burning of crop residue, central authorities have initiated and promoted approaches to alleviate the problem. These approaches include the use of crop (particularly cereals) residues as fodder, fuel for bio-thermal power plants, mushroom cultivation, as bedding material for cattle, production of bio-oil, paper production, biogas production and incorporation of rice residue into the soil, energy technologies and thermal combustion (Kumar *et al*., 2015). Among different strategies, only combustion technology is currently being commercialized, whereas the other technologies are at different stages of development.

Additionally, industrial demand for crop residues is also increasing. The plywood market has grown at a compound annual growth rate (CAGR) of nearly 5 % during 2009-2020. There are several options for crop residues utilisation such as animal feed, composting, energy generation, bio-fuel production and recycling into soil to manage the residues in a productive and profitable manner. Conservation agriculture (CA) offers a good promise in using these residues for improving soil health, increasing productivity, reducing pollution and enhancing the sustainability and resilience of agriculture. The resource-conserving technologies (RCTs) involving no or minimum-tillage, direct seeding, bed planting and crop diversification with innovations in residue management are possible alternatives to conventional energy and input-intensive agriculture.

4. Crop Residues Burning in India

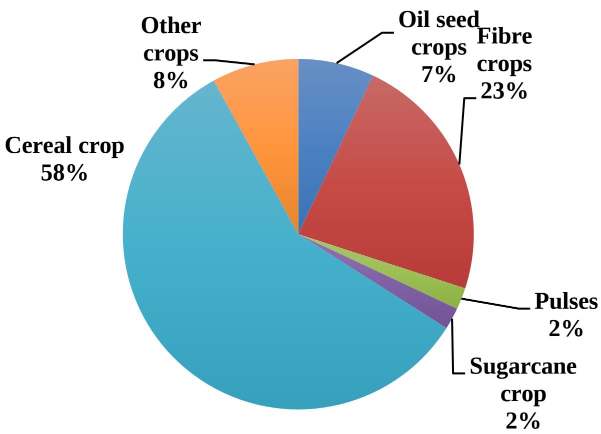
The surplus residues, i.e., total residues generated minus residues used for various purposes are typically burned on-farm. Rice, wheat and maize are the main staple crops cultivated in India. The cultivation method of these crops implies that the farmers have to deal with an abundance of stalks, the remaining part of the plant left on the field once the grain is harvested. Since the stalks have no palpable value and interfere with planting of the subsequent crop, smallholders are compelled to clear them from the field. With little resources at hand and a tight seeding schedule for the next cycle, which cannot be delayed without negative effects on the crop yield, on-farm residue burning is the most convenient and cheapest option to farmers (ESCAP, 2020).

Vadrevu *et al*. (2011) reported that about 75 % of rice harvesting was done by mechanical harvesting rather than manual harvesting. The number of combine harvesters in India increased from 5,000 to 50,000 between 1990–91 and 2019-20 (Mehta and Badegaonkar, 2021). The use of combine harvesters generates large amount of 'root-bound and loose crop residues', which are difficult to manage (Ravindra *et al*., 2019). It is reported that due to very short time interval (10–20 days), labour scarcity, unavailability of farm implements to plough back the stubbles into the soil or spread the stubbles as mulch, the farmers followed the practice of on-site burning of crop residues (Shyamsundar *et al*., 2019; Kaur, 2020; Venkatramanan *et al*., 2021).

The absence of appropriate crop residue management technology and lack of awareness about the downside of crop residue burning also drive the farmers to stubble burning (Chawala and Sandhu, 2020). Further, paddy straw, due to poor digestibility and low nutritive value, is less preferred as ruminant feed. Lohan *et al*. (2018) reported that the lack of storage facilities and market opportunities also drives the farmers to burn crop residues. The farmers also believed that the on-site burning of crop residues controls problematic weeds, pests, and disease-causing organisms. Residue burning is the easiest way for the farmers to quickly dispose of the crop residues. Crop residue burning activity is influenced by the agricultural practices that include crop cycle, crop type, harvesting season, potential uses of residues, agricultural mechanization, the feasibility of on-farm residue collection and transportation and profitability of alternate options (Venkatramanan *et al*., 2021).

IARI (2012) notes that the contribution of cereals and fibre crops in on-farm burning of crop residues is 58 % and 23 %, respectively (Figure 3) and the remaining 19 % is from sugarcanes, pulses, oilseeds and other crops. Out of 82 Mt surplus residues from the cereal crops, 44 Mt is from rice, followed by 24.5 Mt from wheat, which is mostly burned on-farm. In the case of fibre crops (33 Mt of surplus residue), approximately 80 % of the residues are from cotton and are subjected to on-farm burning.

Figure 3: Share of unutilized residues in total residues generated by different crops in India



Source: IARI (2012)

Jain *et al*. (2014) reported that the fraction of crop residue subjected to burning ranged from 8 to 80 % for rice crops across the states. In the states of Punjab, Haryana and Himachal Pradesh, 80 % of rice straw was burned in-situ, followed by 50 % in Karnataka and 25 % in Uttar Pradesh, which can be attributed to the mechanized harvesting using combine harvesters

(Gupta *et al*., 2003). At present, 75–80 % of rice-wheat area in Punjab is harvested with combines. It is estimated that 23 % of wheat straw is burned in the states of Haryana, Himachal Pradesh, Punjab and Uttar Pradesh, and 10 % for the rest of the states. For sugarcane trash, approximately 25% of the trash is burned in the fields. For the rest of the crops, the fraction of crop residues burned on the farm was estimated as 10 % across the states.

The amount of residue burned on the farm ranged from 98.4 Mt (Jain *et al*., 2014) to 131.9 Mt (using Intergovernmental Panel on Climate Change (IPCC) coefficients). According to IPCC, 25 % of the crop residues are burned on farm. With IPCC coefficients, the contribution of Uttar Pradesh was the highest, followed by West Bengal, Andhra Pradesh, Punjab, Maharashtra and Haryana. But with Jain *et al*. (2014) coefficients, the highest amount of crop residues was burned in the states of Uttar Pradesh (22.25 Mt) and followed by Punjab (21.32 Mt), Haryana (9.18 Mt) and Maharashtra (6.82 Mt). The highest amount of cereal crop residues was burned in Punjab, followed by Uttar Pradesh and Haryana. Uttar Pradesh burned the most sugarcane trash, followed by Karnataka. Oilseed residues were burned in Rajasthan and Gujarat, while burning of fibre crop residue was dominant in Gujarat (28.6 Mt), followed by West Bengal (24.4 Mt), Maharashtra, and Punjab. Among the different crop residues, the major contribution was from rice (43 %), wheat (21 %) and sugarcane (19 %).

The problem of burning of crop residues has intensified in recent years. The residues of rice, wheat, cotton, maize, millet, sugarcane, jute, rapeseed-mustard and groundnut are typically burned on-farm across different states of the country. The problem is more severe in irrigated agriculture, particularly in the mechanized rice-wheat system of the north-west India. As per available estimates, the burning of crop residues is predominant in four states namely, Haryana, Punjab, Uttar Pradesh and West Bengal. In recent years, the burning of crop residues has resulted in a scarcity of fodder and simultaneously increased the price of fodder across the country. It is a paradox that the burning of crop residues and scarcity of fodder co-exists in India simultaneously, and there has been a significant increase in fodder prices in recent years.

5. Adverse Effects of Crop Residues Burning

The burning of crop residues generates various environmental issues. The most adverse effects of crop residue burning are the emission of greenhouse gases (GHGs) that contribute to global climate change. In addition to that, enhanced levels of Particulate Matter (PM) and other air pollution cause health hazards, loss of diversity of agricultural land, and the deterioration of soil fertility (Jin and Bin, 2014). The burning of the crop stubble in an open field influences soil fertility, eroding the sum of soil nutrients.

Economic impact: Crop residue is not a waste but rather a useful natural resource. About 25 % of nitrogen (N) and phosphorus (P), 50 % of sulphur (S) and 75 % of potassium (K) uptake by cereal crops are retained in crop residues, making them valuable nutrient sources. According to the study by Sidhu *et al*. (2007), the paddy straw has 39 kg/ha N, 6 kg/ha P, 140 kg/ha K, and 11 kg/ha S. Sidhu and Beri (2005) shared their experience with managing rice residues in intensive rice-wheat cropping system in Punjab. According to them, the approximate amount of the nutrients present in the straw burned in 2003–2004 was 106, 65 and 237 thousand tonnes of N, P_2O_5 and K_2O, respectively, in addition to secondary and micro-nutrients. About 90 % of N and S and 15-20 % of P and K contained in rice residue are lost during burning. Burning of 23 million tonnes of rice residues in north-west India leads to a loss of about 9.2 million tonnes of C equivalent (34 million tonnes CO_2 equivalent) per year and a loss of about 1.4×10^5 t of N (INR 2000 million) annually. In a long-term field study on rice-wheat system at Ludhiana, it was found that the incorporation of rice straw in wheat for three years had no yield advantage for wheat. However, the yield of following rice crop was the same with the application of 90 kg N/ha as compared to the application of 120 kg N/ha on straw removed plots, thereby saving of 30 kg N/ha.

Impact on Health: Social impact includes the impact on human and animal health in particular. The burning of crop stubble has severe adverse impacts, especially for those people suffering from respiratory and cardiovascular diseases. Pregnant women and small children are also likely to suffer from the smoke produced from stubble burning. Inhaling of fine particulate matter of less than $PM_{2.5}$ triggers asthma and can even aggravate symptoms of bronchial attack. According to Singh *et al*. (2008), more than 60 % of the population in Punjab live in the rice-growing areas and is exposed to air pollution due to the burning of rice stubbles. They observed a 10 % increase in the number of patients within 20–25 days of the burning period in the rice-wheat belt every season. Besides, the burning of crop residue also emits a large amount of particulates composed of a wide variety of organic and inorganic species. Many of the pollutants found in large quantities in biomass smoke are known or suspected carcinogens and could lead to various air borne/lung diseases.

The burning of crop waste also has an adverse effect on the health of milk producing animals due to smoke. There can also be a potential decrease in the yield of milk-producing animals.

Environmental impact: According to the Report on Ex-situ Crop Residue Management Options (ICAR, 2021), the burning of crop residues results in the emission of gases such as CH_4, CO, N_2O and NO; particulate matters (PMs), loss of plant nutrients and adversely affects the atmosphere, the environment and soil health. The entire amount of C, approximately 80 to 90 % of N, 25 % of P, 20 % of K and 50 % of S present in the crop residues are lost in the form of various gaseous and particulate matters resulting in atmospheric pollution. It is also estimated that about 70 % CO_2, 7 % CO, 0.66 % CH_4 and 2.1 % N are emitted as N_2O due to crop residue burning, which impacts on environment heavily. It is estimated that one tonne of rice residue on burning releases 13 kg particulate matter, 60 kg CO, 1460 kg CO_2, 3.5 kg NO_x, 0.2 kg SO_2.

The total emissions of eight major air pollutants from crop residue burning in India for 2018 are estimated. The estimated total emissions of four particulate pollutants, viz $PM_{2.5}$, PM_{10}, BC and OC are 0.99 Mt/year, 1.23 Mt/year, 0.12 Mt/year and 0.41 Mt/year, respectively; of four gaseous pollutants viz CO, NOx, SO_2, VOC are 11.20 Mt/year, 0.48 Mt/year, 0.14 Mt/year, 1.28 Mt/year respectively; and two Greenhouse gases (GHGs) viz CH_4 and CO_2 are 0.78 Mt/year and 262.05 Mt/year respectively (Sahu *et al*., 2021).

In the case of $PM_{2.5}$, rice contributes around 41 % (0.408 Mt), followed by wheat (27 %), sugarcane (14 %), maize (8 %) and coarse cereals (7 %). In the case of PM_{10}, the maximum contribution comes from rice (36 %), followed by wheat (24 %) and sugarcane (24 %). The relative contribution of pollution load from different crops keeps on changing (Sahu *et al*., 2021).

The emissions of N_2O and CH_4 due to biomass burning of important crops in India are reported in Table 3. The biomass burned during four consecutive years (2016-2019) for rice crop is the highest amongst all crops, which also results in the high emissions of N_2O and CH_4 for rice.

Table 3: Biomass burned and emission data for important crops in India

Crop	Year	Production (Mt)	Straw production (Mt)	Biomass burned (dry matter), (Mt)	N_2O emissions (kt)	CH_4 emissions (kt)
Wheat	2016	92.29	161.51	12.17	0.85	32.85
	2017	98.51	172.39	12.31	0.86	33.24
	2018	99.87	174.77	11.86	0.83	32.02
	2019	103.6	181.30	11.72	0.82	31.66
Rice	2016	104.41	156.62	24.07	1.66	64.13
	2017	109.7	164.55	24.07	1.68	65.00
	2018	112.7	169.05	24.28	1.7	65.57
	2019	116.48	174.72	24.07	1.68	65.01
Maize	2016	22.57	33.86	9.9	0.693	26.73
	2017	25.9	38.85	9.63	0.67	26.00
	2018	28.75	43.13	9.38	0.66	25.32
	2019	27.72	41.58	9.02	0.63	24.37
Sugarcane	2016	348.44	139.38	3.22	0.22	8.68
	2017	306.07	122.42	2.88	0.20	7.78
	2018	379.90	151.96	3.07	0.21	8.31
	2019	405.11	162.04	3.289	0.23	8.88

Source: MAFW (2022a); Calculations by the authors using Sahu et al. (2021)

The release of carbon dioxide in the atmosphere due to crop stubble burning leads to the depletion of the oxygen layer in the natural environment causing greenhouse effect. The black carbon emitted during residue burning warms the lower atmosphere and is the second most important contributor to global warming after CO_2.

Impact on Soil: Crop residue burning depletes the soil of its organic matter and major nutrients and reduces soil microbial biomass, ultimately impairing application of organic matter's efficacy in the next crop. In addition, it causes the loss of vital components such as nitrogen, phosphorus, sulphur and potassium from the topsoil layer, making the land less fertile and unviable for agriculture in the long run. Generally, crop residues of different crops contain 80 % of Nitrogen (N), 25 % of Phosphorus (P), 50 % of Sulphur (S) and 20 % of Potassium

(K). If the crop residue is incorporated or retained in the soil itself, it gets enriched, particularly with organic C and N. Heat from burning residues elevates soil temperature causing death of beneficial soil organisms. Frequent residue burning leads to complete loss of microbial population and reduces the level of N and C in the top 0-150 mm soil profile, which is important for crop root development.

6. Integrated Management of Crop Residues

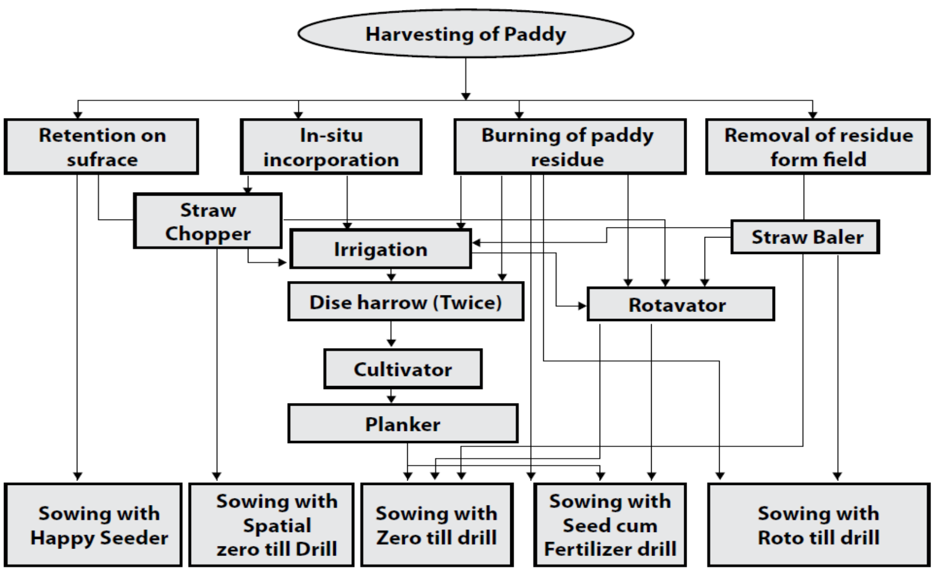
Crop residues can be managed by in-situ and ex-situ management methods. The retaining or mulching and incorporating of crop residues in the field, and decomposing using consortia of microbes are two in-situ crop residue management methods. Ex-situ management refers to the baling and transporting of straw outside the field for other alternative uses. The ex-situ method is more capital intensive and requires a significant subsidy amount for farmers and the user industry to be sustainable. The interventions in crop residue management are conservation agriculture, in-situ straw incorporation, biomass energy production, bio-fuel generation, crop residue-based biorefinery, biochar production, composting and mushroom production (MoA, 2014; Lohan *et al*., 2018).

6.1 In-situ management of crop residues

In-situ management of the crop residues involves on-farm utilization through:

- Residue mulching: Zero tillage and Happy seeder machine, preferably after operation of combines with a Straw Management System (SMS)
- Residue incorporation: operating paddy chopper cum spreader and the reversible mould board plough or rotavator, which requires a lot of energy

Figure 4: Paddy straw management techniques



Source: Lohan et al. (2018)

Such practices are adopted by many farmers as it is a natural process and it imparts certain benefits to the soil. Mulching and incorporation are two main ways of conducting field applications, but both methods involve leaving crop residue on the farmland after harvesting. In the mulching method, planting in the next season is carried out in zero-tillage or reduced tillage conditions. In the incorporation method, crop residue is mixed into the soil by mechanical means during tillage (Figure 4). While in-situ management of crop residues can offer long-term cost savings on equipment and labour, both methods need special (new) equipment and machinery for crop residue incorporation into soils or no-till seeding equipment.

Farmers do not prefer in-situ incorporation because the stubble takes a long time to break down into the soil (particularly paddy crops). However, there are advantages to the soil properties by in-situ incorporation of straw.

Ploughing back or surface retention of farm waste in-situ, yields many benefits on physical, chemical and biological properties of soil. These practices increase hydraulic conductivity and reduce the bulk density of soil by modifying soil structure and aggregate stability. Mulching with plant residues raises the minimum soil temperature in winter due to a reduction in upward heat flux from soil and decreases soil temperature during summer due to the shading effect.

The crop residues act as a reservoir for plant nutrients, prevent leaching of nutrients, increase cation exchange capacity (CEC), provide a congenial environment for biological N_2 fixation, increase microbial biomass and enhance activities of enzymes such as dehydrogenase and alkaline phosphatase. Increased microbial biomass can enhance nutrient availability in the soil as well as act as a sink and source of plant nutrients. Leaving substantial amounts of crop residues evenly distributed over the soil surface reduces wind and water erosions, increases water infiltration and moisture retention, and reduces surface sediment and water runoff.

The role of crop residues on carbon sequestration in soils would be an added advantage in relation to climate change and GHGs mitigation. While reduced tillage and soil organic carbon build-up contribute to stable soil structure, this undisturbed structure produces macro pores and preferential flow channels that can direct nutrients, including phosphorous, downward into deeper parts of the soil profile. Conservation tillage can reduce overall nitrogen loss by reducing ammonium-nitrogen loss and organic-nitrogen loss with sediment; however, it may not reduce nitrogen leaching in the nitrate form. Yield response with residue management varies with soil characteristics, climate, cropping patterns, and level of management skills. Higher yields with crop residue application result from increased infiltration and improved soil properties, increased soil organic matter and earthworm activity and improved soil structure after a period of four to seven years. Incorporation of crop residues in conservation agriculture has direct and indirect effects on pests too. Crop residues generally increase the diversity of useful arthropods and help in reducing pest pressure.

The brief details of farm machinery suitable for in-situ management of crop residues are as follows.

Zero till drill

Zero till drill is used to directly drill wheat seeds in standing paddy stubbles (Figure 5). In this type of drill, inverted T type furrow openers are used. It is particularly useful where basmati rice is cultivated and which is manually harvested, leaving short-anchored stubbles. It is a lighter machine as compared to a Happy seeder and can be pulled easily by low power tractors. However, the problem of choking of furrow openers and higher insect and weed infestations are reported in sowing with a zero till drill (Choudhary *et al*., 2019).

Figure 5: Zero till drill

Courtesy of ICAR/PAU

Happy seeder

Punjab Agricultural University (PAU) has developed the Happy seeder for sowing wheat directly into the combine harvested paddy fields without any other operation (Figure 6). A Happy seeder can be operated by a 45 hp or above tractor. It cuts straw in front of furrow openers and throws it over the sown crop in a single operation which acts as mulch. This mulch helps to conserve soil moisture, prevent soil erosion, and suppress weed growth. Mulch helps to reduce irrigation requirements by about 15-20 % and weed emergence by about 50 %. Sowing with the help of Happy seeder reduces labour requirements by 80 %, saves fertilizers up to 10 % and increases yields up to 5 %. It also prevents choking of the machine under a heavy straw load. A Happy seeder can cover about 2.4 - 3.2 ha in one day and is commercially available in 10, 11 and 13 row models (Manes *et al*., 2017).

Figure 6: Happy seeder

Courtesy of ICAR/PAU

Strip till seeder (Smart seeder)

The Strip till seeder **(**Smart Seeder) (Figure 7) was developed by PAU, Ludhiana centre of All India Coordinated Research Project (AICRP) on Farm Implements and Machinery. It can be operated with a 45 hp or above tractor. This tractor mounted machine is essentially a seed drill which is capable of operating in a paddy stubble and straw laden fields (as available after combine harvesting). The Smart seeder incorporates only a small part of the straw into the soil and retains the majority of straw as surface mulch; due to this, the chances of seeds dropping on

Figure 7: Smart seeder

Courtesy of ICAR/PAU

straw are reduced. The effective field capacity and fuel consumption of the machine are 0.40 ha/h and 5.58 l/h, respectively.

Super seeder

The super seeder (Figure 8) can be operated after harvesting paddy with a combine harvester having a SMS. The machine is operated by a 55 hp or above tractor. The super seeder sows wheat seeds and also mixes crop residue into the soil in a single pass. The machine consists of a straw managing rotor for incorporation of paddy straw and a seeding unit for sowing wheat directly after combine harvesting. The effective field capacity and fuel consumption of the machine are 0.25-0.30 ha/h and 8.0-9.0 l/h, respectively.

Figure 8: Super seeder

Courtesy of ICAR/PAU

Super straw management system (SMS)

The combine harvester harvests cereal crops in a width equal to its cutter bar width and throws straw residues from straw walkers in the centre of the harvested area. The width of straw walkers is usually one-third the width of the cutter bar of the combine. This forms the lines of loose residues (as wide as straw walker width) parallel to the operation of combine harvester. This uneven residue load hinders the operation of Happy seeders. To solve the problem of uniform spreading of loose straw before the operation of Happy seeder, PAU developed a straw management system (PAU Super SMS) as an attachment for the self-propelled combine harvester (Figure 9). The Super SMS is an attachment fitted at the rear of the combine harvester which chops and uniformly spreads the loose straw coming out of harvester straw walkers. It facilitates the working of the Happy Seeder and increases its capacity.

Figure 9: Super SMS

Courtesy of ICAR/PAU

Straw chopper-cum-spreader

A straw chopper cum spreader is a machine which chops and uniformly spreads straw left by combine harvester in a single operation (Figure 10). In this machine, the harvesting and chopping operations are combined. It is operated by 45 hp or above tractor. The harvesting unit consists of a cutter bar unit, reel, beater and platform auger through which the crop is cut, collected and conveyed to the chopping unit. The chopped and evenly spread straw can be mixed into the soil by using tillage machinery like mould board plough, rotavator, etc., under dry or wet conditions (Mahal *et al*., 2019). The effective field capacity and fuel consumption of the machine are 0.35-0.38 ha/h and 6.5-7.0 l/h, respectively (Manes *et al*., 2017).

Figure 10: Straw chopper cum spreader

Courtesy of ICAR/PAU

Reversible mould board plough

The reversible plough has two mould board ploughs mounted back-to-back, one turning to the right and the other to the left (Figure 11). While one is operated on the land, the other is carried upside-down in the air. The basic functions of the plough are breaking and inverting the soil. Therefore, the chopped straw is incorporated into the soil, and the underground soil comes above with the inversion. It costs INR 0.10 million. Reverse ploughing helps to effectively incorporate straw into the soil, and the next crop can be sown easily over this soil bed. After chopping-spreading paddy straw, potato growers prefer to bury the straw deep, up to 300 mm, so that ridges to place potato seed tubers are free from any trash (Choudhary *et al*., 2019).

Figure 11: Reversible MB plough

Courtesy of ICAR/PAU

Roto till drill

The roto seed drill is a combination of a rotavator and a seed drill (without tines) (Figure 12). The rotavator attached in front of the seeding unit cuts and incorporates the straw into the soil. It is used for sowing a wide variety of crops like maize, wheat, pea, mustard etc., directly into the untilled soil.

Figure 12: Roto till drill

Courtesy of ICAR/PAU

Mulcher

A Mulcher with a vertical axis of rotation is a rotation mower (Figure 13). It is used to chop the straw into smaller pieces which are then pressed by a roller attached at the rear side. It compresses the straw creating a mulch layer over the topsoil. Then, a Happy seeder or reversible MB plough can be used to sow wheat or invert straw into the soil, respectively (Choudhary *et al*., 2019)

Figure 13: Mulcher

Courtesy of ICAR/PAU

Straw reaper

The straw reaper is normally used after operation of the combine harvester to cut the leftover stubble and convert it into bruised fine straw locally known as *bhusa* either for animal feed or spread over the field for mulching purposes. It is trailed behind tractor PTO powered machinery (Figure 14). The reaper can perform cutting, picking, threshing and blowing operations in single action and is economically viable for the wheat crop (Verma *et al*., 2016; Shukla *et al*., 2020). It has straw recovery from 80 to 95% (Ujala *et al*., 2020).

Figure 14: Straw reaper

Courtesy of ICAR/PAU

Sugarcane trash chopper cum spreader

Sugarcane trash chopper cum spreader is used to chop the trash and spread it into the field uniformly (Figure 15). The unit has two rotary members with swinging type blades. The rotary cutting units can be sled inward or outward according to the row to row spacing of the standing sugarcane crop. The unit shreds the sugarcane trash of sizes from 600 to 900 mm into small pieces of about 75 mm size (Kumar *et al*., 2016).

Figure 15: Sugarcane trash chopper cum spreader

Courtesy of ICAR/PAU

Rake

Rakes are commercially available and can be used to collect the cut and loose paddy straw from fields and make a windrow of narrow width, thereby providing dense straw input for the baler machine (Figure 16). The side delivery rake and star wheel rake are popular in India. The side delivery rake usually has a gear-driven or chain-driven reel mounted at an angle of 45° to the windrow, so the straw is gathered and pushed to one side of the rake as it moves across the field. A side delivery rake could be pulled longitudinally along the windrow. The approximate cost of these machines is INR 0.20-0.25 million. The wheel rakes or star wheel rakes consist of 5, 6, 7, or more spring-tooth encircled wheels mounted on a frame and ground driven by free-wheeling contact as the implement is pulled forward. These rakes are mechanically simple and trouble-free, gentle on the straw than a side-delivery rake, and cheaper to operate. A smaller wheel rake costs INR 85,000 and the approximate cost of a 5 m rake is INR 0.18 million (Manes *et al*., 2017).

Figure 16: Rake

Courtesy of ICAR/PAU

Baler

The straw baler is used for collection and baling straw in the combine-harvested field (Figure 17). Before baling, a stubble shaver is operated to harvest the stubbles from the base level. It can form bales of varying length from 0.40 to 1.10 m. The weight of bales varies from 20 to 30 kg depending on the moisture content of the straw and the length of the bales. The effective field capacity of the baler ranges from 0.30 to 0.35 ha/h. However, these balers recover only 25–30 % of

Figure 17: Baler

Courtesy of ICAR/PAU

potential straw yield after combining, depending upon the height of the plant cut by combines. Balers make rectangular or round bales by collecting the loose straw from the ground. Thus, balers provide a solution for straw management in an environmentally friendly way (Sharma and Bhattu, 2015; Krishnaveni and Dayana, 2021).

6.2 Ex-situ management of crop residues

Despite its clear environmental merits, in-situ management cannot entirely address the issue due to technical challenges. The large amount of available crop residues makes it impossible to plough back all the residues into the soil (CII and NITI Aayog, 2018). Therefore, keeping in view the increasing problems associated with crop stubble burning, several technologies for ex-situ management of crop residues are also being promoted. Ex-situ management of crop residue involves off-farm utilization through the collection of straw by operating a straw chopper followed by hay rakes and balers and transportation to other places for numerous competing uses such as animal feed fodder, fuel, roof thatching, packaging, composting, power generation, etc. Globally, removing excess residue and using it as feedstock for energy purposes proved to increase farmer income. Various existing and emerging technologies such as pyrolysis (bio-char), bio-methanation (bio-gas), and conversion to bio-fuels (such as briquettes, pellets, bio-compressed natural gas [CNG], and bio-diesel) have been recommended for ex-situ uses of crop residues (CII and NITI Aayog, 2018). The following ex-situ residue management methods offer an attractive option for managing the excess crop residue generated.

Briquetting of crop residues as an industrial fuel supplement

Biomass briquetting is a standard method for producing high density, solid energy carriers from biomass. Briquettes/Pellets are manufactured in several types and grades as fuels for electric power plants, other industrial uses, homes, and other applications. Pellet-making equipment is available in different sizes and scales, which allows manufacturing at domestic as well as industrial scales (Figure 18a). Pellets have a cylindrical shape and are about 6-25 mm in diameter and 3-50 mm in length (Figure 18b). Before feeding biomass to pellet mills, the biomass should be reduced to small particles of not more than 3 mm in size. If the pellet size is too large or too small, it affects the quality of the pellet and, in turn, increases the energy consumption. Size reduction is done using a hammer mill equipped with a screen of sizes from 3.2 to 6.4 mm. The feedstock passes through a chipper before grinding if it is quite large.

Figure 18a: Pellet making machine **Figure 18b: Prepared pellets**

Courtesy of ICAR/PAU

Courtesy of ICAR/PAU

Binders or lubricants may be added in some cases to produce high-quality pellets. Binders increase the pellet density and durability. Wood contains natural resins which act as a binder. However, agricultural residues do not contain much resins or lignin, so a stabilizing agent needs to be added. Distillers of dry grains or potato starch are some commonly used binders. The cost of the commercially available biomass pellets is INR 9,000-10,000 per tonne.

The briquetting plants have been installed in India since the mid-1990s, in the western and southern regions. A rough estimate says that around 50,000 tonnes of briquettes are consumed annually by the tea industry alone in the state of Tamil Nadu, and 20,000 tonnes by the Indian Tobacco Company in the state of Karnataka.

Bio-gas production

Paddy straw can be digested by anaerobic means to produce biogas as fuel for the kitchen as well as for power generation. The semi-dry fermentation of organic wastes is carried out in the anaerobic digester. The digested material produced from such anaerobic digestion is good quality manure ready for use in the fields. Biogas production through anaerobic digestion is the most efficient way in terms of energy output per unit of energy input for handling biomass resources.

Figure 19: Paddy straw-based bio-gas plant

Courtesy of ICAR/PAU

The PAU, Ludhiana centre of the AICRP on Energy in Agriculture and Agro-Industries (EAAI) has developed a biogas plant for alternate use of paddy straw for bio-gas production (Figure 19). This process of semi-dry fermentation is a batch process, and each batch of biomass produces biogas for a period of about three months after loading and activation. Each batch can hold 1.60 tonnes of paddy straw and 0.40 tonnes of cow dung as feed materials. Water is added in plant to saturate the paddy straw.

Gas production starts after about 7-10 days. The quantity of gas produced in the plant will be about 3-4 m^3 per day (equivalent to 2 to 3 cylinders of LPG per month). This gas may be used for cooking purposes or other energy options. This technology may be a viable alternative for a cluster of farmers or a community-based biogas plant in a small village.

The estimated cost of the biogas plant for handling about 1.6 tonnes of paddy straw is INR 0.12 million, which is about four times more costly as compared to conventional animal dung-based biogas plant of the same capacity. One biogas plant can manage 4.5-5.0 tonnes of paddy straw per year. Six biogas plants have been installed in Punjab and are working very well.

Bio-CNG/Compressed biogas (CBG)

The utilization of surplus crop residue, especially the paddy straw, to generate Bio-CNG/CBG creates better opportunities for reducing environmental pollution and employment generation. The estimated total energy yield per tonne of paddy straw is 8.0 GJ when converted to bio-methane compared with the energy yield of 5.6 GJ when converted to bio-ethanol. The large quantities of raw biogas generated from the paddy straw by anaerobic digestion can be used for producing bio-CNG or bio-power (electricity). The process of bio-CNG production generally includes feedstock collection, segregation, pre-treatment, bio-methanation, biogas scrubbing and compression and bottling of scrubbed biogas. Bio-CNG comprises more than 90% methane of calorific value ranging from 11,200 to 11,500 kcal/kg. Biogas production potential of paddy straw ranges from 250 to 300 m^3 per tonne of straw with a methane content of 55 - 60%, and from this volume, about 120 to 140 kg of CNG or about 550 to 600 kWh of electricity can be produced.

During the year 2008-09, a new initiative was taken by MNRE for technology demonstration on biogas bottling projects through entrepreneurs, for installation of medium-size mixed feed biogas plants for generation, purification and bottling of biogas under a Research, Design, Development and Demonstration (RDD&D) policy. Installation of such plants aims at production of CNG quality of Compressed Biogas (CBG) to be used as a vehicle fuel in addition to meeting stationary and motive power, electricity generation and thermal application. This was a decentralized establishment of a sustainable business model in this sector. So far, 11 animal dung-based biogas bottling projects of various capacities have been commissioned in the country after obtaining the required licenses for filling and storage of compressed biogas in CNG cylinders.

The purified biogas is filled in a CNG cylinder and supplied to mid-day meal schemes, messes, hotels, industries, etc., for various purposes such as cooking, heating, etc. The calorific value of purified biogas is equivalent/similar to CNG.

Power generation from biomass

Crop residue-based power generation process includes biomass combustion, biomass gasification and bagasse cogeneration. India has an installed capacity of over 5,940 MW biomass-based power plants comprising 4,946 MW grid-connected and 994 MW off-grid power plants. Out of the total grid-connected capacity, a major share comes from bagasse cogeneration, and around 115 MW is from waste to energy power plants. The off-grid capacity comprises 652 MW non-bagasse cogeneration, mainly as captive power plants, about 18 MW biomass gasifier systems being used for meeting electricity needs in rural areas, and 164 MW equivalent biomass gasifier systems deployed for thermal applications in industries.

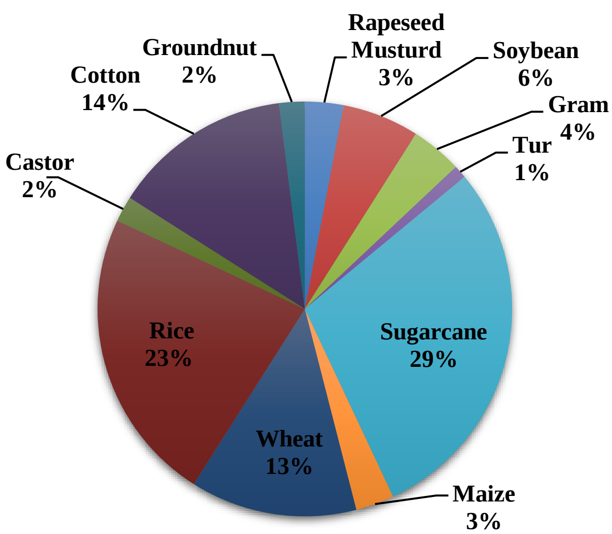
The biomass power projects are environmentally friendly because of relatively lower CO_2 and particulate emissions. They displace fossil non-renewable fuels such as coal. The biomass consumption in power plants is about 30 tonne/day/MW and ash coming out from the plant is about 4.5 tonnes per day/MW plant.

There is a requirement of considerable area for the safe storage of bales for their utilization during off season periods. Hence, the land available in the village may be taken on lease or Panchayat (community) land may be made available for decentralized storage of bales. Ultimately, transportation distance is a decisive factor in the economics of biomass pellets-based power plants. It was concluded that transportation of bales is quite feasible and economical from a distance of 15 km radius. Hence, transportation of the bales up to the safe storage place and the smaller size plants of capacities from 4 to 10 MW power generation may be encouraged.

Bio-ethanol production

Biofuels have been used globally for years to increase energy self-sufficiency, reduce vehicular emissions and increase transport sustainability. The global biofuel supply has increased by 8 % since 2000, which is equivalent to 4 % of the world's transport fuels in 2015. The global biofuel supply was approximately 35 billion gallons in 2015, with approximately three fourth of ethanol and one fourth of biodiesel supply. Until 2015, 70 % of the global biofuel supply was met by Brazil and the United States (Araujo *et al.*, 2017). The main raw materials used by these countries were sugarcane (Brazil) and corn (USA) for bio-ethanol production. This type of biofuel which is produced from food-based crops is also known as first generation biofuel.

Figure 20: Bio-ethanol production potential of different crops



Source: TIFAC and IARI (2018)

Conversion of lignocellulosic biomass into alcohol is of immense importance as the competition for cropland between biofuels and food can be minimized. The biofuels produced from non-food crops and residues (lignocellulosic/cellulosic biomass) or waste materials are known as second-generation biofuels. The technology of ethanol production from crop residues is, however, evolving in India (TIFAC and IARI, 2018). The study estimated a total annual bio-ethanol production potential of 51.35 billion litre (Bl) from 178 Mt of surplus crop biomass generated in country. The crop wise maximum bio-ethanol potential was of sugarcane crop biomass followed by rice, cotton and wheat crop biomass (Figure 20). A viable operational system of using surplus biomass for generating biofuel provides prospects for increasing the revenue of famers and contributes to energy security of the country.

7. Alternative Technologies for Management of Crop Residues

Bio-char

In recent years, increased concerns for healthy food production and environmental quality and increased emphasis on sustaining the productive capacity of soils have raised interests in the maintenance and improvement of soil organic matter through appropriate land use and management practices. Biochar is produced via the burning of waste biomass at 300-600ºC in the partial or complete exclusion of oxygen, a process known as pyrolysis. It is a fine-grained charcoal and can potentially play a major role in the long-term storage of carbon in soil, i.e., C sequestration and GHG mitigation. Biochar offers significant prospects for sequestering about 40 – 50 % of original biomass carbon into soil in a chemically altered form that is biologically stable and could last in soil for centuries, but remain active physically and chemically. Due to its greater stability against microbial decomposition and its superior ability to retain nutrients compared to other forms of soil organic matter, applying biochar to soil also offers a significant potential for mitigating climate change and enhancing environmental quality. Biochar can stimulate native soil microbial activity providing favourable habitat for microbes and encourage mycorrhizal fungal colonisation for improved plant water and nutrient supply and may promote rhizobia for N_2 fixation in leguminous plants.

Specifically, biochar is used in various applications such as the water treatment, construction industry, food industry, cosmetic industry, metallurgy, treatment of wastewater and many other chemical applications. In India currently, the biochar application is limited and mainly seen in villages and small towns.

With the current level of technology, it is not economically viable and cannot be popularized among the farmers. However, once all the valuable products and co-products such as heat energy, gas like H_2 and bio-oil are captured and used in the biochar generation process, it would become economically viable. There is a need to develop low-cost pyrolysis kiln for the generation of biochar to utilize surplus crop residues, which are otherwise burned on-farm. There is a need to evaluate and maximise the benefits of biochar application on soil health, carbon sequestration and nutrient use efficiency in different soils under different cropping systems in India.

Compost making

The crop residues have been traditionally used for preparing compost. The high organic content in crop residue makes it an ideal raw material for compost similar to animal manure and food waste. Composting is the natural process of rotting or decomposition of organic matter by micro-organisms under controlled conditions. As a rich source of organic matter, compost plays an important role in sustaining soil fertility and thereby helping to achieve sustainable agricultural productivity. Addition of compost to the soil improves physio-chemical and biological properties of the soil and can completely replace application of agricultural chemicals such as fertilizer and pesticides. Higher potential for increased yields and resistance to external factors such as drought, disease and toxicity are the beneficial effects of compost amended soil. These techniques also help in higher nutrient uptake, and active nutrient cycling due to enhanced microbial activity in the soil.

For compost making, crop residues are used as animal bedding and are then heaped in dung pits. In the animal shed, each kilogram of straw absorbs about 2-3 kg of urine, which enriches it with N. The residues of rice crop from one hectare land, on composting, give about 3 tonnes of manure as rich in nutrients as farmyard manure (FYM).

The option of composting paddy straw is not recommended for crop residues management due to diversion of land area for composting resulting into grain production loss. The process of collecting and transporting the straw from the field to the compost site and managing it over the composting period are labour intensive and cumbersome. In-situ composting using consortia of microbes developed may become more viable and easier option than off the field composting.

PUSA decomposer

PUSA decomposer technology has been developed by the Indian Agricultural Research Institute (IARI) and Punjab Agricultural University (PAU). The decomposers are in the form of four capsules made by extracting fungi strains that help the paddy straw to decompose at a much faster rate than usual. The fungi help to produce the essential enzymes for the degradation process. The decomposer mixture involves making a liquid formulation using decomposer capsules and fermenting it for 8-10 days and then spraying the mixture on fields with crop stubble to ensure speedy bio-decomposition of the stubble. The farmers can prepare 25 litres of liquid mixture with 4 capsules, jaggery and chickpea flour. The mixture is sufficient to cover 1 hectare of land. It takes around 20 days for the degradation process to be completed.

The decomposer improves the fertility and productivity of the soil as the stubble works as manure and compost for the crops and fertiliser consumption is reduced. It is an efficient and effective, cheaper and practical technique to stop stubble burning. It is an eco-friendly and environmentally useful technology. IARI has licensed this technology to 12 companies for mass multiplication and marketing of the PUSA decomposer. In addition, ICAR-IARI, New Delhi has produced about 20,000 packets of PUSA decomposer in 2021 at its own facility for use by the farmers.

Fodder for animals

In India, crop residues are traditionally utilized as animal feed on its own or by supplementing with some additives. However, crop residues, being unpalatable and low in digestibility, cannot form a sole ration for livestock. Crop residues are low-density fibrous materials, low in nitrogen, soluble carbohydrates, minerals and vitamins with varying amounts of lignin which acts as a physical barrier and impedes the process of microbial breakdown. To meet the nutritional requirements of animals, the residues need processing and enriching with urea and molasses, and supplementing with green fodders (leguminous/non-leguminous) and legume (sunhemp, horse gram, cowpea, gram) straws.

The rice residue as fodder for animals is not a very popular practice among farmers in Punjab. This is mainly because of the high silica content in the rice residue. It is believed that almost 40% of the wheat straw produced in the state is used as dry fodder for animals. The availability of crop residue is highest in Uttar Pradesh, followed by Maharashtra, Bihar, Rajasthan and Andhra Pradesh. Except Assam almost all the North-eastern states and Kerala have least availability of crop residue. States like Punjab, Haryana and Bihar has higher per animal availability of crop residues as fodder as compared to other states of India.

Bedding material for cattle

In the study conducted by the Department of Livestock Production and Management, Punjab Agricultural University, it has been observed that the use of paddy straw bedding during winter helped in improving the quality and quantity of milk as it contributed to animals' comfort, udder health and leg health. Paddy straw bedding helped the animals to keep themselves warm and maintain reasonable rates of heat loss from the body. It also provides clean, hygienic, dry, comfortable and non-slippery environment, which prevents the chances of injury and lameness. Healthy legs and hooves ensure enhancement of milk production and reproductive efficiency of animals. The paddy straw used for bedding could be subsequently used in bio-gas plants.

Mushroom cultivation

One kg of paddy straw can be used for the cultivation of 300, 120–150 and 600 g Agaricus bisporus, Volvariella Volvacea and Pleurotus varieties of mushroom, respectively. Paddy Straw Mushrooms (Volvariella Volvacea) are also known as grass mushrooms. Paddy straw mushrooms are high temperature mushrooms grown largely in tropical and subtropical regions of Asia, e.g., China, Thailand, Indonesia, India and Madagascar. In Indonesia and Malaysia, mushroom growers just leave thoroughly moistened paddy straw under trees and wait for harvest. This mushroom can be grown on a variety of agricultural wastes for preparation of the substrate such as water hyacinth, oil palm bunch waste, dried banana leaves, cotton or wood waste, though with lower yield than with paddy straw, which is most successful. Paddy straw mushroom accounts for 16 % of total production of cultivated mushroom in the world.

Paper production

The paddy straw is also being used in conjunction with wheat straw in a 40:60 ratio for paper production. The sludge can be subjected to bio-methanation for energy production. The technology is already operational in some paper mills, which are meeting 60 % of their energy requirements through this method. Satia Industries Limited located in Punjab is manufacturing eco-friendly paper by using agricultural residues. Paddy straw is also used as an ideal raw material for paper and pulp board manufacturing. It contains lesser lignin compared to conventional wood and thus requires mild chemical pre-treatment. Bio-plastics, derived from rice straw by mixing with starch, cellulose, glycerol and protein is ready to substitute the conventional plastic as it is readily biodegradable within 180 days of use compared to 500 years required for plastics to degrade (Dwibedi *et al*., 2021).

8. Schemes and efforts of the Government of India

The National Green Tribunal (NGT) established under the National Green Tribunal Act (2010) laid down directives to states for curbing crop residue burning through recycling initiatives and awareness among the people. On 10 December 2015, the NGT banned crop residue burning in states of Rajasthan, Uttar Pradesh, Haryana, and Punjab. These states have reportedly imposed fines in the range of INR 2500- 15,000 on farmers found to burn crop residue (Jitendra *et al*., 2017).

The Ministry of Agriculture developed a National Policy for Management of Crop Residue (NPMCR) in 2014 with the following major objectives to prevent agricultural residue burning and circulated the same to all the states/union territories.

i. To promote technologies for optimum utilization and in-situ management of crop residues,

ii. To promote appropriate machineries for farming practices,

iii. To use satellite-based technologies to monitor crop residue management with National Remote Sensing Agency (NRSA) and Central Pollution Control Board (CPCB), and

iv. To provide financial support through multi-disciplinary approach and fund mobilization in various ministries for innovative ideas and project proposals to accomplish the goal of zero residue burning.

During 2019–20, the Punjab government disbursed INR 190 million among 29,343 non-basmati cultivating small and marginal farmers (INR 6,250/ha) who did not burn paddy residue (PTI, 2019).

In order to curb burning and reducing winter smog pollution, a Central Sector Scheme on "Promotion of Agricultural Mechanization for In-situ Management of Crop Residue in States of Punjab, Haryana, Uttar Pradesh and NCT of Delhi" was approved by Government and operated through the Machinery and Technology Division of the Department of Agriculture and Farmers Welfare, New Delhi. Budget allocated to the scheme was INR 11.52 billion for two years (INR 5.92 billion for 2018-19 and INR 5.60 billion for 2019-2020). It was extended for two more years (2020-21 and 2021-22) with budgetary allocation of INR 13.00 billion. The objectives of the scheme are as follows.

i. Protecting the environment from air pollution and preventing loss of nutrients and soil micro-organisms caused by burning of crop residue.

ii. Promoting in-situ management of crop residue by retention and incorporation into the soil through the use of appropriate mechanization inputs.

iii. Promoting Farm Machinery Banks for custom hiring of in-situ crop residue management machinery to offset the adverse economies of scale arising due to small land holding and high cost of individual ownership.

iv. Creating awareness among stakeholders through demonstration, capacity building activities and differentiated information, education and communication strategies for effective utilization and management of crop residue.

Under this scheme, there was financial assistance on purchase of nine straw management implements of 50 % of the cost of the implement for individual farmers and 80 % of the cost of implements for Custom Hiring Centre (CHC) by Co-operative Societies of farmers, groups or SHGs, FPOs and Private Entrepreneurs. Name of the implements included in the scheme are i) Super Straw Management System (Super SMS) to be attached with Combine Harvester; ii) Happy Seeder; iii) Paddy Straw Chopper/Shredder/Mulcher; iv) Shrub Master/Cutter cum Spreader; v) Hydraulic Reversible M.B. Plough; vi) Rotary Slasher; vii) Zero Till Seed cum Fertilizer Drill; viii) Super seeder, ix) Rotavator.

An amount of INR 24.17 billion were released to different states and ICAR during last four years under the scheme. The money released to Punjab, Haryana, Uttar Pradesh, NCT Delhi and ICAR were INR 11.25 billion, INR 6.93 billion, INR 5.34 billion, INR 45.2 million and INR 0.55 billion, respectively. During past four years, total 0.213 million equipment/machines were supplied in these states (Punjab- 85,386, Haryana- 72,237, and UP-55,711) under the scheme (Table 4). Custom hiring centres (39,391) were established in Punjab (25,403), Haryana (6,775) and Uttar Pradesh (7,213) for making easy availability of equipment/machines to the small and marginal farmers on a hire basis. A mobile app-based aggregator platform was developed to facilitate hiring of machines from Custom Hiring Centres.

Table 4: Machines delivered and CHC established from 2018-19 to 2021-22

Number of crop residue management machines delivered and CHC established													
Year	**Punjab**			**Haryana**			**Uttar Pradesh**			**NCT of Delhi**			**Total Machines**
	Machine to Individual farmers	**CHC Machines (No. of CHCs)**	**Sub-Total machines**	**Machine to Individual farmers**	**CHC Machines (No. of CHCs)**	**Sub-Total machines**	**Machine to Individual farmers**	**CHC Machines (No. of CHCs)**	**Sub-Total machines**	**Machine to Individual farmers**	**CHC Machines (No. of CHCs)**	**Sub-Total machines**	
2018-19	12,056	15,691 (3,888 CHCs)	27,747	3,549	7,078 (1194 CHCs)	10,627	16,406	6,900 (2,300 CHCs)	23,306	0	0	0	61,680
2019-20	5,402	17,666 (5,140 CHCs)	23,068	5,228	8,850 (1,685 CHCs)	14,078	2,104	4,950 (1,650 CHCs)	7,054	111	0	111	44,311
2020-21	9,972	14,568 (12,100 CHCs)	24,540	23,172	5,308 (1,345 CHCs)	28,480	8,695	4,956 (1,652 CHCs)	13,651	51	0	51	66,722
2021-22	3,265	6,766 (4,275 CHCs)	10,031	8,842	10,210 (2,551 CHCs)	19,052	6,867	4,833 (1,611 CHCs)	11,700	40	0	40	40,823
Total	**30,695**	**54,691 (25,403 CHCs)**	**85,386**	**40,791**	**31,446 (6,775 CHCs)**	**72,237**	**34,072**	**21,639 (72,13 CHCs)**	**55,711**	**202**	**0**	**202**	**213,536**

Source: MAFW (2022b)

The Krishi Vigyan Kendras (KVKs) under the Indian Council of Agricultural Research (ICAR) have put lot of efforts for creating awareness among farmers to use machines for in-situ crop residue management through Information, Education and Communication (IEC) activities in Punjab (22 KVKs), Haryana (15 KVKs) and Uttar Pradesh (23 KVKs) states. The following IEC activities were conducted during last four years:

- 2558 awareness programmes
- 33,508 demonstrations of machines for crop residue management
- 856 training programs to the farmers,
- 517 exposure visits to farmers
- 147 Kisan Melas organised
- 117,700 students were mobilized from 1125 schools
- 1.36 million leaflets/pamphlets distributed
- 425 TV programmes/panel discussions organised
- 3,649 hoardings fixed
- 39,071 posters/banners placed
- 1,274 advertisements in print media, and 10,690 wall writings.

The survey conducted by the ICAR-KVKs in Punjab and Haryana states revealed that the Happy seeder sown (in-situ crop residue managed) wheat farmers got on average 2.7 % higher wheat yield and resulted in saving of 25 % water for irrigation (usually one irrigation) and about 20 kg urea/ha.

The paddy residue burning events were monitored by multiple satellites with thermal sensors during the paddy harvest period from 1 October to 30 November in the states of Punjab, Haryana and Uttar Pradesh. There was a considerable reduction in the burning events of the rice crop residue. Overall, the total burning events recorded during 2019 in three states (Punjab, Haryana and UP) were 18.8 % less as compared to 2018, 31 % less as compared to 2017, and 51.9 % less as compared to 2016. Burning events in these states during 2020 were 46 % higher as compared to 2019 (burning events during 2020 were 89,430 as compared to 61,332 during 2019). The satellite estimated paddy burned area in Punjab decreased from 1.66 million ha in 2020 to 1.59 million ha in 2021. The adoption of in-situ method of straw management may have resulted in a saving of 30 – 35 % Nitrogen; 20 – 25 % Potassium and substantial amount of organic carbon, nearly 25 % of irrigation water and further helps in restoring microbial activities in the soil.

To encourage in-situ management of paddy straw, the Punjab Pollution Control Board has made it mandatory for all the combine harvesters to attach a Super Straw Management System (Super SMS). The violators of the NGT order will have to pay fine based on the landholding. In 2018, 3997 cases, 510 cases, and 6193 cases of crop residue burning were registered against farmers of Haryana, Uttar Pradesh, and Punjab, respectively and environmental compensation of INR 3.2 million, 2.6 million, and 1.9 million, respectively were recovered. In 2019, a penalty of around INR 61.30 million was imposed on 23,000 farmers in Punjab. In contrast, in

2020, around INR 2.60 million penalty was imposed on farmers from Punjab and Haryana states, where more than 700 free cases were registered against farmers.

In 2018, the central government reported that 1.10 million tonnes of paddy residue (5.5 % of total residue generated) were used in various ex-situ methods such as in paper/cardboard mill and biomass power projects (Ministry of Agriculture and Farmers Welfare, 2018). The Central Electricity Authority (CEA), Government of India, has issued a policy advisory for biomass utilization for power generation through co-firing in pulverized coal fired boilers (CEA, 2017). In order to promote the use of biomass pellets, all fluidized bed and pulverized coal units (coal-based thermal power plants) of public and private power generating utilities are advised to use 5–10 % blend of biomass pellets, primarily agro-residues, along with coal. With the overall thermal power generation capacity of 236 GW in September 2022 (CEA, 2022), the estimated daily biomass pellets requirement would be about 177,808 tonnes (assuming 0.275 million tonnes of biomass pellets for 7 % blending in a thermal power plant of 1000 MW capacity). This would utilize about 64.9 Mt of crop residues annually, which is about 36 % of the total annual surplus crop residue in the country. NTPC has placed an order for 930,000 tonnes of biomass pellets that will increase its co-firing in 2022 and beyond. The largest Indian utility is also executing a tender to procure another 20 Mt of biomass, which will enable the firm to co-fire 5 Mt/year of pellets at its 17 power plants.

The Ministry of New and Renewable Energy (MNRE), Government of India launched a programme on energy from agricultural waste/residue in the form of biogas/bio-CNG, enriched biogas/power. Projects based on bio-waste from urban and agricultural waste (paddy straw, agro-processing industry residue, green grasses, etc.) are eligible for Central Finance Assistance (CFA) in the form of capital subsidy and grant-in-aid under the programme (MNRE, 2018).

In India, the National Policy on Biofuels was announced in 2009 with an aim of promoting of bio-ethanol and bio-diesel blending with fossil fuels. The biofuel policy made it mandatory for oil companies to sell petrol blended with 5-10% of ethanol. The Union Cabinet of India has approved a new National Policy on Biofuels on 4 June 2018 promoting production and use of biofuels in the country. The policy promotes the target of 20% blending of ethanol in gasoline by 2025. The policy categorizes biofuels as (i) basic biofuels viz. 1G bio-ethanol, bio-diesel and (ii) advanced biofuels viz. 2G ethanol, bio-CNG, etc. Under the policy, a funding for 2G ethanol refineries of INR 50,000 million will be made available in six years besides additional tax incentives and higher purchase price (in comparison to 1G ethanol). The main aim of this policy is to expand the scope of raw materials used for ethanol production such as surplus food grains that are unfit for human consumption, solid waste, crop biomass, etc., in order to reduce the dependency on imports, create a cleaner environment, management of municipal solid waste, and additional income to farmers.

On the occasion of World Biofuel Day (10 August 2022), the Prime Minister of India, Honourable Shri Narendra Modi dedicated the second generation (2G) ethanol plant set up at the Indian Oil Corporation’s (IOC) Panipat refinery in Haryana at a cost of over INR 9.00 billion (US$113.4 million). Once fully operational, the plant is expected to produce around

30 million litres of ethanol using 200,000 tonnes/year of paddy straw as feedstock. This plant will also utilise maize and sugarcane waste besides paddy straw to produce ethanol. Twelve centres are being set up to collect feedstock paddy straws from fields in the vicinity of the plant site. This is also expected to address pollution being caused by the burning of these materials in northern India. This would help India achieve its target of blending 20% ethanol with auto fuel by 2025. State-run oil companies such as IOC, Bharat Petroleum Corp Ltd (BPCL), Hindustan Petroleum Corp Ltd (HPCL), Mangalore Refinery and Petrochemicals Ltd (MRPL) have announced plans to invest INR 100 billion to set up 12 2G ethanol plants across the country (MoPNG, 2018).

On the ex-situ crop residue management front, under the New and Renewable Sources of Energy (NRSE) Policy 2019, the Punjab government is encouraging the setting up of biomass power generation units and production of biofuels (bio-compressed natural gas [CNG], bio-ethanol, and bio-diesel) using biomass (mainly rice straw) as feedstock. As of September 2020, Punjab has 11 operational biomass power plants, with an aggregate capacity of 97.5 MW, in which 0.88 million tonnes of paddy straw are consumed annually (Chaba, 2020).

According to section 9 sub-section of the Air Pollution (Prevention and Control) Act (1981), burning of any material which is not fuel and likely to cause air pollution should be prohibited. Again, Chapter 3 section 7 of the Environmental Protection Act (1986) prohibits any person to carry out activities that emit environmental pollutants in the excess of the prescribed national standard. Any person found to violate the Environmental Protection Act (1986) shall be deemed guilty (section 16). However, the manner of exercise of power has not been framed. The government invokes Section 144 of the Civil Procedure Code (CPC) to ban the burning of paddy, which is hardly implemented, and little effort is made to sensitize the farmers on the same.

9. Gaps in Crop Residues Management in India

A series of challenges exist in using in-situ and ex-situ crop residues management techniques**.**

9.1 Gaps in In-situ Management of Crop Residues

These include problems in use of in-situ management machinery in the region and socio-economic issues. A huge demand-supply gap has been observed for in-situ management machinery and the local manufacturers are unable to cater to the needs of farmers. Another key concern with adoption of new machinery for mulching/mixing rice straw is availability of high horsepower (> 50 hp) tractors which is not available for marginal to medium farmers in India.

Further limiting factors in adoption of in-situ management of crop residue pointed out by farmers include subsidy issues, financial support, additional management skills, high operational cost, apprehension of lower crop yields and/or economic returns, negative attitudes or perceptions, and institutional constraints. In addition, farmers have strong preferences for clean and good-looking tilled fields vis-a-vis untilled or unkempt looking fields. Because of fundamental changes in farming practices, real-time support to address farmers’ concern is crucial for ensuring long-term sustainability of undertaken efforts.

Several machinery-specific challenges experienced by farmers, which need to be addressed, are as follows (Sharma *et al*., 2019).

Happy Seeder

a. Happy Seeders cannot be used on unlevelled fields.
b. Large quantities of straw with paddy varieties will hinder sowing operation by Happy seeder and may lead to patches of non-germinating wheat.
c. Uneven spreading of straw manually without the use of Super SMS will cause thick layer of mulch in some patches of the field which might hinder the sprouting of wheat.
d. Happy Seeders require higher horsepower tractors to work properly.
e. The field settings and operation of Happy seeders require constant attention and technical training.
f. Depth of sowing with Happy seeders is leading to longer germination period.
g. Happy seeder is not suitable to work in early morning and late evening hours when straw is wet with dew, thus limiting its practical use to only a few hours of the day during the peak period of wheat sowing.

Rotavator

a. Rotavators cannot work properly on standing straw and usually require 2-3 runs in such cases. This results in higher maintenance costs due to the breakdown of its blades.
b. Irrigation requirement of rotavator sown (incorporation of straw) fields is more, almost comparable to the burned fields.
c. There is no significant reduction in the weed growth in the case of straw incorporation, compared to mulching.

Super SMS

a. In most of the cases, cost of renting an SMS attached combine harvester is higher (incremental cost of INR 1250-1500/ha) which is a major concern to the farmers.
b. SMS causes a significant reduction in the field capacity of combine harvesters and leads to higher fuel consumption.
c. Farmers also reported excessive heaping of straw with super SMS at times which led to burning of heaps in these pockets.

Mulcher

a. Mulcher is used to cut the standing stubble and form a uniform mulch layer of stubble on the field on which either a Happy seeder or zero till drill can be used to sow wheat.
b. In cases where the straw is moist, mulchers cannot be used as the blades of the mulcher will slip and not effectively cut the standing straw.

9.2 Gaps in Ex-situ Management of Crop Residues

The use of crop residues as fodder for animals or for generation of electricity requires various on and off-farm operations, including collection, packing, handling, transportation, storage and pre-feed processing. For collection of straw after combining, imported conventional field balers are available. The bulky nature of the straw makes them expensive to transport even for short distances. However, the problem with these balers is that they recover only 25–30% of the potential straw yield after combining, depending upon the height of crop harvested by combines.

Various existing and emerging technologies such as pyrolysis (biochar), bio-methanation (biogas), and conversion to biofuels (such as briquettes, pellets, bio-compressed natural gas [CNG], and bio-diesel) have been recommended for ex-situ use of paddy crop residue (CII and NITI Aayog, 2018). Lack of an assured supply of biomass in adequate quantities proves to be a dampener for private firms to set up biomass plants as they find it economically unviable.

Given the voluminous nature and seasonal availability of the crop residue, its handling and on-time delivery become a central issue, as it requires a vast workforce, heavy vehicles for logistics and extensive storage infrastructure. A reliable supply of biomass to the end-user requires a dense network of collection centres and supply chain management (SCM) facilities. But the high cost of collection and transportation of residues from the field to end-user proves to be the prime impediment for scaling up ex-situ management practices (Singh *et al*., 2010). Therefore, entrepreneurship in the supply chain finds the economics of handling crop residue unattractive. The supply chain of crop residue involves several steps such as residue collection from the field, first-mile transportation to collection centre/straw bank, interim storage at the straw bank, processing of biomass and final transportation to the end-user.

As briquette and pellets are preferred over bales because of their increased energy content in industries and power plants, the high cost of pelleting makes transporting pelletised residue the costliest among all the options available. In most cases, SCM entities prefer to transport residue in the form of bales to avoid the high investment needed for biomass processing. However, biomass bales have limited end-use applications. They are used as packing material, as raw material in cardboard and paper industries, in animal bedding, and in biochar and bio-gas production. For other end uses that require densified biomass, the end-user needs to invest in processing bales to briquettes or pellets.

10. Way Forward and Future Strategies

Crop residues are of great economic value as livestock feed, fuel and industrial raw material. However, management challenges of the crop residues are varied across the States and Districts and its socio-economic needs. The way crop residues are used and managed by millions of farmers depends on their individual perceptions about the benefits, largely economic, both short and long-term and the opportunities available. There is a need to undertake policy-related research to quantify the benefits under a range of situations to aid policy level decisions. In the past, the role of crop residues has been viewed and evaluated largely in terms of nutrients balance ignoring the multi-functionality of soils in terms of maintaining biodiversity, GHGs mitigation, improved input-use efficiency, sustaining agriculture and human health. Several technologies are available for efficient use of crop residues in conservation agriculture. However, they require minor improvement for large sale adoption by resource poor and low-skill farmers. These are the new dimensions of the problems which Indian agriculture is currently facing and need to be addressed.

Mechanization for crop residue management (CRM)

- Development of multi-functional farm machinery for management of crop residues.
- Further refinements are needed in existing CRM machinery for fertilizer drilling, reducing power requirement and improving their ability to work in moist straw and other adverse conditions.
- Improving access to conservation agriculture machinery through appropriate financial incentives and promoting custom hiring system
- Promotion of appropriate farm machinery to facilitate cost effective collection, volume reduction and transportation.
- Establishing self-help groups and encouraging unemployed youths to take up custom hiring of conservation agriculture machineries as a profession.
- Capacity building of under and post-graduate students and training of farmers with regards to appropriate use and optimal performance of in-situ management machinery.
- Organizing large scale demonstrations and trainings to address limiting factors in adoption of CRM machinery for some farmers including requirement of additional management skills, apprehension of lower crop yields and/or economic returns, negative attitudes or perceptions, and institutional constraints.
- Supporting on-farm adaptation of CRM machinery in both large and scattered small fields and developing focused institutional and policy support including appropriate incentives for widespread dissemination and adoption.

Laws and legislation

- Developing a crop residues management policy for each state defining clearly various competing uses.
- Developing and implementing appropriate legislation on prevention and monitoring of on-farm crop residue burnings through incentives and deterrence.
- Introducing Carbon-credit schemes to benefit the farmers who follow conservation agriculture for carbon sequestration and GHGs mitigation.
- Classifying crop residues as amendments (like lime or gypsum) so that their use in agriculture should attract subsidy like any other mineral fertilizer or amendment.

Other interventions

- Promoting utilization of crop residues through community mobilization for animal bedding, fodder, composting and mushroom cultivation;

- Promoting use of biomass pellets from crop residues as a fuel substitution in thermal power plants;
- Promoting industrial level production of Bio-CNG/Compressed Bio-gas (CBG) from paddy straw;
- Incentivising power generation from bio-mass and establishment of such plants in a Public Private Partnership (PPP) mode;
- Promoting biogas production from crop residues at community level;
- Promoting 2G biomass-based ethanol plants in a PPP mode.
- Promotion and encouragement of the use of crop residue/rice straw in paper/board/panel and packaging;
- Implementing scheme of in-situ management of crop residues in other states based on availability of surplus crop residues.
- Promotion of collection of crop residue for feed, brick making etc. and extending support for transporting of such residue to fodder deficient areas;
- Education of farmers about the advantage of reduced agro-chemical cost resulting from the utilization of crop residues in agricultural land.
- Promoting sustainable solutions involving short distance transportation, affordable technology, or low capital investment to feed the nutrients in the crop residue back into the same crop lands which have greater promise to be successful.
- As individual small-scale farmers do not have the capacity to establish a long-lasting solution, encouraging the local government, the municipality, or a farmers' association/cooperative societies to fill this void and launch community programs to assist such as equipment rentals, waste transportation, and possible linking of waste to industry where it can be utilized as raw material.
- Governments should also work with local self-help groups or Farmer Producer Organisations for creating awareness, having common holding area and processing of crop residues for various end products (like generating bio-energy) at village level rather than at house-hold level.
- Introduce the policy for supporting such actions under the Corporate Social Responsibility (CSR) of private sector.

The prospects for crop residue utilization in non-conventional ways are limited. However, the drive to change is increasing rapidly due to different industries using crop residue as raw materials. Even though the issue of crop residue burning touches many sectors, such as environment, agriculture, economy, social aspects, education, and energy, the past governmental efforts mainly revolved around agriculture and energy. This sectorial thinking is another barrier that needs to be broken. The government of India as well as governments of other developing countries can benefit from the emerging concept of nexus thinking in managing environmental resources. Nexus thinking promotes a higher-level integration and higher level of stakeholder involvement that goes beyond the disciplinary boundaries, providing a supporting platform to solve issues such as crop residue burning.

References

Araújo, K., Mahajan, D., Kerr, R. and M. D. Silva (2017). Global biofuels at the crossroads: An overview of technical, policy, and investment complexities in the sustainability of biofuel development. *Agriculture*, 7(4), 32.

Bhuvaneshwari, S., Hettiarachchi, H. and J. N. Meegoda (2019). Crop residue burning in India: Policy challenges and potential solutions. *International Journal of Environmental Research and Public Health*, 16(5), 832. https://doi.org/10.3390/ijerph16050832.

Central Electricity Authority (CEA) (2017). Biomass utilization for power generation through co-firing in pulverised coal fired burners. Advisory dated 24 November 2017 issued by Office of the Secretary, Central Electricity Authority, Ministry of Power, Government of India. https://cea.nic.in/wp-content/uploads/2020/04/Biomass-Utilization-Advisory.pdf.

Central Electricity Authority (CEA) (2022). All India installed capacity of power stations (as on 30.09.22). Office of the Secretary, Central Electricity Authority, Ministry of Power, Government of India. https://cea.nic.in/installed-capacity-report/?lang=en.

Chaba, A. A. (2020). Explained: How Punjab plans to spin paddy stubble into gold. *The Indian Express*, 13 September. https://indianexpress.com/article/explained/biomass-power-plants-bio-cng-bioethanol-how-peda-plans-to-spin-paddy-stubble-into-gold-6590158/.

Chaudhary, A. *et al*. (2019). In-situ paddy straw management practices for higher resource use efficiency and crop productivity in Indo-Gangetic Plains (IGP) of India. *Journal of Cereal Research*, 11(3), 172-198.

Chawala, P. and H. A. S. Sandhu (2020). Stubble burn area estimation and its impact on ambient air quality of Patiala and Ludhiana district, Punjab, India. *Heliyon*, 6(1), 1-10. https://doi.org/10.1016/j.heliyon.2019.e03095.

Confederation of Indian Industry (CII) and NITI Aayog (2018). Action plan for biomass management. Cleaner air better life initiative of CII-NITI Aayog. Sansad Marg, New Delhi https://www.drishtiias.com/summary-of-important-reports/action-plan-for-biomass-management/print_manually.

Dwibedi, S. K. *et al.* (2021). Sustainable Biowaste Management in Cereal Systems: A Review. In *Cereal Grains: Volume 2*, Aakash Kumar Goyal, ed. London: IntechOpen. https://doi.org/10.5772/intechopen.97308.

Economic and Social Commission for Asia and the Pacific (ESCAP) (2020). Reducing straw residue burning and air pollution through sustainable agricultural mechanization. ESCAP/CED/2020/INF/4. https://www.unescap.org/sites/default/files/CED6_INF4.pdf.

Gupta, R.K. *et al*. (2003). Sustainability of Post-green Revolution Agriculture: The Rice-wheat Cropping Systems of the Indo-Gangetic Plains and China. In *Improving the Productivity and Sustainability of Rice-wheat Systems: Issues and Impact*, Jagdish K.

Ladha *et al.*, eds. Wisconsin: ASA Special Publication.

Indian Agricultural Research Institute (IARI) (2012). Crop residues management with conservation agriculture: Potential, constraints and policy needs. New Delhi: Indian Agricultural Research Institute. https://www.iari.res.in/files/Important_Publications-2012-13.pdf.

Indian Council of Agricultural Research (ICAR). (2021). Ex-situ crop residue management options. New Delhi: Directorate of Knowledge Management in Agriculture, ICAR. https://www.icar.org.in/content/ex-situ-crop-residue-management-options.

Jain, N., Bhatia, A., and H. Pathak. (2014). Emission of air pollutants from crop residue burning in India. *Aerosol and Air Quality Research*, 14(1), 422-430. https://aaqr.org/articles/aaqr-13-01-oa-0031.pdf.

Jin, Y. and, C. Bin. (2014). Global warming impact assessment of a crop residue gasification project - A dynamic LCA perspective. *Applied Energy*, 122(1), 269–279. https://doi.org/10.1016/j.apenergy.2014.02.034.

Jitendra *et al*. (2017). India's burning issue of crop burning takes a new turn. *Down to Earth*, 31 May. https://www.downtoearth.org.in/coverage/agriculture/river-of-fire-57924.

Kaur, S. (2020). Public preferences for setting up a biomass power plant to combat open-field burning of rice crop residues: A case study of district Sangrur, Punjab, India. *Biomass and Bioenergy*, 138 (1), 1-7. https://doi.org/10.1016/j.biombioe.2020.105577.

Kumar, A. *et al*. (2016). Sugarcane trash chopper cum spreader - A viable machine to avoid trash burning. *Journal of Applied and Natural Science*, 8(2), 1075-1079.

Kumar, P., Kumar, S., and L. Joshi, (2015). Socio-economic and Environmental Implications of Agricultural Residue Burning: A Case Study of Punjab, India. New Delhi: Springer Open. https://library.oapen.org/bitstream/handle/20.500.12657/27961/1002038.pdf?sequence=1&isAllowed=y.

Krishnaveni, A. S. and K. Dayana, (2021). Crop residue management – A review. *International Journal of Current Microbiology and Applied Sciences*,10(3), 28-33. https://www.ijcmas.com/10-3-2021/S.%20Anandha%20Krishnaveni%20and%20K.%20Dayana.pdf.

Lohan, S. K *et al*. (2018). Burning issues of paddy residue management in north-west states of India. *Renewable and Sustainable Energy Reviews*, 81(1), 693–706. doi:10.1016/j.rser.2017.08.057.

Mahal, J. S. *et al*. (2019). Complementing solutions and strategies for managing rice straw and their impact in the state of Punjab. *Agricultural Research Journal*, 56(1), 588-593.

Manes, G.S. *et al*. (2017). Mechanical Management of Paddy Straw. Technical Bulletin No. CIAE/FIM/2017/219. Bhopal: Central Institute of Agricultural Engineering.

https://aicrp.icar.gov.in/fim/wp-content/uploads/2017/02/Mechanical-Management-of-Paddy-Straw.pdf.

Mehta, C. R. and U. R. Badegaonkar, (2021). Farm mechanization in India: A perspective. *Agricultural Research Journal*, 58(6), 1142-1146.

Meshram, J.R. (2002). Biomass resources assessment programme and prospects of biomass as an energy resource in India. *IREDA News*, 13(4), 21-29.

Ministry of Agriculture (MoA) (2014). National Policy for management of crop residue. New Delhi: Department of Agriculture and Cooperation, Government of India. http://agricoop.nic.in/sites/default/files/NPMCR_1.pdf.

Ministry of Agriculture and Farmers Welfare (MAFW) (2018). Central Sector Scheme on Promotion of Agricultural Mechanization for In-Situ Management of Crop Residue in the States of Punjab, Haryana, Uttar Pradesh and NCT of Delhi: Operational Guidelines. New Delhi: Department of Agriculture, Cooperation and Farmers Welfare. https://agrimachinery.nic.in/Files/Guidelines/CRM.pdf.

Ministry of Agriculture and Farmers Welfare (MAFW) (2022a). Second advance estimates of production of food grains for 2021-22. Ministry of Agriculture and Farmers Welfare, Government of India.

https://eands.dacnet.nic.in/Advance_Estimate/Time%20Series%202%20AE%202021-22%20(English).pdf.

Ministry of Agriculture and Farmers Welfare (MAFW) (2022b). Annual Report 2021-22. New Delhi: Department of Agriculture and Farmers Welfare, Government of India.

Ministry of New and Renewable Energy Resources (MNRE) (2018). File. No. 20/222/2016-17-WTE dated 30/07/2018. New Delhi: Waste to Energy Division, Government of India.

Ministry of *Petroleum* and *Natural Gas (MoPNG)* (2018). Energising and Empowering India, Annual Report 2018-19. New Delhi: Ministry of Petroleum and Natural Gas, Government of India.

Pathak, B. S. (2004). Crop Residue to Energy. In *Environment and Agriculture*, K.L. Chadha and M.S. Swaminathan, eds. New Delhi: Malhotra Publishing House, pp. 854-869.

Pathak, H., Singh, R., Bhatia, A. and N. Jain. (2006). Recycling of rice straw to improve wheat yield and soil fertility and reduce atmospheric pollution. *Paddy Water Environment*, 4(1), 111–117.

Pathak, H., Bhatia, A., Jain, N., and P. K. Aggarwal, (2010). Greenhouse Gas Emission and Mitigation in Indian Agriculture – A Review. In *ING Bulletins on Regional Assessment of Reactive Nitrogen, Bulletin No. 19*, Bijay-Singh, ed. New Delhi: Society for Conservation of Nature - Indian Nitrogen Group.

Press Trust of India (PTI) (2019). 29,000 Punjab farmers get Rs 2500 per acre for not burning crop residue. The New Indian Express, 25 November. https://www.newindianexpress.com/nation/2019/nov/15/29000-punjab-farmers-who-did-not-burn-crop-residue-compensated-2062234.html.

Ravindra, K., Singh, T. and S. Mor (2019). Emissions of air pollutants from primary crop residue burning in India and their mitigation strategies for cleaner emissions. *Journal of Cleaner Production*, 208(1), 261–273. https://doi.org/10.1016/j.jclepro.2018.10.031.

Sahu, S. K.et al. (2021). Quantifying the high-resolution seasonal emission of air pollutants from crop residue burning in India. *Journal of Environmental Pollution*, 286(1), 1-11. https://doi.org/10.1016/j.envpol.2021.117165.

Sharma, A. and B. S. Bhattu (2015). Baler technology for the paddy residue management – Need of the hour. *International Journal of Computer Applications*, 975(1), 22-23. https://research.ijcaonline.org/icaet2015/number9/icaet4135.pdf.

Sharma, M. *et al*. (2019). Impact Assessment Report for Crop Residue Management Project. New Delhi: Confederation of Indian Industry. https://ciifoundation.in/document/NewsLetter/CII-Final-CRM-Impact-Assessment-Report-05Aug2019.pdf.

Shukla P. *et al.* (2020). Field test analysis of straw reaper combine for optimized operating condition to improve the performance. *Current Journal of Applied Science and Technology*, 39(8), 77-86. https://doi.org/10.9734/cjast/2020/v39i830595.

Shyamsundar, P. *et al.* (2019). Fields on fire: Alternatives to crop residue burning in India. *Scienc*e. 365 (6453), 536–538. https://doi.org/10.1126/science.aaw4085.

Sidhu, B. S., and V. Beri. (2005). Experience with managing rice residues in intensive rice wheat cropping system in Punjab. In *Conservation agriculture: Status and prospects*, Abrol, I. P., Gupta R. K. and R. K. Malik., eds. New Delhi: Centre for Advancement of Sustainable Agriculture (CASA), pp 55-63.

Sidhu, H. S. *et al.* (2007). The Happy seeder enables direct drilling of wheat into rice stubble. *Australian Journal of Experimental Agriculture*, 47 (7), 844–854. https://doi.org/10.1071/EA06225.

Singh, B., and Y. Singh. (2003). Management of crop residues in rice-wheat cropping system in the Indo Gangetic plains. In *Nutrient Management for Sustainable Rice-Wheat Cropping System*, Yadvinder-Singh *et al*., eds. National Agricultural Technology Project, Indian Council of Agricultural Research, New Delhi and Punjab Agricultural University, Ludhiana, India, pp. 286-301.

Singh, R. P. *et al.* (2008). Economic evaluation of the Happy Seeder for rice-wheat systems in Punjab, India. Presented at 52nd Annual Conference of the Australian Agricultural and Resource Economics Society (AARES). DOI: 10.22004/ag.econ.5975.

Singh, Jagtar, Panesar, B. S. and S.K. Sharma (2010). A mathematical model for transporting the biomass to biomass based power plant. *Biomass and Bioenergy*, 34 (4), 483–88.

https://doi.org/10.1016/j.biombioe.2009.12.012.

Technology Information Forecasting and Assessment Council (TIFAC) (1991). Techno market survey on "Utilization of agriculture residue (farms and processes)". New Delhi: Department of Science and Technology.

Technology Information Forecasting and Assessment Council (TIFAC) and Indian Agriculture Research Institute (IARI) (2018). Estimation of Surplus Crop Residues in India for Biofuel Production. Technology Information, Forecasting and Assessment Council (TIFAC), Department of Science and Technology (DST), New Delhi.

Tyagi, P.D. (1989). Fuel from Wastes and Weeds. New Delhi: Batra Book Service.

Ujala, A. K. *et al*. (2020). Performance evaluation of paddy straw reaper in paddy variety Pusa-44. *Forage Research*, 45(4), 328-34.

Vadrevu, K. P. et al. (2011). MODIS derived fire characteristics and aerosol optical depth variations during the agricultural residue burning season, north India. *Environmental Pollution* 159(6), 1560–1569. https://doi.org/10.1016/j.envpol.2011.03.001.

Venkatramanan, V. *et al.* (2021). Nexus between crop residue burning, bioeconomy and sustainable development goals over North-western India. *Frontiers in Energy Research*, 8,1-14. https://doi.org/10.3389/fenrg.2020.614212.

Verma, A. *et al*. (2016). Performance evaluation of tractor operated paddy straw mulcher, *Journal of Krishi Vigyan*, 4(2), 70-75.