SUSTAINABLE MANAGEMENT OF CROP RESIDUES IN BANGLADESH, INDIA, NEPAL AND PAKISTAN: CHALLENGES AND SOLUTIONS

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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 and Uday R. Badegaonkar was commissioned by ESCAP-SSWA and the Centre for Sustainable Agricultural Mechanization (CSAM) to better understand the status of crop residue management in South Asia. The burning of crop residue is a major reason for severe air pollution in the Indo-Gangetic plain region. Crop residue 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 degrades soil fertility that needs to be compensated by greater use of fertilizers 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).

This paper summarizes findings of national studies undertaken in Bangladesh, India, Nepal and Pakistan to better understand the situation of crop residue management in these countries. Good practices and technologies of crop residue management are identified and interventions are proposed to reduce straw burning. Given the cross-border nature of air pollution, this report also proposes a subregional framework for cooperation to promote sustainable and integrated management of crop residue.

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Sustainable Management of Crop Residues in Bangladesh, India, Nepal and Pakistan: Challenges and Solutions

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Abstract

The burning of crop residue contributes to the creation of 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 increases 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 provides a subregional overview on the status of crop residue management in Bangladesh, India, Nepal and Pakistan. Based on findings from national studies undertaken, the paper provides a summary on the amounts of crop residues produced, the in-situ and ex-situ management techniques utilized by farmers to make use of residues, the major factors that influence their burning and the various socio-economic and environmental impacts that such burning has in the subregion. An overview is also provided on the different kinds of agricultural machinery used to manage crop residues in the study countries, government efforts to reduce the level of burning as well as the various technologies that exist to use biomass for power generation.

The paper also highlights the various challenges countries face in the adoption of suitable technologies for the sustainable management of crop residues. It is felt that the strategy to address the residue burning should focus on interventions that can assign a real economic and commercial value to crop residues so that their burning results in an economic loss to the farmer. The banning of residue burning and levying of fines does not address the crux of the problems farmers face and there is a need for a combination of technologies and incentives to reduce burning. There are a variety of in-situ and ex-situ crop residue management options available, but solutions involving long-haul transportation of residues, expensive technology or high capital investment are less likely to succeed. It is argued that the promotion of in-situ management practices should be preferred as it feeds nutrients back into the soil, reduce use of

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irrigation water, increase soil organic carbon and restore microbial activities in the soil. Such in-situ management practices should also be supplemented with ex-situ management techniques.

The paper provides a variety of recommendations for interventions that can help to address the issue of crop residue burning. As the problems created by the burning of residues is transboundary in nature, a framework for subregional cooperation and activities to reduce burning in the subregion is also proposed. The major areas of cooperation include:

- Joint research and analytical studies on availability, utilization, surplus and burning of crop residues as well as fire mapping studies to monitor burning which can help to inform policy interventions.
- Sharing of experiences to develop mechanisms for aggregation of crop residue biomass to facilitate viability of ex-situ management options.
- Sharing and popularization of technologies, equipment and practices for the management of crop residues through development of a common pool for funding for collaborative R&D of machines/solutions, technical exchanges of knowledge between countries, organization of skill development programmes and pilots of crop residue management practices.
- Harmonization of testing standards and promoting more integrated trade of in-situ and ex-situ agriculture machinery.

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

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

1. Introduction

Agriculture is central to South Asian economies, lives and livelihoods. However, the challenges of an increasing population and brisk economic growth are straining the agriculture sector as it struggles to meet the present and future demand for food, nutritional security, and economic development. Agricultural production in the countries of the subregion remains centred around a rice-wheat cropping system. Rice and wheat cultivation are the main agricultural production activity, accounting for a greater share of gross production value than any other commodities. The harvesting of crops by combine harvester in the subregion generates large amount of crop residues. Burning of crop residues is a common practice in Bangladesh, India, Nepal and Pakistan in the subregion to clear fields for sowing of next crop. It highlights the need for in-situ and ex-situ management of surplus crop residues in the region for soil health management and environment protection.

In Bangladesh, agriculture contributes nearly 13.02 % of Bangladesh's Gross Domestic Product (GDP) and employs 40.6 % of the country's workers (BBS, 2019; BBS, 2020). Food production, especially cereal production, is more emphasized along with vegetables and fruits production. Rice, wheat, and maize are the major food-grains in Bangladesh, and the volume of production is increasing to meet the demand of an increasing population. The net cultivated area of Bangladesh is 8.7 million ha, and the cropping intensity is 197 % (BBS, 2021). The food-grain production has increased 4.8 times from 9.77 to 47.12 million tonnes between 1972 and 2021 (FAO-STAT, 2021).

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 the world population. The agriculture sector in India has experienced buoyant growth in the past two years. 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 has been the major drivers of overall growth in the sector. The growth in total food-grains production has been phenomenal from 51 million tonnes in 1950–51 to 316 million tonnes in 2021–22.

Nepal is an agricultural country with 60.4 % of the population engaged in agriculture. Only 28 % of the total land is cultivable, and agriculture (excluding livestock, forestry and fisheries) contributes 15.44 % to GDP (2019-20). Paddy, maize and wheat crops contribute 15.35 %, 8.85 %, and 6.34 %, respectively to agriculture GDP of the country.

The agricultural sector in Pakistan contributes more than 19.2 % of Pakistan's aggregate GDP and employs 38.5 % of its labour force. More than 62 % of the country's population lives in rural areas and is directly dependent on agriculture. In Pakistan, out of a total area of 79.6 million hectares, 22.1 million hectares are cultivated around Punjab, Sindh, Khyber Pakhtun Khawa and Baluchistan provinces. The most important crops in Pakistan are wheat, rice, maize, sugarcane and cotton, which account for more than 75 % of the value of total crop output.

The need for providing food-grains for a growing population, while sustaining the natural resource base, has emerged as one of main challenges, in these countries. Agricultural growth has caused enormous pressure on environmental health. Prominent among them is the crop residue burning. In recent times, this practice has drawn the attention of policy makers and the public due to its adverse effects on the environment including air pollution which impacts the life of millions of people across countries, contributes to climate change and leads to a loss of fertility on agricultural land.

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

The fertility of soil is highly dependent on soil organic matter. Intensive cropping and tillage systems have led to a substantial decrease in soil organic matter levels and thereby declines in soil fertility and crop production. Technological advances and use of machinery for crop harvesting leave behind large quantities of crop residues. This has further worsened the problem because the leftover residue is burned by farmers as the cheapest and easiest method to clear the fields with the misconception that the 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 soil. As soil organic matter may be maintained by the addition of crop residues, the management of crop residues becomes very important for soil health and crop production.

Appropriate farm mechanization technologies can help farmers adopt sustainable and integrated management of crop residues through in-situ and ex-situ utilization. Appropriate finance, education, training and advisory services can be offered to farmers, and they can learn to implement technologies and practices from research and development efforts.

This report summarizes findings of national studies undertaken in Bangladesh, India, Nepal and Pakistan on the issue of crop residue management to get a better understanding of how residues are managed and various issues faced. Key actions and areas for subregional cooperation to tackle the issue of crop residue burning are also proposed.

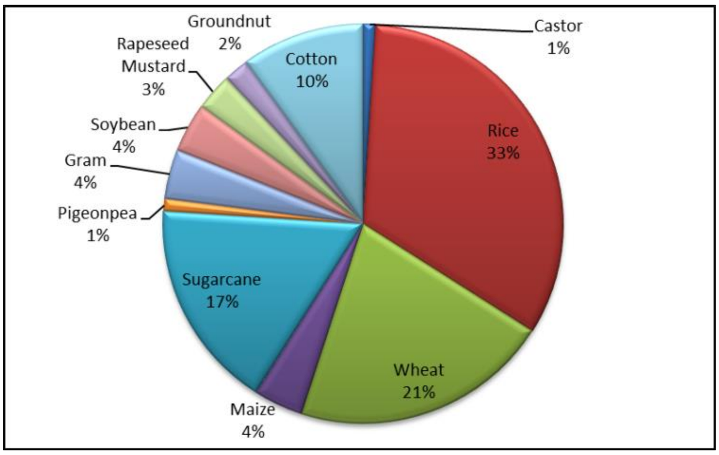
2. Crop Residue Generation in the Subregion

Harvesting of various crops generates a large volume of residues on the farm. In four countries of this study, a large variability exists in the estimates of generation, utilization and on-farm burning of crop residues.

The findings of a survey (TIFAC and IARI, 2018) in India, indicated that about 683 million tonnes (Mt) of total dry biomass were generated in three crop growing seasons. Out of this total 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 from rice crop

(33 %), followed by wheat (22 %), sugarcane (17 %) and cotton (8 %) crops. The remaining 20 % of biomass was generated from maize, pigeon pea, gram, soybean, rapeseed-mustard, groundnut and castor crops (Figure 1). About 59 % biomass was generated during the kharif season[2] and 39 % during the rabi season[3]. The remaining about 2 % was generated during summer season. The total annual surplus crop biomass[4] was estimated as 178 Mt, which is about 26 % of total dry biomass generated. The season-wise surplus biomass was highest in kharif (monsoon) season (72 %) and the major crops contributing to surplus biomass are rice, sugarcane, cotton and soybean. In the rabi (winter) season, wheat, gram, rice and mustard were the crops contributing to the surplus crop biomass.

Figure 1: Share of crop in total dry biomass generated for selected crops



Source: TIFAC and IARI (2018)

In Bangladesh, Nepal and Pakistan, straw yield data are not available in the national crop research institutes or the agricultural universities of the country. Information on crop yield, crop production, and other related data was collected from research reports, published journal papers, and statistical yearbooks. Straw yield data were calculated with the help of the crop harvest index (HI) found in research reports and papers of research institutes. The equations below were used to estimate amounts of straw generated by major crops.

$$\text{Harvest Index (HI)} = \frac{\text{Grain Yield (GY)}}{\text{Grain Yield (GY)+Straw Yield(SY)}}$$

$$\text{Straw Yield (SY)} = \text{GY}\ ((1/\text{HI})\text{-}1))$$

The crop-wise cultivation area, estimated total biomass and surplus biomass of selected crops in the countries of the subregion are reported in Table 1.

Due to the unavailability of data, the quantification of surplus biomass is missing in the Bangladesh, Nepal and Pakistan reports. Quantification of surplus biomass generation is important to predict the real scenario of crop residue burning in the subregion. The crop biomass usage pattern by farmers for their self-use as well as the biomass sold to others for industrial or any other purposes can be compiled to estimate the factors for surplus crop biomass generation in these countries.

[2] Kharif season in India starts in June and ends in October.
[3] Rabi season in India starts in October-December and ends in April - June
[4]Surplus crop biomass is equal to total residues generated minus residues used for various purposes.

Table 1: Crop-wise area, total dry biomass and surplus biomass of selected crops in the subregion

Crop	Countries	Area (Mha)	Biomass Produced (Mt)	Surplus Biomass (Mt)
Rice	Nepal	1.55	5.98	-
	Bangladesh	11.39	65.90	-
	Pakistan	3.03	7.41	-
	India	44.36	225.48	43.85
Wheat	Nepal	0.74	2.23	-
	Bangladesh	0.38	1.86	-
	Pakistan	8.80	25.25	-
	India	30.84	145.45	25.07
Maize	Nepal	0.9	3.08	-
	Bangladesh	0.56	5.70	-
	Pakistan	1.40	9.85	-
	India	8.78	27.88	6.03
Sugarcane	Nepal	-	-	-
	Bangladesh	-	-	-
	Pakistan	1.17	7.95	-
	India	5.04	119.17	41.56
Cotton	Nepal	-	-	-
	Bangladesh	-	-	-
	Pakistan	2.08	5.30	-
	India	12.16	66.58	29.47
Pigeon pea	India	4.11	9.16	1.75
Soybean	India	10.69	27.78	9.95
Rapeseed	India	5.87	17.08	5.16
Gram	India	8.48	26.51	8.72
Groundnut	India	5.47	12.90	3.87
Castor	India	1.19	4.60	3.02

Source: TIFAC and IARI (2018), Country Reports of Bangladesh, Nepal and Pakistan
Note: Data given in Table 1 for Pakistan and Nepal are of 2019-20, for Bangladesh of 2020-21 and for India of 2017-18.

3. Utilization of Crop Residues

Despite the fact that straw burning is still a widely used practice in the subregion, it is important to understand that not all straw residues are burned in the field. Since crop straw is rich in fibre, lignin, starch, protein, enzymes and nutrients, it is also used as fertilizer, fodder, bio-energy, base stock, industry material, etc. Crop residues are being utilized differently, varying with the country and its socioeconomic status, type of cultivated crop, number of crops grown per year, etc. Traditionally crop residues in the subregion have been utilized in numerous competing uses such as animal feed, fodder, fuel, roof thatching, packaging and composting. Cereal residues are mainly used as cattle feed.

> Conservation agriculture (CA) offers a good promise in using these residues for improving soil health, increasing productivity, reducing pollution and enhancing sustainability and resilience of agriculture.

Rice straw and husk are used as domestic fuel or in boilers for parboiling rice in a few states in India. Farmers use residue either themselves or sell it to other landless households or intermediaries, who in turn sell the residues to industries. The crop residues are also used as mulch or incorporated into soil. The remaining residues left unused are burned in field.

In the areas where rice residues are not used as cattle feed, large amounts of rice straw are burned in the field. Sugarcane tops in most of the areas are either used for feeding to dairy animals or burned in field for ratoon crop. Residues of groundnut are burned as fuel in brick kilns and lime kilns. Cotton, pulses, oil-seed crops, chilies, coconut shells, rapeseed and mustard stalks, sunflower and jute residues are mainly used as fuel for household needs (Pathak *et al*., 2010).

Wheat is the second most consumed crop after rice in India. The large amount of wheat straw is used for cattle feeding, domestic fuel, paper board making and oil extraction (TIFAC, 1991). However, in areas of the Indo-Gangetic Plain (IGP) such as Haryana, Punjab, Uttaranchal and Uttar Pradesh where intense cropping systems are adopted, the straw is burned as it is the easiest and most economical option to get rid of straw in the short period available between rice harvesting and wheat sowing. Unlike wheat and rice, corn straw and millet stalks are relatively hard and 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 by burning for 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). Likewise, 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 have received considerable attention in recent years. With the increased incidence of burning of crop residue, central authorities have initiated and promoted approaches to alleviate the problem. These approaches include the use of crops (particularly cereals) residues as fodder, fuel for bio-thermal power plants, mushroom cultivation, as bedding material for cattle, production of bio-oil, paper production and biogas production. Other uses include incorporation of paddy straw in soil, energy technologies and thermal combustion (Kumar *et al*., 2015).

Additionally, industrial demand for crop residues is also increasing. There are several options such as animal feed, composting, energy generation, bio-fuel production and recycling in soil to manage the residues in a productive and profitable manner. Conservation agriculture (CA) also offers a good promise in using these residues for improving soil health, increasing productivity, reducing pollution and enhancing 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 the conventional energy and input-intensive agriculture.

In **Pakistan**, wheat and rice straws are not utilized as an industrial raw material on a large scale. The other uses of these residues are limited to animal bedding, garden mulch, heating fuel, ethanol production, paper making, building material, mushroom growing, fruit packing, industrial product packaging, etc. As per estimates, 40 % of wheat straw is used for other sectors which include exports. Of this 40 %, nearly 5 % is used by the pulp and paper industry and constitutes approximately 85 % of total cost of low-quality papers (Haq, 2019). Rice straw has a lower forage value than the cost of its baling and transport. In less than 20 % of situations, rice straw is utilized as animal feed and it is used when wheat straw is scarce. Rice straw, except for rice husk, is not frequently used as an industrial raw material on a large scale. Maize plants are left in a field after manual harvesting. It is a valuable addition to ruminant feeding systems (dairy, beef, heiress, sheep and goats) as it has the highest feeding value of all cereal straws. The stover left after grains are husked is used as cattle feed. Maize straw is mostly consumed by cattle and the remaining straw is mixed into the soil using rotavators or disc harrows. Sugarcane topping is traditionally utilized as animal feed, either on its own or by supplementing with some additives. A few farmers use disc harrows in stubble roots and trash is retained for mulching. When this crop residue is ploughed beneath the soil, it supplies rich organic materials. A disc type trash incorporator is used for mixing of trash within inter-row spaces of sugarcane. The stalk of the cotton plant is manually cut close to ground level in the field, collected and piled near the houses. Over 60 % of it is directly used as a fuel in rural areas, whereas about 20 % is mulched into the soil using shredders and rotavators. Recently big cotton growers have started making pellets and briquettes as fuel.

Rice straw in **Bangladesh** is traditionally used as feed for cows and buffaloes, animal bedding, cottage roof thatching, as fuel for heating water either by direct burning or by producing briquettes (Islam et al., 2020), biogas production and packaging materials such as for glassware. There are 85,514 biogas plants in Bangladesh (SREDA, 2022). In many cases, straw residue (rice, wheat, corn stalk) is left in the field in the form of piles for composting. The straw is used together with other agricultural residues generated at the village level. The exact statistics on actual crop straw utilization in Bangladesh is not available. Rice (7-10 %) and wheat (25 %) straws after harvesting are directly incorporated in the soil by ploughing. Rice and wheat straws are also used as mulch in the strawberry fields and tomato fields for better weed control and moisture preservation on limited scale (Ashrafi et al., 2019). Moderate levels of wheat and maize residues are also used as surface mulch in conservation agriculture cultivation in some pockets of Bangladesh. Use of rice and wheat straw is also popular in making value-added items such as domestic mats, baskets, trays, etc. Chopped green corn stalk is also a good feed for animals, but wheat straw is not fed to cows and buffaloes in Bangladesh. Rice, wheat and sugarcane straws are also used for industrial applications such as for paper, board making, packaging items and as a base material for mushroom cultivation.

In **Nepal**, the most common use of straw is for consumption as fodder. Straw is collected during the harvesting season and stored in different forms under the shed or in an open space. Almost all rural households have a few, or at least one domesticated livestock (e.g., cows, buffalos, bullocks) for ploughing land, producing milk, etc., and their major feed sources are rice and wheat straws. The loose paddy straw is being transported to mid-hill regions of eastern Nepal for off-season feeding to livestock. However, the quantity transported is limited due to high transportation cost. Rural households use paddy straw for livestock bedding. This bedded straw, when it becomes wet, is dumped into composting pits and finally used as fertilizer. Paddy straw is also used as an energy source to supplement the fuel wood for cooking food. The use of cow dung cakes as cooking fuel is common in rural households where other sources of energy are not available or for those who cannot afford to pay for modern forms of energy. Different types of crop residues are mixed with cow dung and dried in the sun to make cow dung cakes for cooking fuel. Cow dung cakes are also burned in open areas of settlements, called *ghoor* in the local language, to keep warm during cold waves in the winter. The volume of paddy straw consumed, however, is much less compared to production. Incorporation of straw into the soil, using plough and rotavator is a common practice as tractors and rotavators are easily accessible to the farming community in Terai region. Surface mulching of paddy residue is also used where conservation agriculture cultivation using Happy seeders is prevalent.

Paddy straw in Nepal is widely used as a substrate for the cultivation of mushrooms. The shed for mushroom production is also made of paddy straw over the plastic sheet lining. Use of crop residue as raw materials for production of paper, ethanol, briquettes, biogas fuel, gasification is reported to be limited in Nepal. Craft production from straw is considered as a cottage industry and is quite common in rural areas. Paddy straw, *paral* in the local language in Nepal, is used as raw material for the production of value-added items like floor carpets (*sukul*), ropes (*dori*), mats (*chakati*), mattress (*gundri*), shoes, stool, handbags, wall hangings, etc.

Present uses of crop residues in the subregion are summarized in Table 3.

Table 3: Present uses of crop residues in the subregion

Straw uses	Nepal	Bangladesh	Pakistan	India
Animal feed	√	√	√	√
Bedding material for cattle	√	√	√	√
Residue incorporation	√	√	√	√
Residue mulching	√	√	√	√
Domestic fuel	√	√	√	√
Value added items	√	√	√	√
Biogas production	-	√	-	√
Mushroom production	√	√	-	√
Briquetting of crop residues	-	-	-	√
Bio-CNG/Compressed biogas (CBG)	-	-	-	√
Power generation from biomass	-	-	-	√
Bio-ethanol production	-	-	-	√

Straw uses	Nepal	Bangladesh	Pakistan	India
Bio-char production	-	-	-	√
Compost making	√	√	√	√
Paper manufacturing	√	√	√	√
Building material	√	-	-	√

Source: Compiled from Bangladesh, India, Nepal and Pakistan country reports on Integrated Straw management

4. Crop Residue Burning in the Subregion

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 produced in all four countries. The harvesting of these crops with combine harvesters 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 crop, which cannot be delayed without negative effects on the subsequent crop yield, on-farm residue burning is the most convenient and cheap option to farmers (ESCAP, 2020).

Crop residue burning activity is influenced by the agricultural practices that include crop cycle, crop type, harvesting season, the potential use of residues, agricultural mechanization, the feasibility of on-farm residue collection and transportation and profitability of alternate options (Venkatramanan *et al*., 2021). 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 in India and Pakistan and burned in field. Farmers also believe that on-site burning of crop residues controls problematic weeds, pests and disease-causing organisms.

Additionally, weather (humidity and rain), disproportionate incentives, inefficient straw collection technology, inefficient management by agricultural agencies, lack of logistic facilities (baler machines, storage and transportation), lack of capital to manage straw, and a low level of skills and knowledge are a few reasons due to which farmers prefer to go for rice straw burning being the easy and cheaper option.

Overall, the studies suggest that the main reasons contributing to straw burning are the high cost of straw collection, transportation and storage, partially caused by the shortage of rural labour, lack of adequate methods and machinery to treat straw residue and low awareness of the impacts on the environment, food security risks and health concerns. Ahmed *et al.* (2013) in their study in Pakistan estimated that the cost of collection of straw from the field was approximately US$140 per hectare, which is far more expensive than field burning.

However, the factors that influenced farmers to practice alternative techniques i.e., mulching, incorporation, or rice straw removal instead of burning were farm type, location, number of household members, cow ownership, distance from farm to house, training, perceptions of incorporation benefits, income from non-rice farming, cultivated area, tenure status, and provincial regulations of burning.

> The main reasons contributing to straw burning are high cost of straw collection, transportation and storage, partially caused by shortage of rural labour, lack of adequate methods and machinery.

In **India**, the crop residue burned on-farm in different states is highly variable depending upon the usage pattern in the respective states. Jain *et al*. (2014) reported that crop residues subjected to burning ranged 8–80 % for rice crop across the states. In the states of Haryana, Himachal Pradesh and Punjab, 80 % of rice straw was burned in-situ followed by Karnataka (50 %) and Uttar Pradesh (25 %), which can be attributed to the mechanized harvesting with combine harvesters (Gupta *et al*., 2003). At present 75–80 % of rice-wheat area in Punjab is harvested with combines. Approximately 23 % wheat straw was burned in the states of Haryana, Himachal Pradesh, Punjab and Uttar Pradesh and for rest of the states it was 10 %. For sugarcane trash, an estimated 25 % of the trash is burned in the fields. For rest of the crops, the crop residues burned on farm was estimated at 10 % across the states. The amount of residue burned on farm ranged from 98.4 Mt (Jain *et al*., 2014) to 131.9 Mt (using IPCC coefficients). With IPCC coefficients, the contribution of Uttar Pradesh was the highest, followed by West Bengal, Andhra Pradesh, Punjab, Maharashtra and Haryana. But as per Jain *et al*. (2014) coefficients, the highest amount of crop residue was burned in the states of Uttar Pradesh (22.25 Mt) and Punjab (21.32 Mt), followed by Haryana (9.18 Mt) and Maharashtra (6.82 Mt). The highest amount of cereal crop residue was burned in Punjab followed by Uttar Pradesh and Haryana. Uttar Pradesh contributed maximum to the burning of sugarcane trash followed by Karnataka. Oil-seed residues were burned in Rajasthan and Gujarat while burning of fibre crop residue was dominant in Gujarat (28.6 Mt) and followed by West Bengal (24.4 Mt), Maharashtra and Punjab.

Among the different crop residues in India, major contributions were 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, burning of crop residues is predominant in four states namely, Haryana, Punjab, Uttar Pradesh and West Bengal. During recent years, the burning of crop residues results in scarcity of fodder and simultaneously increases fodder prices across the country. It is a paradox that the burning of crop residues and scarcity of fodder coexists simultaneously and that there has been a significant increase in fodder prices in recent years.

In **Pakistan**, the burning of combine harvested wheat straw is reported to have increased. Due to challenging management practices, limited resources of the farming community and a short window for seeding the next crop, rice straw accounts for a substantial percentage of residue burning in Pakistan. According to a survey, rice straw burning is the most common activity in Punjab province, accounting for 72 % of all practices. The available combine harvesters cut the standing rice crop at the height of 400-800 mm and leave behind a swath of loose straw spreading a width of 2 metres and weighing about 3-4 tonnes/hectare. In a lodged situation (Basmati crop is generally lodged more than 40 % at maturity level), harvesting is even more difficult as it requires cutting closer to the ground level and loose straw weight increases to about 5-8 tonnes/hectare, which is usually subjected to burning. It is estimated that less than 5 % of maize straw is burned. Burning sugarcane trash is a common practice in Pakistan. During cane harvesting, cane trash is left on the surface of the fields, and cane growers mostly get rid of the trash by burning, while stubbles are uprooted. This practice is however reducing due to the imposition of penalties for burning.

Open-field burning of rice straw is not widely practiced in **Bangladesh**, as a major part of the crop is harvested manually and carried to the threshing yard for mechanical threshing. The straw remaining in the field is manageable by ploughing with a rotavator. However, the recent growing trend is that the farmers are considering the option of straw burning with the increasing use of combine harvesters and reapers. Farmers in Bangladesh choose to burn long types of straw, such as creeper vegetables and poor-quality rice, wheat and maize straw residues, since these types of straw cannot be used as animal feed or domestic fuel.

In **Nepal**, statistical figures on the amounts of straw burned in terms of severity, location-wise volume, etc., are lacking and not readily available. Research conducted by Das *et al*. (2020) indicated that open burning of crop residue varies according to the geographical region of the country. During the year 2016-17, the highest residue burning occurred in the Terai region (90.7 %), followed by the hills (6.4 %) and the mountains (2.9 %). Due to the accessible land-use area, the Terai region has higher agricultural production than hill and mountain regions, with 66.8 %, 27.7 % and 5.5 % of residue burning occurring in these regions, respectively. In addition, both the supply and demand of dry fodder determined the level of crop residue burning. In districts where there were feed deficits, i.e., the mountain and hills, open burning was low to none. Likewise, in districts where there was feed surplus, open burning was high.

5. Consequences of Crop Residue Burning

Burning of crop residue results in severe consequences for the environment due to the emission of greenhouse gases (GHGs) and soil deterioration. In addition, enhanced levels of particulate matter (PM) and other air pollution factors 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 negatively influences soil fertility as it erodes soil nutrients. Soil nutrients, pH level, moisture, available phosphorus, soil organic matter and microbial population are all adversely influenced by burning. In other words, farmers seeking to intensify agricultural production end up eliminating essential micro-nutrients from the soil by burning, resulting in infertile land in the long run.

Soil nutrients, pH level, moisture, available phosphorus, soil organic matter and microbial population are all adversely affected by crop residue burning. Farmers seeking to intensify agricultural production end up eliminating essential micro-nutrients from the soil by burning and degrading land fertility in the long run.

The other side effect of residue burning is air pollution caused by the emission of carbon dioxide, carbon monoxide, nitrogen oxides, methane and nitrous oxide gases and discharge of ash. Worsening of air quality causes a negative effect on human health, resulting in respiratory, cardiovascular and other diseases. Disruptions in society and the economy can occur as smog may cause problems for transportation, closure of schools and public venues, and interfere with everyday life. Air pollution caused by straw burning can also pose a trans-boundary issue as smog may be easily picked up by the wind and carried over extended distances across countries and regions (ESCAP, 2020).

5.1 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. Sidhu *et al*. (2007) estimated the quantity of nutrients available in rice. According to the study, 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 the intensive rice-wheat cropping system in Punjab. According to them, the approximate amounts of the nutrients present in the straw, which was burned in 2003-04 were 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 tonne CO_2 equivalent) and a loss of about 1.4×10^5 t of N per annum.

5.2 Social impact

Social impact includes the impact on human and animal health. 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 due to 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 in India live in the rice growing areas and is exposed to air pollution due to 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, burning of crop residue also emits large amounts of particulates that are composed of 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 adverse implications on the health of milk producing animals. Air pollution can result in the death of animals, as the high levels of CO_2 and CO in the blood can convert normal haemoglobin into deadly haemoglobin. There can also be a potential decrease in the yield of the milk produced by animals.

5.3 Environmental impact

The burning of crop residues results in emission of gases such as CH_4, CO, N_2O and NO; particulate matters (PMs), loss of plant nutrients and adversely affects the atmosphere, environment and soil health. The entire amount of C, approximately 80 – 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 emitted as N_2O from crop residue burning impact the environment. 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. (ICAR, 2021)

The release of carbon dioxide in the atmosphere due to crop residue burning results in the depletion of the oxygen layer in the natural environment causing the greenhouse effect. The black carbon emitted during residue burning has light absorbing properties that allow it to convert light energy to heat and warm the air around it and is the second most important contributor to global warming after CO_2. In addition, and unlike GHGs, black carbon affects climate through its influence on cloud formation and properties, as well as through deposition on the earth's surface. (Cassou 2018). Research by Gul *et al*. (2021) in the central Himalayas has estimated that black carbon contributed to approximately 39% of total glacial mass loss in the pre-monsoon season. Melting of glaciers and snow changes river discharge patterns, water availability and the frequency of glacial lake outbursts which affect lives and livelihoods of millions of people residing in downstream communities.

> The release of carbon dioxide in the atmosphere due to crop residue burning results in 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.

The total emissions of major air pollutants from crop residue burnings in India in 2018 for four particulate pollutants including $PM_{2.5}$, PM_{10}, BC and OC were 0.99 Mt/year, 1.23 Mt/year, 0.12 Mt/year and 0.41 Mt/year, respectively; four gaseous pollutants including CO, NOx, SO_2, VOC were

11.20 Mt/year, 0.48 Mt/year, 0.14 Mt/year, 1.28 Mt/year, respectively; and two greenhouse gases of CH_4 and CO_2 are 0.78 Mt/year and 262.05 Mt/year, respectively. In the case of $PM_{2.5}$, rice contributes around 41 % (0.408 Mt) and followed by wheat (27 %), sugarcane (14 %), maize (8 %) and coarse cereal (7 %). In the case of PM_{10}, the highest contribution was 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).

Table 4: Biomass burned and emission data for important crops in India

Crop	Year	Production*(Mt)	Straw production (Mt)	Biomass burned (dry matter) (Mt)	N_2O emission (kt)	CH_4 emission (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: *Ministry of Agriculture and Farmers Welfare (2021-22)*

The emission of N_2O and CH_4 due to biomass burning of important crops in India is reported in Table 4. The biomass burned during four consecutive years (2016-2019) for rice was the highest amongst all crops.

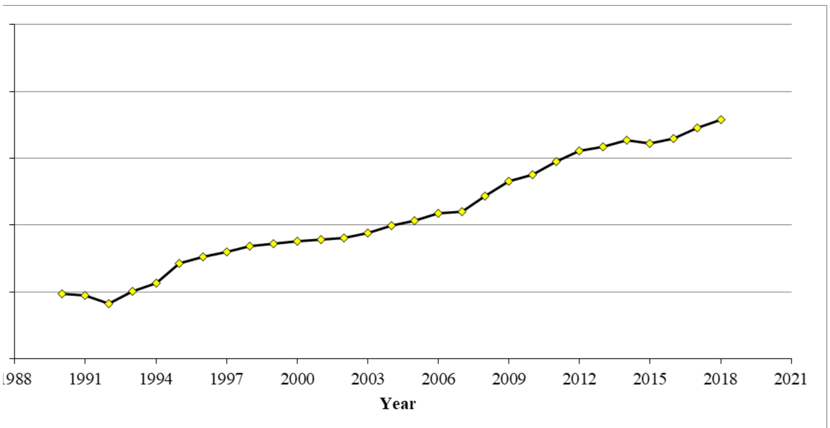
In **Pakistan**, pollution due to crop residue burning starts at the end of October when the harvesting of coarse varieties begins and reaches a peak level in the first week of November in rice growing areas of Punjab province. The condition worsens when there is no rain during this period resulting in heavy smog. In 2015, the WHO estimated, that over 60,000 Pakistanis died from the high level of fine particles in the air, one of the world's highest death tolls from air pollution. In February 2019, FAO reported the causes of smog related to the agriculture sector with an aim to assist government institutions in the development of appropriate policies, action plans and interventions to alleviate detrimental effects of smog on economy, health, and environment in Pakistan's Punjab province. The sectoral emission inventory shows that the major portion of total air pollutant emissions is from the transport sector with 43 % share, followed by 25 % from industrial sector and 20 % from agriculture.

The air quality index (AQI) is a yardstick that ranges from 0 to 500. The higher the AQI value, the greater the level of air pollution and the more serious the health concern. In Pakistan, an AQI of 300 and more (Level 6) means the air quality of a particular locality is severely polluted. As per a Gulf News report dated 23 November 2021, Lahore (capital of Punjab Province) crossed the 450 AQI level which forced the closure of schools and private workplaces for three days a week as the city battled the winter smog. Air quality in Lahore is caused by a combination of vehicle and industrial emissions, smoke from brick kilns, the burning of crop residues and general waste, and dust from construction sites. It usually worsens during the winter season from October to December, when farmers widely set fire to crop residues, producing smoke that adds to smog. Lahore city is ranked first or second in AQI Visual's live rankings of major global cities.

Agriculture contributes to 39 % of **Bangladesh's** GHG emissions. The emissions from agricultural in the country increased by about 29 % from 1990 to 2013 and 21.4 % from 2014 to 2018 (Climate Watch, 2021a and 2021b). Bangladesh's GHG emissions is reported as 195.6 Mt of CO_2 in 2014 and increased to 220.7 Mt in 2018. Biswas (2017) estimated that 40 % of nitrogen, 80-85 % of potash, 30-35 % of phosphorous, and 40-50 % of sulphur were left in the stubble or straw after harvest. All nitrogen was lost after burning. Approximately 20-25 % of the potash and phosphorous and 5-60 % of sulphur were lost after burning. Burning of wheat straw also had similar results, with losses of 100 % nitrogen, 70-90 % sulphur, and 20-40 % phosphorous and potassium.

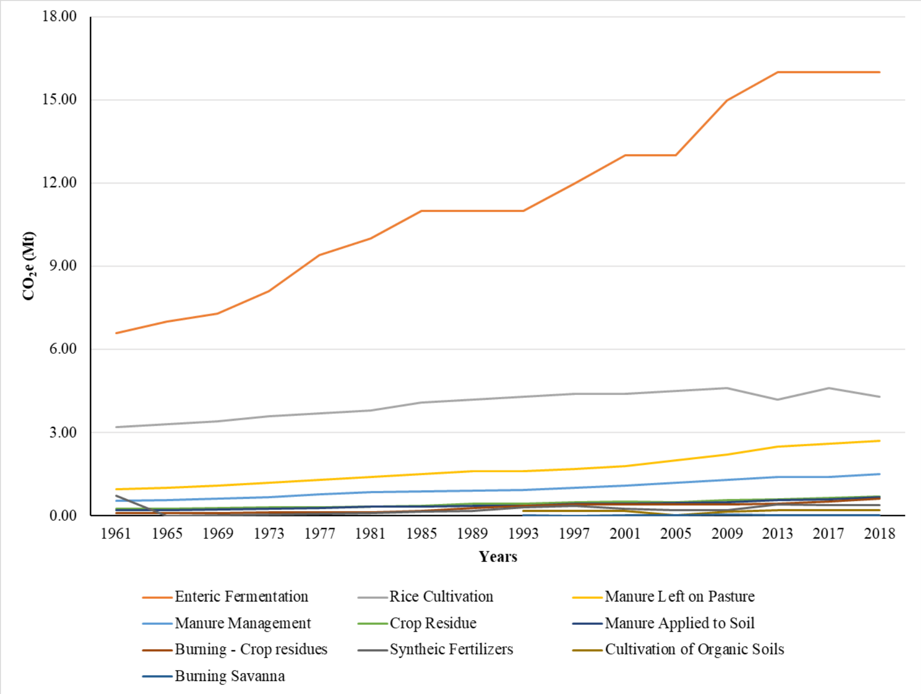
Greenhouse gas (GHG) emissions in **Nepal** was recorded as 40 Mt CO_2e in 2013, with agriculture contributing 52 % of the total emissions. The main sources of GHG emissions in the agriculture sector include enteric fermentation (around 55 %), rice cultivation (14 %) and manure left on pastures (13 %). Crop residue burning contributes to only 1 % of agriculture sector GHG emissions.

Figure 2: GHG emissions in **agriculture sector**



Source: Climate watch (2021a)

Figure 3: GHG emissions from sub-sectors in agriculture



Source: Climate watch (2021b)

In 2018, total GHG emissions, excluding land-use change and forestry (LUCF), was 51.2 Mt CO_2e and including LUCF was 54.6 Mt CO_2e. The agriculture sector contributed 25.7 Mt CO_2e GHG emissions, representing 50.23 % of 51.2 Mt CO_2e excluding LUCF and 47.16 % of 54.6 Mt CO_2e including LUCF. As can be seen from Figure 2, GHG emissions have been increasing from 1990 to 2018. The emissions from crop residue burning increased from 85 kt CO_2e in 1961 to 160 kt CO_2e in 2018. The share of agriculture in GHG emissions is increasing gradually with respect to other sectors (Figure 3).

5.4 Impact on Soil

The burning of crop residue depletes the soil of its organic matter, major nutrients and reduces microbial biomass in soil that ultimately impairs the efficacy of organic matter application in the next cropping season. In addition, it causes 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. It is estimated that burning of one tonne of rice straw accounts for a loss of 5.5 kg Nitrogen, 2.3 kg phosphorus, 25 kg potassium and 1.2 kg sulphur besides, organic carbon. Generally, crop residues of different crops contain 80 % nitrogen (N), 25 % phosphorus (P), 50 % sulphur (S) and 20 % 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 of residues elevates soil temperature causing death of beneficial soil organisms. Frequent residue burning leads to a 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. Existing Practices and Mechanisms of Crop Residue Management

Crop residues can be managed by in-situ and ex-situ management methods. Retaining or mulching and incorporating the crop residues in the field and decomposing using consortia of microbes are methods of in-situ crop residue management. Baling and transporting straw outside the field for other alternative uses is known as ex-situ management method.

6.1 In-situ Management of Crop Residue

Farmers do not prefer in-situ incorporation because the stubble takes long time to break down into the soil (particularly paddy crop). However, there are advantages to the soil properties by in-situ incorporation of straw. Ploughing back or surface retention of farm waste yields many benefits on physical, chemical and biological properties of soil. These practices increase hydraulic conductivity and reduce bulk density of soil by modifying soil structure and aggregate stability. Mulching with plant residues raises the minimum soil temperature in winter due to reduction in upward heat flux from the soil and decreases soil temperature during summer due to the shading effect of mulch.

The crop residues act as a reservoir for plant nutrients, prevent leaching of nutrients, increase cation exchange capacity (CEC), provide 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 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 erosion, 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 C build-up contribute to stable soil structure, this undisturbed structure produces macro pores and preferential flow channels that can direct nutrients, including P, downward into deeper parts of the soil profile. Yield response with residues management varies with soil characteristics, climate, cropping patterns, and level of management skills. Higher yields with crop residues application result from increased infiltration and improved soil properties, increased soil organic matter and earthworm activity and improved soil structure after a period of 4-7 years. Incorporation of crop residues in conservation agriculture has direct and indirect effects on pests too. Crop residues generally increase diversity of useful arthropods and help in reducing pest pressure.

The brief details of machinery and technology being utilized for in-situ management of crop residue in the subregion are as follows:

6.1.1 Straw chopper-cum-spreader

Straw chopper cum spreader is a machine which performs chopping and uniformly spreads straw left by the combine harvester in a single operation (Figure 4). It can be operated by a 45 hp or above tractor. The chopped and evenly spread straw can be mixed in the soil by using tillage machinery such as a 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 4: Straw chopper

Courtesy of ICAR/PAU

6.1.2. Stubble Chopper/Shredder

The Pakistan Agricultural Research Council (PARC) developed a machine called the FMI stubble chopper (Figure 5), collaborating with a local manufacturer at Daska, Sialkot in 1997. This machine was used for rice stubble chopping only. It cuts anchored stubbles as well as loose straw into small pieces. However, when disc harrows were used for mixing with soil (a common practice), they skidded instead of penetrating the field, so there were issues in farmers' acceptance of this machine.

Figure 5: FMI stubble chopper

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6.1.3 Reversible mould board plough

The reversible plough has two mould board ploughs mounted back-to-back, one turning to the right, the other to the left (Figure 6). Reverse ploughing helps to incorporate straw into the soil effectively and seeds for next crop can be sown easily over this soil bed. Potato growers after chopping-spreading prefer to bury the straw deep up to 300 mm so that ridges are free from any trash to place potato seed tubers (Chaudhary *et al*., 2019).

Figure 6: Reversible MB plough

Courtesy of ICAR/PAU

6.1.4 Tractor PTO powered Disc Plough

After combine harvesting, most of the paddy fields generally remain wet due to the presence of stubbles and left-over straw stock which can cause tractor tyres to slip during land preparation. In this situation, the penetration of disc harrow into the soil is limited to a depth of 75-100 mm and requires many passes to complete field preparation. Irrigation water remains for a longer period in the root zone, and in case of rain, the situation further worsens with the wheat crop becoming yellowish and drastically decreasing crop yield against its potential. In the developed equipment, the power take-off (PTO) of 50 hp tractor is connected to right rotating discs with 200 mm row spacing instead of a traction wheel (Figure 7). These discs can easily penetrate the soil to about 250 mm depth and help the tractor in completing the mixing of stubbles and residues in one pass. The effective field capacity of the implement is 0.4 ha/h and fuel consumption is about 7 l/h.

Figure 7: Tractor powered PTO disc plough

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6.1.5 Power Tiller Operated Rotary Tiller

Minimum tillage is a Resource Conservation Technology (RCT) that is cheap and best suited for marginal farmers. Straw is chopped into small pieces with an S-type rotary tiller blade and incorporated into the soil. Seeds with fertilizers are simultaneously sown in a row, followed by a roller covering the seed. Seed cum fertilizer drills are driven by a power tiller. This type of minimum tillage is very common among the smallholder farmers of the far-west and mid-west, but not popular in the eastern parts of Nepal. It is estimated that around 1,000 units are in operation.

Figure 8: Power tiller operated rotary tiller

©M.S. Basnyat

6.1.6 Roto till drill

The roto seed drill is a combination of a rotavator and a seed drill (without tines) (Figure 9). The rotavator attached in front of 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 9: Roto till drill

Courtesy of ICAR/PAU

6.1.7 Mulcher

Mulcher with vertical axis of rotation is a rotation mower (Figure 10). Rotary mulchers cut standing stubble and leftover straw into small pieces and lays them over the surface of the field. Small pieces of straw are then pressed by a roller attached to the rear side creating a mulch layer over the topsoil. A Happy seeder or reversible MB plough can then be used to sow wheat or invert straw into the soil, respectively (Chaudhary et al., 2019).

Figure 10: Mulcher

Courtesy of ICAR/PAU

6.1.8 Zero till seed cum fertilizer drill

A Zero-till (ZT) seed cum fertilizer drill does not chop the straw (Figure 11). It sows seeds and fertilizers directly into the soil without any tillage. It is good for standing stubble field and requires less powerful tractors than for Happy seeders. In India, the rapid and widespread adoption of ZT started in the Haryana and Punjab states. Zero tillage has offered high potential economic, environmental, and social gains in the Indo-Gangetic Plain (IGP) and is getting propagated in other states as well.

Figure 11: Zero till drill

Courtesy of ICAR/PAU

More than 100 such machines are in operation in Nepal. Since, it is cheaper and requires less powerful tractors to operate, these machines are popular in far-west and mid-west regions compared to the eastern parts of Nepal.

6.1.9 Dual mode RCT Drill

In 1995, the Pakistan Agricultural Research Council (PARC) developed a dual mode Resource Conservation Tillage (RCT) drill for combine harvested rice fields (Figure 12). This drill was used in stubble fields (burned fields) as well as manually harvested rice fields. The seed germination was good especially in burned fields and yield increased by about 12%. However, this drill did not popularize among farmers due to the smoke/dust created during drilling in the burned fields.

Figure 12: Dual Mode RCT Drill

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6.1.10 Punch planter

The punch planter was used for wheat sowing in maize residue. While this machine properly dropped seeds into small holes made by star wheels, it could not perform in heavy residue because loose straw would get wrapped up in the star wheels, trapping seeds within the straw and preventing them from being planted in the soil (Figure 13).

Figure 13: Punch Planter

©Shabbir Ahmed Kalwar

6.1.11 Happy seeder/Pak seeder

Punjab Agricultural University (PAU), Ludhiana, India, has developed a Happy seeder for sowing of wheat directly into the combine harvested paddy fields, without any other operation (Figure 14). Happy seeders can be operated by a 45 hp or above tractor. Happy seeder cuts straw in front of furrow openers and throws it over the sown crop in single operation which acts as mulch, while drilling the seed and fertilizer simultaneously. This mulch helps in conserving soil moisture, preventing soil erosion and suppressing weed growth. Mulch helps to reduce irrigation requirement by about 15-20 % and weed emergence by about 50 %. The sowing with the help of Happy seeders reduces labour requirements by 80 %, saves up to 10 % of fertilizers and increases yield by up to 5 %. It also prevents choking of the machine under a heavy straw load. It can cover about 2.4 - 3.2 ha in one day. Happy seeders are commercially available in 10, 11 and 13 row models (Manes *et al.*, 2017).

Figure 14: Happy seeder

Courtesy of ICAR/PAU

Figure 15: Pak Seeder

©Shabbir Ahmed Kalwar

In Pakistan, the Rocket seeder (eight-row) suitable for removing loose straw without cutting stubbles in front of each tine was modified and named as Pak Seeder (Figure 15). This ten-row machine can undertake direct seeding of wheat into heavy rice residue and can be used immediately after combine harvesting on the same day. The results indicated that the average yield in heavy rice residue increased up to 600 kg/ha.

Figure 16: Happy Seeder

©S. Shakya

Around 40 Happy seeders are being used in the far-west, mid-west, central parts of Nepal by commercial farmers and in research stations (Figure 16). Happy seeders are not used commonly among the marginal farmers as the capital investment required is high.

6.1.12 Smart seeder

Figure 17: Smart seeder

Courtesy of ICAR/PAU

Strip till seeder (Smart seeder) (Figure 17) was developed by PAU, Ludhiana Centre of the All India Coordinated Research Project (AICRP) on Farm Implements and Machinery and was recommended for use by farmers in 2021. This tractor mounted machine is essentially a seed drill capable of operating in a paddy stubble and straw laden field (after combine harvesting). The Smart seeder incorporates only a small part of straw in the soil and retains the majority of straw as surface mulch. This reduces the chances of seeds dropping on straw. It can be operated with a 45 hp or above tractor. The effective field capacity and fuel consumption of the machine are 0.40 ha/h and 5.58 l/h, respectively.

6.1.13 Super seeder

The super seeder (Figure 18) can be operated after harvesting of paddy with a combine harvester having a straw management system (SMS). The super seeder can be used for sowing wheat seeds and also mixes crop residue into the soil in single pass after paddy harvesting. 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 machine is operated by a 55 hp or above tractor. 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 18: Super seeder

Courtesy of ICAR/PAU

6.1.14 Super straw management system (SMS)

The combine harvester 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 combine cutter bar. This forms lines of heaps of loose residues (as wide as the straw walker width) which hinders the operation of Happy seeders. PAU developed a super straw management system (Figure 19) as an attachment for the self-propelled combine harvester. Super SMS chops and uniformly spreads loose straw coming out of straw walkers of harvester. It facilitates the working of Happy seeders and increases its capacity.

Figure 19: Super SMS

Courtesy of ICAR/PAU

In Pakistan, efforts were made to integrate a fine straw mechanism with combine harvesters, but this mechanism has not gained popularity among farmers. It was due to a decrease in operational capacity from 10 to 4 hectares per day, and high cost of operation.

To ensure a better yield utilizing the Pak Seeder/Happy Seeder, it was found vital to spread loose straw uniformly before seeding. A simple, low-cost straw spreading kit was developed in Pakistan to fix onto a combine (Figure 20). Owners/rental companies remove the chopping and spreading mechanism since it requires more power. Farmers who do not want to pay the additional cost of spreading straw also do not see any benefit of spreading out straw in the field.

Figure 20: Combine straw spreading kit

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6.1.15 Sugarcane trash chopper cum spreader

Sugarcane trash chopper cum spreader is used to chop the trash and spread it onto the field uniformly (Figure 21). The unit has two rotary members with swinging type blades. The rotary cutting units can be sled inward or outward based on the row to row spacing of the standing sugarcane crop. The unit shreds the sugarcane trash of size from 600 to 900 mm into small pieces of about 75 mm size (Kumar *et al*., 2016).

Figure 21: Sugarcane trash chopper cum spreader

Courtesy of ICAR/PAU

6.1.16 Pusa decomposer

The Pusa decomposer has been developed by the Indian Council of Agricultural Research - Indian Agricultural Research Institute (IARI), New Delhi. The decomposer is in the form of capsules made by extracting fungi strains that help the paddy straw to decompose at a much faster rate than usual. The fungi helps to produce the essential enzymes for the degradation process. The decomposer mixture involves making a liquid formulation using decomposer capsules and fermenting it over 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 using 4 capsules, jaggery and chickpea flour. The mixture is sufficient to cover one hectare of land. It takes around 20 days for the degradation process to complete.

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 effective, cheaper, and practical technique to stop stubble burning. It is also 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, the ICAR – IARI, New Delhi has produced about 20,000 packets of Pusa decomposer in 2021 at its own facility.

6.2 Ex-situ Management of Crop Residues

The ex-situ method is more capital intensive and requires significant subsidies for farmers and user industry to be sustainable. Ex-situ management of crop residues involves off-farm utilization through collection of straw by operating straw choppers and then hay rakes followed by 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 has proved to increase farmer income. The Governments of the countries in the subregion have various programmes to manage the crop residues ex-situ, which may play an important role in the overall ecosystem of biomass management, as the options are proven for commercial deployment. In view of increasing problems associated with crop stubble burning, various technologies being promoted for ex-situ management in the subregion are detailed in this section.

6.2.1 Straw reaper

The straw reaper is normally used after combine harvester operation to cut the left-over stubble and to convert it into bruised fine straw locally known as *bhusa* either for animal feed or spread over the field for mulching purpose. The straw reaper is a trailed behind tractor PTO powered machinery (Figure 22). The reaper can perform cutting, picking, threshing and blowing operations in a single action and is economically viable for wheat crop (Verma *et al.*, 2016; Shukla *et al*., 2020). It has straw recovery rate from 80 to 95 % (Ujala *et al*., 2020).

Figure 22: Straw reaper

Courtesy of ICAR/PAU

Approximately 75 % of harvesting is done by combine harvesters in India (Deepika, 2021), whereas straw reapers are mostly adopted for crop residue management of wheat. The machine is easily accessible to small and marginal farmers in India through custom hiring centres.

In Pakistan, there are about 2,000 straw reapers in use and more than 25 agricultural machinery manufacturers are manufacturing this machine.

In Nepal, straw reapers are widely used to reap standing wheat straw after combine harvesting in the far-west and mid-west Terai. This straw is then transported to the settlement, stored in bulk and fed to livestock during lean season. The demand for such wheat straw is quite high. These machines are imported from India along with combine harvesters for custom hiring during wheat harvesting.

6.2.2 Straw Rake

Straw rakes are commercially available and can be used to collect the cut and loose paddy straw from fields and make a windrow of narrower sections thereby providing dense straw input for baler machines (Figure 23). The side-delivery rakes and star wheel rakes are popular in India. The star wheel rakes are mechanically simple and trouble-free, gentle on the straw than a side-delivery rake, and cheaper to operate. The cost of smaller wheel rake is INR 85,000 and the approximate cost of a 5 m rake is INR 0.18 million (Manes et al., 2017).

Figure 23: Rake

Courtesy of ICAR/PAU

6.2.3 Straw Baler

The straw baler is used for collecting and baling loose straw in combine-harvested fields (Figure 24). Before baling, a stubble shaver is first used to harvest the stubbles from base level. It can form rectangular or round bales varying in length from 0.40 to 1.10 m. The weight of the bales varies from 20 to 30 kg depending on moisture content of straw and bale length. The capacity of the baler ranges between 0.30 - 0.35 ha/h.

In some parts of Nepal, farmers have started using baling machines to facilitate the transport and storage of bulky rice and wheat straws in small spaces.

In Bangladesh, machinery for ex-situ management of crop residue is not very common and therefore, there is a need for more straw collectors, small size transportation trolleys, small size straw balers, hay makers and corn stalk choppers to help in the collection of straw within a short period of time.

Figure 24: Baler

Courtesy of ICAR/PAU

6.2.4 Briquetting of crop residues

Fig. 25 (a) Pellet making machine (b) Prepared pellets

Courtesy of ICAR/PAU

Biomass briquetting is a standard method for production of high density, solid energy carriers from biomass. Briquettes/pellets are produced in several types and grades as fuel for electric power plants and other industrial and home applications. Pellet making equipment are available in different sizes and scales, which allow for manufacturing at the domestic as well industrial scales (Figure 25a). Pellets have a cylindrical shape and are about 6-25 mm in diameter and 3-50 mm in length (Figure 25b). 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 pellet and in turn increases the energy consumption. Size reduction is done using a hammer mill equipped with a screen size from 3.2 to 6.4 mm. If the feedstock is quite large, it goes through a chipper before grinding. 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 many resins or lignin, and so a stabilizing agent needs to be added. Distillers' dry grains or potato starch are some of commonly used binders. The use of natural additives depends on biomass composition and the mass proportion between cellulose, hemicelluloses, lignin and inorganics. The cost of the commercially available biomass pellets is INR 9,000-10,000 per tonne. In Pakistan, recently big cotton growers have started producing pellets and briquettes as fuel.

6.2.5 Biogas production

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

The PAU, Ludhiana centre of the AICRP on Energy in Agriculture and Agro-industries (EAAI) has developed a biogas plant considering the alternate use of paddy straw for biogas production (Figure 26). 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 the biogas 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 purpose or other energy options. Gas production continues for about three months and reloaded after emptying it. 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 tonne paddy straw is INR 0.12 million which is about four times costly as compared to conventional animal dung based biogas plants 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 state of India and are working very well.

Figure 26: Paddy straw-based biogas plant

Courtesy of ICAR/PAU

In Bangladesh, cow dung with wet rice straw is used in biogas plants. There are 85,514 biogas plants in Bangladesh (SREDA, 2022).

6.2.6 Bio-CNG/Compressed biogas (CBG)

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 as compared with an 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 methane content of 55 – 60 % and from this volume about 120 - 140 kg of CNG or about 550 – 600 kWh of electricity can be produced.

During the year 2008-09, a new initiative was taken by the Ministry of New and Renewable Energy (MNRE) of India to demonstrate technology of biogas bottling in an entrepreneurial mode. It includes installation of medium-size mixed feed biogas plants for generation, purification and bottling of biogas under the Research, Design, Development and Demonstration (RDD&D) policy of the initiative. Installation of such plants aimed at production of CNG quality of compressed biogas (CBG) for use as a vehicle fuel in addition to meeting stationary and motive power, electricity generation and thermal applications. 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 India after obtaining required licenses for filling and storage of compressed biogas in CNG cylinders.

Purified biogas is filled in CNG cylinders and supplied to mid-day meal schemes, messes, hotels, industries, etc., for various purposes such as cooking and heating. The calorific value of purified biogas is equivalent to CNG. Biogas bottling plants are one of the most potent tools for mitigating climatic change by preventing black carbon emission from biomass chulhas since biogas is used as a cooking fuel and methane emissions from untreated cattle dung and biomass wastes are also avoided.

6.2.7 Power generation from biomass

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

Biomass power projects have following inherent advantages over thermal power generation:

- They are environmentally friendly because of relatively lower CO_2 and particulate emissions.
- They displace fossil non-renewable fuels such as coal.
- They are decentralized, load-based means of power generation because electricity is produced and consumed locally. Therefore, the losses associated with transmission and distribution are reduced.
- They offer employment opportunities to locals and help in local revenue generation and upliftment of the rural population.
- They have a low gestation period and low capital investment.

There are some environmental problems with biomass-based power plant such as no satisfactory disposal methods of ash coming out from the plant. The biomass consumption in a power plant is about 30 tonnes/day/MW and ash coming out from the plant is about 4.5 tonnes per day/MW. A large area is also needed for safe storage of bales for use during off-season periods. Hence, land available in the village may be secured on lease or Panchayat 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. The transportation of bales from a distance of 15 km radius is quite feasible and economical. Hence, transportation of the bales to a safe storage place and smaller size plants from 4 to 10 MW may be encouraged.

In Pakistan, the government has taken the initiative to install biomass energy facilities and revise renewable energy legislation. The National Electric Power Regulatory Authority (NEPRA) of Pakistan is aiming to increase the country's power generation capacity by providing attractive incentives for the construction of new cogeneration power plants that burn garbage. Table 5 shows the details of installed power plants that used agricultural crop waste.

Table 5: Biomass energy power plants in Pakistan

Location	Capacity	Crop Residue
Jhang, Punjab	12 MW	Cotton stalk, rice husk, sugarcane trash, bagasse
Mirpurkhas, Sindh	12 MW	Bagasse, rice husk, cotton stalks, wood chip
Faisalabad, Punjab	12 MW	Rice husk, corn cob, cotton sticks
Matli, Sindh	9 MW	Bagasse

Source: Country Report of Pakistan on Integrated Straw Management

It is reported that the use of straw to generate energy is not common in Nepal. A study was conducted in three agro-ecological zones of Nepal (Bajhang for mountain, Lamjung for hill and Morang for Terai districts) to identify the potential of using crop resides to generate energy. It was found that:

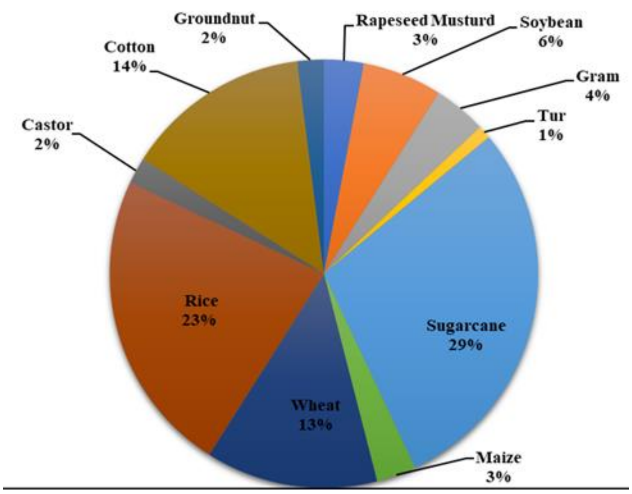
- Availability of crop residues in the lowlands was higher (954 kg dry matter per capita per year) than in the hill districts (547 kg per capita per year).
- The amount of crop residue used for energy generation was higher in the hills (207 kg per capita per year) than in the lowland district (152 kg per capita per year).
- In the mountain district, crop residue production was 263 kg per capita per year, of which 26 kg per capita per year is used for energy generation.
- The annual per capita energy equivalent from crop residues in the lowland, hills and mountains is 2.49, 3.42 and 0.44 GJ which represent 30 %, 33 % and 3 %, respectively, of the total annual cooking energy consumption of the country.

6.2.8 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 bio-fuel supply was approximately 35 billion gallons in 2015, with approximately three-fourths from ethanol and one-fourth from bio-diesel. Until 2015, 70 % of the global biofuel supply was met by Brazil and 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 biofuels.

Conversion of lingo-cellulosic 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 (lingo-cellulosic/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 litres (Bl) from 178 Mt of surplus crop biomass generated in the country. Out of total annual bio-ethanol production potential, 38.04 Bl can be produced in the K*harif* season and 13.08 Bl in the *Rabi* season. The crop wise maximum bio-ethanol potential was from sugarcane crop biomass followed by rice, cotton and wheat crop biomass (Figure 27). A viable operational system of using surplus biomass for generating biofuels provides prospects for increasing the revenue of famers and contributes to the energy security of the country.

Figure 27: Bioethanol production potential of different crops



Source: TIFAC and IARI, 2018

6.2.9 Bio-char

Bio-char is produced via the burning of waste biomass at 300-600º C in the partial or complete exclusion of oxygen, a process known as pyrolysis. As a fine-grained charcoal, biochar can potentially play a major role in the long-term storage of carbon in soil, i.e., C sequestration and GHG mitigation. Bio-char offers significant prospects for sequestering about 40 – 50 % of original biomass carbon in the soil in a chemically altered form that is biologically stable and may last in soil for centuries, while remaining physically and chemically active. Due to its greater stability against microbial decomposition and its superior ability to retain nutrients compared to other forms of soil organic matter, applying bio-char to soil also offers a significant potential for mitigating climate change and enhancing environmental quality.

Bio-char can be used for energy generation (as fuel), as a soil amendment agent to improve crop productivity; as a carbon sequestration agent to bring negativity in the carbon cycle, and as adsorbing agent for capturing the polluting elements. The pyrolysis process temperature, retention time and heat flow method are important parameters which affect the carbon content in the char. For the purpose of carbon sequestration and capturing atmospheric CO_2, the significant quantum of bio-char with maximized C-content in it with maximum level of stability is needed.

Currently, the application of bio-char in agriculture is limited in India. 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 bio-char generation process, it would become economically viable. There is a need to develop low-cost pyrolysis kiln for bio-char production. There is also a need to evaluate and maximize the benefits of bio-char application on soil health, carbon sequestration and nutrient use efficiency in different soils under different cropping systems in India.

6.2.10 Compost making

Composting is the natural process of organic matter decomposition 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. The addition of compost improves the physio-chemical and biological properties of soil and can completely replace the 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.

The crop residues have been traditionally used for preparing compost. The high organic content in crop residues makes it an ideal raw material for compost similar to animal manure. 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, gives about 3 tonnes of manure as rich in nutrients as farmyard manure (FYM). IARI, New Delhi, has developed a biomass-compost unit for making good quality compost. This mechanized unit efficiently uses waste biomass and crop residues. The decomposition process, which is hastened by a consortium of micro-organisms takes 75-90 days.

This compost making option is not recommended for crop residue management due to diversion of land area for composting resulting in loss of food-grain production. 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.

6.2.11 Fodder for animals

In **India**, crop residues are traditionally utilized as animal feed as such 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.

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

In **Pakistan**, more than half of the animal dietary needs are fulfilled by crop residues, one-third by grazing, and the rest from other crops and their by-products. In local dairy sheds, animal fodder mainly comprises of wheat straw which has immense nutritional value for cattle and has no close substitutes. Wheat straw constitutes about 60 % of fodder used for meeting dietary needs of livestock. It is so critical that an increase in its price leads to a corresponding increase in the prices of milk and meat. In less than 20 % of situations, rice straw mixed with green fodder is utilized as animal feed when there is shortage of wheat straw. Maize straw is also mostly consumed by cattle. Sugarcane topping is traditionally utilized as animal feed by itself or by supplementing with some additives.

In **Bangladesh**, rice straw is a preferable feed for cows and buffaloes. Wheat straw is not fed to cows and buffaloes. Chopped green corn stalk is also considered a good feed for animals. The chopped rice straw, soaked and mixed with liquid molasses is a quality feed for animals. Similarly, pieces of chopped corn stalk, dried and packed are used in the lean period (Sarker et al., 2019). There is a good prospect of expansion of this animal feed.

In **Nepal**, use of straw for consumption by livestock as fodder is most common. Straw is collected during the harvesting season and stored in different forms under the shed or in an open space. There are huge quantities of loose paddy straw being transported to mid-hill regions of eastern Nepal for off-season feeding of livestock. Crop residues such as paddy straw, wheat straw, corn stover, oat hay, millet and buckwheat, oil seed crops, etc., are important sources of bulk energy for ruminants. They meet about 32-37 % of total digestible nutrients (TDN) required for lean season when green fodder is scarce. TDN supply from crop by-products and milling by-products has increased due to increase in food crop production. Consequently, the deficit feed balance (TDN) at the national level has dropped from 30.9 % in 1980 to 20.05 % in 2017.

In the subregion, straw fodder is used in various forms such as straw chopping/chaffing, straw treated with urea, straw blocks, etc. The chopped paddy straw treated with 4 % urea fed to dairy cattle has positive effects on body health, milk production and consumption of straw improves the crude protein and in-vitro organic matter digestibility. Straw blocks are a densified mixture of 80 parts straw, 10 parts molasses, 2 parts mineral, 1part urea and 1 part salt. Straw wafers are about ten times bigger than the size of straw-based densified complete feed pellets or cylinders with chemical additives and other minerals. Straw wafers are easy to transport, store and feed. Ensilage industries are opening up as the prevalence of commercial livestock farming increases. Green maize plants are harvested and chopped into pieces or left unchopped. They are then wrapped with plastic to make them anaerobic for storage and use.

6.2.12 Bedding material for cattle

It has been observed by Punjab Agricultural University (PAU) 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 biogas plants.

In Nepal, in general, rural households use paddy straw for bedding of domestic livestock. This bedded straw, after getting wet, is dumped into composting pits and finally used as fertilizer. The rice straw is also used for animal bedding in Pakistan and Bangladesh.

6.2.13 Mushroom cultivation

Paddy straw mushrooms are a high temperature mushroom grown largely in tropical and sub-tropical regions of Asia, e.g., China, India, Indonesia, Madagascar, Malaysia, and Thailand. 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 mushrooms account for 16 % of total production of cultivated mushrooms in the world. One kg of paddy straw can be used for the cultivation of 300, 120 - 150 and 600 g of Agaricus bisporus, Volvariella Volvacea and Pleurotus spp of mushrooms, respectively. Paddy straw mushrooms (Volvariella Volvacea) are also known as grass mushrooms for their cultivation on paddy straw in South Asia.

In Nepal, paddy straw is widely used as a substrate for cultivation of oyster and white button mushrooms after sterilization and fermentation. It is considered as the best substrate for high protein content and yield of mushrooms. The shed for mushroom production is also made of paddy straw over the plastic sheet lining. This technology is widely used across the country, but the volume of straw consumption is negligible compared to production. Machines to make balls of straw and package them into plastic bags are used in some commercial mushroom cultivating farms. In general, 1 kg of dry paddy straw produces 700-800 g of oyster mushroom. It is estimated that nearly 105,000 tonnes of rice straw (NPR 52,500,000) at the rate of NPR 5/kg have been used annually for oyster mushroom cultivation. The common field mushroom and many other types of mushrooms grow well on compost made from paddy straw. The organic matter left after mushroom harvest can also be used as fertilizer.

6.2.14 Paper production

The non-wood paper industry in India uses a variety of raw materials such as agro-residues namely bagasse, wheat straw, rice straw, wild grasses, etc., and waste paper (recycled fibre). Non-wood-based paper mills, contributing to over 70 % of India's production, manufacture an eco-friendly paper from agro residues by converting Waste into Wealth and conserving forest resources to an extent of 20 million trees per year. These paper mills, which are predominantly set up in rural areas, provide large-scale employment and livelihood to directly and indirectly almost 4 million people, the majority of which are from lower income groups, i.e., marginal farmers, skilled and semi-skilled workers. Paddy straw is 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. Paddy straw is also used as an ideal raw material for paper and pulp board manufacturing. It contains less lignin as compared to conventional wood and thus requires mild chemical pre-treatment.

In Pakistan, as per estimates, 40 % of wheat straw is used for other sectors which includes exports. Of this, nearly 5 % is used by the pulp and paper industry. It is the main raw material in the production of pulp and paper and constitutes approximately 85 % of total cost of low-quality papers (Haq, 2019).

In Nepal, the paper industry used to be a bulk consumer of paddy straw, but now almost none are using it. The paper mills, such as the Everest Paper Mill which was using straw for paper production, have shifted to recycled paper as raw material to produce paper.

6.2.15 Building Material

In India, a new environment-friendly technology has been developed for turning agricultural residues like bamboo, rice husk, jute, coconut coir, bagasse, wheat straw, chir pine needle, cotton stalk, casuarina leaves, banana stems, etc., into quality value-added composite products using conventional formaldehyde-based resins. This new technology highly favours environmental protection and sustainable development by recovering and re-utilizing organic wastes such as crop residues. Adoption of these technologies also leads to implementation of a green solution as an alternative to crop residues being burned.

In Nepal, compressed soft and hard boards of straw produced by Nepal Straw Board Co. (P) Ltd., Biratnagar are available and widely used in the construction sector since 2015 earthquake.

6.2.16 Handicrafts and Value-added Items

In the countries of the subregion, residues of various crops are utilized to make handicrafts and value-added items. In Nepal, paddy straw, *paral* in the local language, is used as raw materials for production of indigenous products like floor carpets (*sukul*), ropes (*dori*), mats (*chakati*), mattress (*gundri*), shoes, stool, handbags, wall hangings, etc., and also holy materials in Hindu mythology. Craft production from straw is considered as a cottage industry and is quite common in rural areas. Since ancient times, leisure time is used to make products and supports livelihoods through selling of these products. Some of the senior citizens in the rural areas are still making such crafts as a leisure activity. The utilization of straw for craft production can be made into a professional business to reduce the volume of straw that is burned. In Bangladesh, rice and wheat straws are used to make domestic mats, baskets, trays, etc. In India, residues of cereals, oilseeds and horticultural crops are also utilized for such purposes. ICAR has brought out a compilation of such technologies in a publication titled "Creating Wealth from Agricultural Waste" (Kimothi et al., 2020).

7. Schemes and Efforts of Governments in the Subregion

The sustainable management of agricultural waste has become a great challenge, especially for the countries in the subregion with an increasing population, agriculture production and economic growth. Crop residue burning has become a major environmental problem causing health issues as well as contributing to global warming.

The solution to crop residue burning lies in the effective implementation of sustainable management practices with Government interventions and policies. To control crop burning and mitigate trans-boundary air pollution, countries in the subregion have attempted some interventions to reduce the amount of crop residue burned through different campaigns, which are described country wise as follows.

7.1 Bangladesh

The Government of Bangladesh developed its Agriculture Mechanization Policy 2020 (MoA, 2020) to support the timely completion of critical operations, reduce production costs, increase cropping intensity, and mitigate adverse environmental condition for crop production, and efficient handling of postharvest processing activities. In the policy, the introduction of small size farmer-friendly agricultural machinery is encouraged as per the farmers' socio-economic status, farm size, and soil conditions. The policy also assists local agricultural machinery manufacturers and provides an easy process for loan facilities to importers, rental machinery service providers, manufacturers, and farmers. In the policy guideline, farmers can purchase combine harvesters, reapers, rice transplanters and other machines at a subsidized rate of 50 % and in some cases of 70 %. However, crop residue handling machinery has not been given any mention in the policy. It is expected that it would be included in an updated version of this policy.

Modern agricultural machinery such as power tillers, power threshers, reapers, combine harvesters, rice transplanters, etc., were supplied to farmers under an assistance programme of the farm mechanization project (Phase I and Phase II). CIMMYT, Bangladesh introduced a large number of two-wheel tractor-driven seeders, bed planters, zero-till planters, reapers, corn shellers, and axial flow pumps in the farmers' fields, giving crop residue management a priority.

7.2 India

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 is 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.

The Ministry of Agriculture developed a National Policy for Management of Crop Residue (MoA, 2014), and circulated the same to all the states/union territories with the following major objectives:

i. Promoting technologies for optimum utilization and in-situ management of crop residues;

ii. Promoting appropriate machineries for farming practices;

iii. Using satellite-based technologies to monitor crop residue management by National Remote Sensing Agency (NRSA) and Central Pollution Control Board (CPCB); and

iv. Providing 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.

Total burning events recorded during 2019 in states of Punjab, Haryana and Uttar Pradesh in India were 52 % less as compared to 2016.

The adoption of in-situ method of straw management may have resulted in saving of 30 – 35 % Nitrogen; 20 – 25 % Potassium and substantial amount of organic carbon, nearly 25 % of irrigation water and also helps in restoring microbial activities in the soil.

The paddy burned area estimated by satellite 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.

In order to curb crop residue 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 launched by the Government of India and operated through Mechanization and Technology (M&T) 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) and extended for two more years (2020-21 and 2021-22) with budgetary allocation of INR 13.00 billion. The objectives of the scheme were 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 (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), including: 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, and ix) Rotavator.

An amount of INR 24.17 billion was released to different states and ICAR between 2018-2021 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. A total of 0.213 million equipment/machines were supplied in these states (Punjab- 85,386, Haryana- 72,237, and UP-55,711) under the scheme. Custom hiring centres (39,391) were established in Punjab (25,403), Haryana (6,775) and Uttar Pradesh (7,213) for facilitating availability of equipment/machines to the small and marginal farmers on hire basis. A mobile app-based aggregator platform was developed to facilitate hiring of machines from Custom Hiring Centres.

> Government of India implemented a scheme on "Promotion of Agricultural Mechanization for In-situ Management of Crop Residue" in four States and supplied 0.213 million implements/machines in three states (Punjab – 85,386, Haryana – 72,237, and UP - 55,711) during 2018-2021.
>
> Custom hiring centres (39,391) were established for making easy availability of equipment/machines to small and marginal farmers on hire basis.

The Krishi Vigyan Kendras (KVKs), under the Indian Council of Agricultural Research (ICAR), have put considerable effort in 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:

- 2,558 awareness programmes

- 33,508 demonstrations of machines for crop residue management
- 856 training programs for 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.

To encourage in-situ management of paddy straw, equipping combine harvesters with a Super Straw Management System (Super SMS) has been made mandatory. The violators of the NGT order will have to pay fine based on the landholding.

The National Green Tribunal (NGT) banned crop residue burning in the states of Haryana, NCT Delhi, Punjab and Uttar Pradesh. In these states, paddy residue burning events were monitored by multiple satellites with thermal sensors during the paddy harvest season. There was considerable reduction in the burning events of the rice crop residue. Overall, total burning events recorded during 2019 in three states 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 higher number of the burning events during 2020 and 2021 might be due to protest burning by farmers of Punjab. Fines in the range of INR 2,500 – 15,000 were imposed on farmers found to be burning crop residue (Jitendra *et al*., 2017). 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.

For ex-situ crop residue management, the central government reported that 1.10 million tonne of paddy residue (5.5% of total residue generated) was used in paper/cardboard mills 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.

The Ministry of New and Renewable Energy (MNRE) 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). 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).

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 namely 1G bio-ethanol, bio-diesel; and ii) advanced biofuels namely 2G ethanol, bio-CNG, etc. Under the policy, for establishment of 2G ethanol refineries, a funding of INR 50 billion will be made available for six years besides additional tax incentives and a higher purchase price (in comparison to 1G ethanol). Also, oil marketing companies are in the process of setting up twelve 2G bio-refineries with an investment of INR 100 billion (MoPNG, 2018). 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 dependency on imports and to provide additional income to farmers to have cleaner environment by management of municipal solid waste.

7.3 Nepal

Agriculture mechanization is a part of policy frameworks guiding the development of the agriculture sector in Nepal. The Agricultural Development Strategy (ADS) 2015-2035, is Nepal's overarching agricultural development plan for 20 years. The ADS identifies agricultural mechanization as one of thirteen priority areas for achieving higher productivity and recognizes the role of the private sector in the mechanization of Nepal's agriculture. The strategy calls for mechanization to create awareness, stimulate demand, concessionary financing arrangements and build the capacity of a nationwide network of machinery dealers, particularly for appropriate small scales machineries like 2-wheel power tillers and mini-tillers. It also calls for continuing the low levels of import taxes on agricultural machinery and exemption from value added tax (VAT) for selected machines.

While the ADS does not directly mention integrated straw management, the enhancement of good agriculture practices (GAP), soil fertility improvement, use of organic manure, biogas production, biomass utilization, etc., are mentioned in different sections of the document. One of the sustainability indicators in the ADS is soil organic matter, where soil fertility at 1 % organic matter in 2010 will increase to 4 % organic matter by the end of the ADS target year. This can be achieved through the promotion of integrated soil and plant nutrient management, improvement in agricultural practices for cultivation, integrated crop nutrition and crop residue management.

The Agricultural Mechanization Promotion Policy, 2014 (AMPP) encourages the promotion of:

i. Technology and machines appropriate for sustainable agriculture, minimum tillage and resource conservation technologies;

ii. Identification of energy and environment-friendly machines;

iii. Machines for organic fertilizer production; and

iv. Utilization of organic fertilizer, organic and bio-pesticides to achieve Integrated Pest Management (IPM), Integrated Nutrition Management (INM), Good Veterinary Practices (GVP), Good Livestock Practices (GLP), Good Agricultural Practices (GAP) and Good Fishery Practices (GFP).

Through government organizations and donor-funded projects, the Government of Nepal (GON) has also initiated subsidy schemes for individual farmers, farmers' groups, cooperatives, entrepreneurs, and the private sector to increase production and productivity and decrease the cost of production. To discourage residue burning, the Government of Nepal has approved and enforced the law by publishing a notice in the Gazette of Nepal on 20 April 2015 mentioning that the combine harvesters without straw collecting machines such as straw reapers and/or balers, etc. are not allowed to be imported or used for custom hiring businesses.

7.4 Pakistan

The Punjab Environment Protection Council approved a Smog Action Plan which included an Air Quality Index (AQI) classification system. The fifth measure of the Plan is related to controlling burning of municipal waste and crop residue. According to the Third Pole report 2019, the police filed 544 cases under Section 144. The largest number of burning incidents were reported from Sheikhupura (204), Jhang (120), Okara (102) and Nankana Sahib (96) divisions of Pakistan's Punjab. The Punjab Disaster Management Authority (PDMA) had also imposed penalties for crop residue burning, including fines of up to PKR 50,000 (US$ 250) per hectare (Jalil, 2019).

Under the direction of the Prime Minister of Pakistan, the Government of Punjab has initiated a programme to overcome the smog issue. The government is subsidizing rice residue handling machinery for rice growers aiming to support timely sowing of wheat. The project was launched in 2020-21 for two years to distribute 500 rice straw choppers/shredders and Pak seeders/Happy seeders to the farmers/service providers of major rice growing districts of Punjab on a cost sharing basis to manage their rice crop residue without burning. A subsidy of 80 % of the total cost of machine was provided by the Government of the Punjab and the remaining 20 % was paid by the farmer/service providers. Despite the limitations, the Pak Seeder/Happy Seeder have proven so popular that the government has had ten times more applicants for the targeted 500 machines. During the first year of the project, 135 units each of shredders and Pak/Happy seeders were distributed among the farmers.

From the point of view of ex-situ management of crop residue, the government has taken the initiative to build more biomass energy facilities and revise renewable energy legislation. The National Electric Power Regulatory Authority (NEPRA) is aiming to increase the country's power capacity by providing attractive incentives to independent power plants for the construction of new cogeneration power plants that burn garbage.

8. Challenges in Crop Residue Management in the Subregion

Rice, wheat and maize are the main staple crops grown in the subregion. It is observed that most of burning of crop residues in the subregion is practiced for rice and wheat stubbles and are the major contributors for depleting soil health and air pollution along with smog in the winter. 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 subregion and its socio-economic needs. The key challenges in the management of crop residue in the subregion have been classified as follows:

8.1 Challenges in In-situ Management of Crop Residue

A huge supply constraint has been observed to meet the demand of in-situ management machinery and ability of local manufacturers to cater to the needs of farmers. Another key concern with adoption of new machinery for mulching/mixing rice straw is low availability of high horsepower (≥ 50 hp) tractors for marginal to medium farmers in the study countries. In addition to the farm implements, it is found that most of the new implements and machinery in the market, such as Happy seeder and MB Plough, require high horsepower tractors for operating them on fields.

Further limiting factors in adoption of in-situ management techniques of crop residue pointed out by farmers include subsidy issues, lack of financial support, need for additional management skills, high operational costs, 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 shabby-looking fields. As adoption of in-situ crop residue management can entail fundamental changes in farming practices, real-time support to address farmers’ concerns 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.

 *Courtesy of ICAR/PAU*	**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 seeders 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 conditions 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 seeders are 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.
 *Courtesy of ICAR/PAU*	**Rotavator** a. Rotavators cannot work properly on standing straw and usually require 2-3 runs in such cases. This results into higher maintenance costs due to 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 as compared to mulching.
 *Courtesy of ICAR/PAU*	**Super SMS** a. In most of the cases, cost of renting a SMS attached combine harvester is higher (incremental cost of INR 1250-1500/ha) as compared to combine without SMS 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.
 *Courtesy of ICAR/PAU*	**Mulcher** a. Mulchers are used to cut 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.
 *Courtesy of ICAR/PAU*	**Reversible MB Plough** a. MB Plough is used to incorporate straw back into the soil by rotating the top layer of the soil. As a result, it increases the fertility of the soil under normal soil conditions and assists faster degradation of incorporated straw. b. It requires high horsepower tractor and associated diesel consumption is higher. c. MB Ploughs cannot be used in cases where the sub-soil is infertile or sandy. d. MB Ploughs work best in cases of potato sowing as potatoes cannot be sown in mulched soil.

Source: Analysis based on Group Discussions with Farmers (Sharma, M. et al., 2019)

Overall, the issues for in-situ management of crop residues in the subregion are as follows:

Agriculture practices

- Lack of adoption of conservation agriculture practices.
- Lack of crop rotation - rice-wheat and rice-rice cropping systems are being practiced in the subregion year after year.
- Use of combine harvesters increases volume of straw left in field as the combine harvesters cut the rice crop at the height of 400-800 mm in the case of a standing crop and leave behind a swath of loose straw spreading in field.

Machinery/infrastructure issues

- Demand-supply gap - local manufacturers unable to meet demands of farmers.
- Non-availability of high hp (≥ 50) tractors.
- Poorly equipped repair workshops.
- Non-availability of spare parts for new machines in local markets.

Economic issues

- Expensive and seasonal use of crop residue management machinery.
- High operational cost of in-situ management machinery as compared to burning of crop residues.

Capacity and awareness

- Apprehension of yield loss/returns
- Insufficient training facilities for operators adopting new machines
- Additional management skills for operation of in-situ management machinery under straw load

Policy issues

- Lack of standardisation and safety regulations for crop residue management machinery.
- Subsidies are not disbursed to farmers and entrepreneurs on time and subsidised machinery are underutilized.
- Custom hiring services of in-situ management machinery are not adequate to cater all farmers at affordable cost. Therefore, as an immediate measure, it would be best to incentivise the farmers based on the cost-effective straw management initiatives.
- The farmers and custom hiring service providers need additional skill and training to operate and maintain in-situ management machinery.

8.2 Challenges in Ex-situ Management of Crop Residue

The use of crop residues as fodder for animals or for generation of electricity requires various on-farm 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. According to a study by Gupta *et al.* (2004), the baling cost is around INR 800 ha^{-1}. The total cost of operation, including baling, collection, transportation up to 5 km distance and stacking is INR 1,300 ha^{-1} or INR 650 t^{-1} of straw. 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. According to a study by Owen and Jayasuriya (1989), the use of crop stubble in bio-thermal plants has not been very successful. This is mainly due to lack of any technical and economic feasibility studies, lack of assured markets for processed by-products, shortage of funds to undertake research and development, etc.

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.

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. 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. However, the high cost of collection and transportation of residues from the field to the end-user proves to be the prime impediment for scaling up ex-situ management practices (Singh *et al*., 2010). Therefore, entrepreneurs in the supply chain find the economics of handling crop residue unattractive.

Kurinji and Kumar (2021) considered the rental cost of machinery (such as chopper/cutter-cum-spreader, baler, and rake), labour, and fuel required for cutting and baling of paddy residue, loading and unloading cost of bales at farm and straw bank, and transportation charges for carrying bales from farm to straw bank. They estimated that the transit of paddy residue in the form of bales to a distance of 15 km from farm to straw bank typically costs INR 1,330 per tonne of bale. Out of this, the cost associated with the cutting and baling of residue is 50 % of the procurement cost. They estimated that transporting the baled residue to the end-user beyond 50 km entail a delivered cost of INR 2,950 per tonne of bale, which may not be viable for companies engaged in the supply chain. Several studies indicated that densifying biomass in the form of briquettes or pellets would decrease the transportation cost. However, their analysis indicated that the high cost for briquetting and pelletising significantly eats into the benefits of reduced transportation cost of the densified residue. As per their study, delivery of briquettes/pallets over a distance of 50 km costs INR 4,320-4,720 per tonne. 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 uses that require densified biomass, the end-user needs to invest in processing bales to briquettes or pellets.

Overall, the issues behind the ex-situ management of crop residue in the subregion are as follows:

Machinery/infrastructure issues

- Lack of network of collection centres and supply chain management (SCM) facilities for ex-situ utilization of crop residues.
- Need for heavy vehicles for collecting and transporting crop residues from field to plant site.
- Extensive crop residue storage infrastructure needed for operation of biomass-based power plant throughout the year.

Economic issues

- High cost of collection of residues, e.g., rental costs of machinery (such as rake and baler), labour, and fuel required for raking and baling of paddy residue.
- High cost of transportation of straw residues to collection centres (such as loading and unloading cost of bales at farm and straw banks, transportation charges for carrying bales from farm to straw bank).
- Lack of assured markets for processed by-products such as biogas, Bio-CNG, pallets, etc.
- Lack of assured supply of crop residues for operation of bio-ethanol plant, bio-CNG plant, etc.

Capacity and awareness issues

- Lack of technical know-how at local levels on various ex-situ straw management options, such as use of straw for biochar, biogas and biofuels (e.g., briquettes, pellets, bio-compressed natural gas, bio-diesel).

Policy issues

- Lack of technical and economic feasibility studies for use of crop residues for ex-situ management options.
- Need to incentivise power generation from crop-residues to be cost competitive.
- Shortage of funds to undertake research and development of ex-situ straw management options.

8.3 Institutional and Organizational factors

Government and institutional support are most critical elements in curbing the crop residue burning in the countries of the subregion. The curbing of surplus crop residue burning has not been paid due attention in mechanization policies of most of the countries in the subregion due to the lack of availability of in-situ and ex-situ crop residues management technologies and additional cost involved in managing it. As such, suitable laws, policies or orders for prevention of crop residue burning are yet to be formulated in most of the countries. While all the countries have an apex body for formulation and administration of rules, regulations and laws pertaining to agriculture and its practices in the country, only India has formulated a National Policy for Management of Crop Residue (NPMCR) in 2014. There is a lack of stringent monitoring mechanisms in all the countries to monitor the implementation of any intervention undertaken by State governments/provinces for crop residue burning. Central subsidies for purchase of harvesting equipment and machineries (Happy seeders, combine harvesters, super SMS, etc.) to the farmers to facilitate in-situ management of crop residue is also not sufficient. Overall, the institutional and organizational factors to be addressed for crop residue management in the subregion are as follows:

- Insufficient financial support and subsidy for in-situ crop residue management equipment and machineries.
- Lack of relevant statistical information on the utilization and availability of straw resources.
- Lack of crop residue management policy.
- Lack of incentives to entrepreneurs or service providers for offering in-situ straw management services at a price that is affordable to farmers.
- Lack of research and development and feasibility studies for ex-situ management of crop residues.
- Capacity building of under and post-graduate students and farmers on crop residues management practices.
- Incentives to the farmers for management of crop residues in field to stop burning.

8.4 Socio-economic Factors

Management challenges of the crop residues are varied across the region 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. Alternative measures have long been suggested by scientists and agriculturalists over the past decade to counter crop residue burning, but due to a lack of awareness and social consciousness among the farmers these measures have not been fully implemented. Several technologies are available, however, large-scale adoption by resource poor and low-skilled farmers has become difficult. The information on viable technological configurations and projects is limited and as such the knowledge dissemination remains unsuccessful to reach stakeholders, like farmers, co-operations, investors and project developers. In most villages, the farmers are unaware of any technological usage of their agricultural waste and the residue remains unutilized and therefore burnt. Overall, the socio-economic factors requiring urgent attention for crop residue management in the subregion are summarized as follows:

- Lack of education of farmers on crop residue management practices and their environmental benefits.
- Little efforts to create awareness amongst the farming community about benefits of crop residue management.
- Strong preferences of farmers for clean and good-looking tilled fields vis-a-vis untilled shabby looking fields.
- Non-availability of sufficient custom hiring facilities of in-situ machinery in rural areas.
- Negative attitudes or perceptions of farmers for alternative uses of crop residues.

9. Action Plan and Future Strategies

Burning is an inexpensive and labour efficient means of removing unwanted crop residues prior to tillage or seedbed preparation. However, the alarming increase of air pollution levels caused by crop residue burning in the northern areas in India and other countries in the subregion, observed in recent years suggest that the issues need to be addressed without any further delay.

Crop residues are of great economic value as livestock feed, fuel and industrial raw material. However, management challenges and socio-economic needs of crop residues are varied across the subregion. Several technologies are available for efficient use of crop residues. However, they require substantial improvements for large-scale adoption by resource poor and low-skill farmers. These are the new dimensions of the problems which agriculture in the subregion is currently facing and need to be addressed though appropriate policy intervention and action plan in each of the study countries.

9.1 Estimation of Crop Residue Availability

Significant amounts of crop residues are generated from agricultural crop production and partially remain in the field after harvest. The availability of residues depends on the amount that can be removed from land to maintain soil fertility and on their competitive use for agricultural or industrial purposes. The use of agricultural crop residues for bioenergy production (as straw or stover – stalks, ears, leaves, or cobs), requires accurate data on their availability by crop type as well as their local and annual variability. The estimation of the residues available for bio-energy production provides information on the best locations for a bio-energy plant and also on plant size.

Therefore, the first and foremost action required is a proper estimation of the amount of biomass generated from different crops and assessing the amount of surplus crop residues. This is crucial as the availability of data is essential for the formation of an action plan for effective crop residue management. Study countries need to carry out surveys and collect data (primary or secondary sources) for calculation of biomass availability and surplus biomass available. This is necessary to understand location-wise demand and utilization patterns in different areas across the countries. Standard procedures and models developed by various researchers can be utilized for the purpose.

9.2 Propagation of Conservation Agriculture Practices

On-farm use of crop residues is the easiest way to prevent burning, as it requires minimum effort and the cost incurred is also low in comparison to any other ex-situ management techniques. Such on-farm use also provides many other ecological benefits. Conservation agriculture practices can make efficient use of crop residues. Deterioration of land quality/soil health is a major concern in all study countries. The root cause of degradation of agricultural land is its low soil-carbon content that disrupts many important soil-mediated ecosystem functions. Conservation agriculture, with the following three core inter-linked principles, is a viable option for sustainable agriculture and is an effective solution to check land degradation (Friedrich *et al*., 2009).

- Minimizing mechanical soil disturbance and seeding directly into untilled soil to improve soil organic matter content and soil health.
- Enhancing organic matter cover on soil using cover crops and/or crop residues. This protects the soil surface, conserves water and nutrients, promotes soil biological activity and contributes to integrated pest management.
- Diversification of crops in associations, sequences and rotations to enhance system resilience.

Conservation agriculture is a sustainable agriculture production system that helps to avoid straw burning, improve soil organic C, enhance input efficiency and have the potential to reduce GHGs emissions (Pathak *et al*., 2011). Crop residues returned to the soil can maintain or enhance soil quality and productivity through favourable effects on soil properties and life-support processes. The principles of conservation agriculture need to be translated into practices as per site-specific requirements which will not only reduce the crop residue burning but also ensure food security by improving soil health.

An impact assessment of in-situ residue management machinery was conducted by a committee of Ministry of Agriculture and Farmers Welfare, Government of India (MAFW, 2019) and the committee recommended that the best and most environmentally sustainable use of paddy straw is its incorporation in the soil itself. This can be easily achieved by supporting farmers to buy the crop residue management (CRM) machinery and running a sustained IEC campaign for proper utilization of the machinery. Ex-situ utilization of paddy straw would damage soil health in the long run as it would remove green carbon, potash, phosphorous and other nutrients present in the paddy straw. This option may be considered if economically viable.

9.3 Mechanization for Crop Residue Management

The decrease in farm workers and labourers paves a way for farmers in need of adapting mechanization in managing crop residues. However, looking into the adoption of these technologies at the farmers' level, a series of challenges exist in using crop residue management machinery in sowing of seeds and applying fertilizer and pesticides. The following points need to be considered in this regard:

- Development of multi-functional farm machinery for management of crop residues, herbicide application and sowing of the succeeding crop under a layer of residues on soil surface.
- Development of conservation agricultural machinery suitable for small tractors and power tillers.
- 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.
- Crop harvesting machinery need to be developed that retain 30–40 % crop residues in the field while baling the rest of the amount.
- Development of appropriate farm machinery to facilitate cost effective collection, volume reduction and transportation.
- Clear guidelines for optimum irrigation, fertilizer management, pest management and long-term effects on soil health, to facilitate mechanization at the farmers' level.
- Supplying machineries for conservation agriculture on subsidized rates, promoting custom hiring systems and providing soft loans for purchase of implements.
- Establishing self-help groups and encouraging unemployed youths to take up custom hiring of in-situ management machineries as a profession.
- Capacity building of under- and post-graduate students and training of farmers with regards to appropriate use for optimal performance of machinery.
- Limiting factor in adoption of CRM machinery for some farmers include additional management skill requirements, apprehension of lower crop yields and/or economic returns, negative attitudes or perceptions, and institutional constraints. These need to be addressed through large-scale demonstrations and trainings.
- There is a need to support on-farm adaptation of CRM machinery in both large and scattered small fields as well as developing focused institutional and policy support including appropriate incentives for the widespread dissemination and adoption.

9.4 Promotion of Gasification Technology

Gasification is a process that converts biomass (wood, agriculture residues, briquettes, etc.) or fossil fuel-based carbonaceous materials into gases. This is achieved by reacting the feedstock material at high temperatures (typically >700 C), without combustion, via controlling the amount of oxygen and/or steam present in the reaction. The resulting gas mixture is called producer gas which has a calorific value of about 1000 - 1200 kcal/Nm3 and is itself a fuel due to the flammability of the H2 and CO in the gas. Power can be generated from the combustion of the resultant gas, and is considered to be a source of renewable energy if the gasified compounds were obtained from biomass feedstock.

India is one of the few countries in the world having an active research and demonstration programme on small-scale biomass gasification technologies. About 1.2-1.4 kg of biomass is required for producing 1 kWh of electricity (using 100 % producer gas engine). Crop residues can be utilized as fuel for running a biomass gasifier for multiple applications including electricity, agro-processing, and running decentralized cold storage at the village level. This can also provide farmers an alternate option to shift to horticulture crops for which farmers currently are reluctant owing to limited cold storage capacity at the local level. A 250 kW capacity biomass gasifier plant can utilize about 2,000 tonnes of paddy straw annually and support 50 tonnage refrigeration (TR) cold storage facility besides producing electricity (Datta *et al.*, 2020)

Currently, global efforts to reduce dependence on fossil fuels and the consequent search for renewable energy sources are the key drivers of increasing use of gasification systems. The gasification technology has been widely studied for various types of biomass and operating conditions, bringing flexibility and versatility for biomass conversion. Gasification of biomass is seen as a promising technology for clean development, allowing greater economic, social, and environmental sustainability. Although there are a few limitations with various types of gasifiers, the limitations of each type of gasifier should be included in research priority areas that will allow for system optimization in terms of efficiency. The use of this technology offers a number of ecological and economic advantages such as low emission of pollutants, reduction in the environmental effects of waste disposal, generation of non-hazardous by-products when biomass is used as the feedstock, and lower operating cost.

9.5 Biofuel Production

There is a huge potential to offset fossil fuels by generating ethanol from bulk crop residues with efficient commercial technologies. Potentially, 250–350 l of ethanol can be produced from each metric tonne of dry crop residues. Considering that only 20 % of world's rice straw is used for this purpose, this would lead to an annual ethanol production of 40 billion litres, which would be able to replace about 25 billion litres of fossil fuel-based gasoline (Bhattacharyya and Barman, 2018).

In India, potential of annual bio-ethanol production from surplus crop residue (178 Mt) has been estimated as 51.12 billion litres (Bl). Out of the total annual bio-ethanol potential, 38.04 Bl can be produced in the *kharif* season and 13.08 Bl in the *rabi* season. The crop-wise maximum bio-ethanol potential was of sugarcane crop biomass followed by rice, cotton and wheat crops.

In other countries of the subregion, a viable operational system of using surplus biomass for generating biofuel provides prospects for increasing the revenue of famers and energy security of the country.

9.6 Development of Mechanism for Aggregation of Crop Residue Biomass

Ex-situ management of crop residue can be economically viable if a good supply chain management exists. Policies are needed that will encourage private investment in crop residue collection and provide options to the farmers in disposing of their crop residues. This will allow the private sector to invest in crop residue valorisation processes through the production of briquettes, char, paper, tableware, fabric production, etc. In order to establish a supply chain management mechanism, the following needs to be acted upon:

9.6.1 Network of biomass depots

Creating infrastructure for setting up biomass depots for the storage of baled crop residue is crucial for ex-situ management of crop residues. Sourcing of crop residues for ex-situ use is found to be financially viable when the crop residue collection point is located within 15 km and end-user is situated within 50 km. Therefore, a dense network of biomass depots needs to be created for streamlining the supply chain in the study countries. This will also boost the demand for biomass in the private sector. The infrastructure for biomass depots for the storage of baled crop residues may be established and maintained in close vicinity by biomass-based power generation plant or biofuel production plant.

9.6.2 Minimum support price for crop residue and its products

In India, Chhattisgarh State Electricity Regulatory Commission (CSERC), which is one of the largest biomass producing states, fixes the minimum support price for rice husk. Similarly, in countries of the subregion, it is required to establish price regulation for biomass-based products, making adequate allowance for compensating farmers for costs incurred in managing the waste. Such policies may be applied in other countries for integrated management of crop residues and their end products.

9.6.3 Mobile app for easy trading of crop residue

A mobile app, similar to a custom hiring app for agricultural machinery, connecting farmers, straw banks, end-users, and various stakeholders involved would go a long way in streamlining the supply chain of crop residue. The mobile app or use of social media platforms would facilitate farmers to raise a request to collect crop residue in advance and the nearest straw bank could collect the residue from the farm within the stipulated time. This would also be helpful for the supply chain management bodies to optimally plan for storage and logistics.

9.6.4 Creation of market

A decentralized model of production of crop residue briquettes or char briquette involving farmer producer organizations (FPOs), farmers' cooperatives, etc., needs to be prioritized. The use of crop residue briquettes or char briquettes in local industries and hotels/*dhabas* needs to be promoted.

9.7 Laws and Legislation

All of the study countries have policies on agriculture mechanization, but the policies do not adequately consider the management of crop residues. In India, only a few states put due emphasis on the management of crop residues through laws and legislations. The following laws/legislations may form part of crop residues management policy of countries in the subregion.

- Developing a crop residues management policy for each State/province of a country defining clearly various competing uses.
- Developing and implementing appropriate legislation on preventing and monitoring of on-farm crop residues burning through incentives and punishment.
- Introducing carbon-credit schemes to benefit the farmers who follow conservation agriculture practice for carbon sequestration and GHGs mitigation.
- Classifying crop residues as amendments (like lime or gypsum) and their use in agriculture should attract subsidy like any other mineral fertilizer or amendment.

Development partners, international agriculture research institutions and SAARC bodies could consider supporting knowledge exchange activities to share good practices[5] and learnings for development and implementation of laws and legislation for crop residues management.

9.8 Farmers' Awareness and Empowerment

In order to promote no-burning and more sustainable farming practices, acceptability, feasibility and benefit perception should be promoted. Active stakeholder involvement including education and empowerment of farmers along with technical solutions and product manufacturing can assist tremendously.

Educating and empowering the stakeholders are crucially important steps to make a significant impact. The thinking of the farmers is that they are only responsible for producing crops and they are free to deal with crop residues in the manner they find cheaper, i.e., burning. This thinking needs to change and farmers should feel responsible for the residue they produce. This is only possible through proper awareness-raising campaigns. However, raising the knowledge and awareness does not mean much until they find it feasible, beneficial and acceptable.

Farmers also should be educated about the advantage of reduced agro-chemical costs with the utilization of crop residue in agricultural land. Therefore, awareness-raising campaigns should always run parallel with the implementation of practical solutions that empowers them not only technically, but also economically.

Keeping in view the above, the following points are suggested:

- The economic or financial incentive could be a powerful driver for farmers to choose a no-burning approach. Provide a reasonable amount of incentive to farmers not to burn crop straw in the open field.
- Organise trainings of farmers by local research and extension centres (e.g., Krishi Vigyan Kendras in India) and provincial Departments of Agriculture for creating awareness about

[5] One such example is a database on SDG good practices developed by ESCAP. For further reference please see https://www.unescap.org/projects/sans/sdg-good-practices

effects of crop residue burning and adaption of conservation agricultural practices and resource conservation technology by initiating new projects.

- Promote diversified uses of crop residues (rice straw and sugarcane trash) for power generation, bio-ethanol, packing material for fruits and vegetables and glassware, paper/board/panel industry, bio-gas, composting, and mushroom cultivation, etc., by concerned departments of provincial and central government of countries.
- Raise awareness of the negative impacts of crop residue burning on human health and the environment through media campaigns and community awareness programmes.
- Dissemination of appropriate technologies for proper utilization and management of crop straw to prevent loss of important soil nutrients and improve soil microbial activities and soil health.
- If possible, governments can consider cooperating to jointly organise Farmers Awareness Camps in bordering areas, where farmers from neighbouring villages can be brought together to exchange their views. Some of the farmers who successfully adopted the new usage of crop residues could be promoted to champion this cause.

10. Recommendations for Subregional Cooperation

The major areas identified for subregional cooperation for integrated crop residue management are summarized below and further details are given in Annex I. In addition, efforts should be made to exchange information and best practices on crop residue management through subregional initiatives and frameworks for the management of air pollution such as the Malé Declaration on Control and Prevention of Air Pollution and its Likely Transboundary Effects for South Asia.[6]

10.1 Joint Research and Analytical Studies

There is large variability in the estimates of generation, utilization and on-farm burning of crop residues in the countries of the subregion. No systematic study has been conducted in Bangladesh, India, Nepal and Pakistan for estimation of crop residue utilization and on-farm burning in the subregion. The conducting of studies following a uniform protocol on availability, utilization, surplus and burning of crop residues in the subregion will help in formulation of evidence-based national policies/strategies/programmes/laws/regulations.

Remote sensing technologies are being used for spatio-temporal monitoring of crop residue burning in the states of Haryana, Punjab and Uttar Pradesh of India under a scheme for promotion of in-situ management of paddy residue. The same approach may be used for fire

[6] The Malé Declaration was signed in 1998 by members of the South Asia Co-operative Environment Programme (SACEP) to promote regional cooperation on air pollution, building national capacities, assisting policy making, and sharing information and experience. While funding issues and the COVID-19 pandemic led to a slowdown in pace of activities, a relaunch of the Declaration is planned with efforts to finalize new draft agreement and workplan (Kuylenstierna, 2022).

mapping studies between countries in the subregion to map and monitor incidence of crop residues burning. The mapping of fires through satellite images on a regular basis can help to identify location of fire spots, the density of burning and help to understand whether burning is related to specific crops or certain events for a specific year. Looking at such maps over a number of years can provide policymakers with information to better understand the situation of crop residue burning. The leveraging of existing networks of agriculture research institutions to support joint research and analytical studies based on a uniform protocol should be pursued to implement such studies.

10.2 Supply Chains for Aggregation of Crop Residue Biomass

The supply chain of crop residues 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. 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 facilities. However, the high cost of collection and transportation of residues from the field to the end-user proves to be the prime impediment for scaling up ex-situ management practices as entrepreneurs in the supply chain find the economics of handling crop residue unattractive.

Ex-situ management of crop residue can be economically viable if good supply chain management facilities exist to take advantage of local demand/supply gaps. Policies and coordination are needed that will encourage private investment in crop residues collection and provide options to the farmers for their disposal. This will allow the private sector to invest in crop residue valorization processes such as the production of briquettes, pallets, char, paper, tableware, power generation, etc.

The development of supply chains at the local level in respective countries is needed to make ex-situ management practices economically viable. Further assessment on the feasibility of establishing domestic and, where feasible, cross-border supply chain mechanisms could be considered. For instance, this could include the development of a mobile app or use of social media platforms for easy trading of crop residues. The sharing of experiences from India and other Asia-Pacific countries on domestic and cross-border agriculture supply chains and their application for aggregation of crop residue biomass may be useful to provide policymakers with insights on scaling-up of ex-situ crop residue management practices.

10.3 Sharing and popularization of technologies, equipment and practices for in-situ and ex-situ management of crop residues

Farming in future has to be multi-functional and ecologically sustainable so that it can deliver ecosystem goods and services as well as livelihoods to producers and society. Hence farming should effectively address local, national and international challenges of food, water and energy insecurity; issues related to climate change; and degradation of natural resources.

The propagation of conservation agriculture practices can make efficient use of crop residues that avoids burning while providing many ecological benefits that improve soil health and productivity. This does, however, entail fundamental changes in farming practices which require technical support and awareness raising activities on the benefits of conservation agriculture practices.

The decrease in farm workers and labourers paves the way for farmers to adopt and adapt mechanization solutions for managing crop residues. Accordingly, several technologies have been developed for mechanization of crop residue management in the subregion and are being promoted on a pilot basis.

The use of crop residues as fodder for animals or for generation of electricity are ex-situ management practices that can also reduce levels of burning. The promotion of gasification technology and biofuel production from crop residues have potential to generate electricity with lower emission of pollutants and increase revenues of farmers.

However, looking into the adoption of these technologies at the farmers' level, the scenario is challenging. A series of constraints exist in using crop residue management machinery and appropriate funding, R&D, training, scale-up and monitoring interventions are needed to overcome them.

Some areas of subregional cooperation that should be considered include: (i) the establishment of a subregional R&D fund to support development of machinery prototypes as well as other solutions for straw management; (ii) the organization of knowledge sharing and training programmes on best practices of crop residue management in various countries; and (iii) the establishment of a subregional-level monitoring cell on crop residue burning and management.

10.4 Harmonization of testing standards and promoting more integrated trade of in-situ and ex-situ agriculture machinery

The test codes for testing of machinery such as super straw management system (Super SMS) attached with combine harvester, Happy seeder, paddy straw chopper, super seeder, zero till seed cum fertilizer drill, etc., are being developed for promotion and sale of good quality in-situ crop residue management machinery under an Indian government financial assistance programme. Some of these machineries are also exported to neighbouring countries. However, testing codes for ensuring the quality of the machinery vary across countries and some countries may also not have a testing system or facilities in place. This creates a trade bottleneck.

Harmonization of testing codes for machinery among participating countries along with a system of mutual recognition of test results/certificates could help to facilitate trade of better quality and more efficient machinery within the subregion, benefiting both producing and importing countries. It could also lower costs by avoiding the need for repeated testing of the machinery in each country. CSAM is making efforts in this direction through its initiative titled the 'Asian and Pacific Network for Testing of Agricultural Machinery' (ANTAM - https://antam.un-csam.org/).

Improved linkages should be promoted among agricultural machinery manufacturers in the subregion in order to further the development of the agricultural machinery market across countries and support the dissemination of more sustainable and efficient technologies based on a demand driven model. One channel for improving such linkages could be via networking amongst national agricultural machinery manufacturer and distributor associations. CSAM's initiative titled the 'Regional Council of Agricultural Machinery Associations in Asia and the Pacific' (ReCAMA - https://recama.un-csam.org/) is making efforts in this direction.

11. Conclusions

Crop residue burning is a national problem in most developing countries causing severe pollution of land and air at local as well as subregional levels. Repeated burnings in a field permanently diminish the microbial population. Burning of crop residues leads to the release of soot particles and smoke causing human and animal health problems. It also leads to the emission of greenhouse gases namely carbon dioxide, methane and nitrous oxide, causing global warming and loss of plant nutrients. The burning of crop residues is a wastage of valuable resources which could be a source of carbon, bio-active compounds, feed and energy for rural households and small industries.

In the subregion, harvesting of cereal crops is mainly done using combine harvesters and generates large volume of crop residues on-farm. There is large variability in the estimates of generation, utilization and on-farm burning of crop residues. Crop residues are utilized differently, varying with the country and its socio-economic status, type of cultivated crop, number of crops per year, etc. Traditionally, crop residues in the subregion have been utilized in numerous competing uses such as animal feed, fodder, fuel, roof thatching, packaging, composting, etc. Cereal crop residues are mainly used as cattle feed. The use of crop residues for other purposes except as cattle feed is in limited quantity. The remaining residue left unused is burned in field.

The sustainable management of crop residues has become a great challenge for countries in the subregion. There are many approaches and technologies for in-situ and ex-situ management of crop residues which have been tested and demonstrated, but some of these alternatives are not economically viable and practically feasible. The major problems include the short time available in rice wheat cropping system between the harvesting of rice and sowing of wheat crop, followed by the high cost of transport, storage and handling of crop residues.

In-situ management of crop residues on-farm is the easiest, economical and environment friendly way to prevent burning. Promotion and adoption of conservation agriculture practices can manage large amounts of crop residues and prevent burning. At the same time, it also increases production in a sustainable way by improving water use efficiency, and reducing fertilizer consumption, machinery use and fuel consumption. Through this approach, one can reduce production costs, without compromising yield. This can be easily achieved by supporting farmers to buy or access the crop residue management machinery.

Ex-situ utilization of crop residues could be considered if economically viable. The government support should primarily be confined to those techniques that promote consumption of crop residues in the soil. Ex-situ management also suffers from a lack of resources to aggregate, store and supply the residue efficiently. Power producing companies are dependent on supply of biomass, but there is also uncertainty of year-round availability of crop residue due to its seasonal nature, coupled with the lack of supply chain management infrastructure. What is needed is to create a uniform decentralized mechanism for the collection, storage and commercial sale of crop residue. This will facilitate easy procurement of biomass fuel for power generation and other uses.

The best alternatives could be the ones that make end-products to be used by the agricultural industry itself, and on-site if possible. It was suggested that there is a need to share knowledge of best practices and machinery of crop residue management among countries of the subregion through workshops/seminars/visits. Policies for adaptation and testing standards of CRM machinery also needs to be harmonized. These are activities that could be supported by CSAM.

Sustainable management of crop residues has not become very popular in the subregion due to low availability of economically viable and practically feasible options of crop residue management as well as a lack of awareness and social consciousness among the farmers. Therefore, educating and empowering the farming stakeholders and providing them financial support for adoption of crop residue management technologies are important steps to make a significant impact. Creating awareness raising campaigns should always run parallel to implementation of practical solutions that empowers them not only technically, but also economically. Establishing demonstration projects also helps promote the acceptance of residue utilization.

The banning of crop residue burning does not reduce burning. It is important that the policymakers engage in a rigorous analysis of the reasons that keep the fields on fire time and again. While some of the measures taken by the Governments in the subregion are laudable, there are shortcomings within the existing solutions. Overcoming these challenges requires a combination of technologies and incentives. The strategy, broadly, should be to make farmer realize the real economic and commercial value of the crop residue.

References

Ahmed, T. and B. Ahmad (2013). Why Do Farmers Burn Rice Residue? Examining Farmer's Choices in Punjab, Pakistan. *SANDEE Working Paper 76-13*. Kathmandu: South Asian Network for Development and Environmental Economics. http://www.sandeeonline.org/uploads/documents/publication/1006_PUB_Working_Paper_76_Tanvir.pdf

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.

Ashrafi, R. *et al*. (2019). Utilization of rice straw compost for strawberry and tomato production. *Progressive Agriculture*, *30*(4), 335-343.

Bangladesh Bureau of Statistics (BBS) (2019). Statistical Yearbook Bangladesh 2018. Dhaka: Ministry of Planning, Government of Bangladesh.

Bangladesh Bureau of Statistics (BBS) (2020). Statistical Yearbook Bangladesh 2019. Dhaka: Ministry of Planning, Government of Bangladesh.

Bangladesh Bureau of Statistics (BBS) (2021). Yearbook of Agricultural Statistics 2020. Dhaka: Ministry of Planning, Government of Bangladesh.

Bhattacharyya, P. and D. Barman (2018). Crop residue management and greenhouse gases emissions in tropical rice lands. In: Maria Angeles Munoz, Raúl Zornoza (Eds.), Soil Management and Climate Change: Effects on Organic Carbon, Nitrogen Dynamics, and Greenhouse Gas Emissions, Academic Press, pp 323-335.

Biswas, B. *et al*. (2017). Pyrolysis of agricultural biomass residues: Comparative study of corn cob, wheat straw, rice straw and rice husk. *Bioresource Technology*, *237*, 57-63.

Cassou, Emilie (2018). Field Burning. *Agricultural Pollution*. Washington DC: World Bank. http://hdl.handle.net/10986/29504.

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 2020. 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

Climate watch (2021a). Drivers of Emissions in agricultural sectors. https://www.climatewatchdata.org/sectors/agriculture?emissionsCountry=BGD#drivers-of-emissions

Climate watch (2021b). Drivers of Emissions in agricultural subsectors. https://www.climatewatchdata.org/sectors/agriculture?emissionType=137&emissionsCountry=BGD&filter=#drivers-of-emissions

Das, B. *et al*. (2020). A model-ready emission inventory for crop residue open burning in the context of Nepal. *Environmental Pollution*, 266 (3), https://doi.org/10.1016/j.envpol.2020.115069

Datta, A.M.A. *et al*. (2020). Crop Residue Management: Solution to Achieve Better Air Quality. New Delhi: The Energy and Resources Institute (TERI). https://www.teriin.org/sites/default/files/2020-01/crop-residue-management.pdf.

Deepika, Rashmi Tyagi (2021). Socio-economic Impact of Straw Reaper on Farmers in Rural Community of Haryana. *Journal of Community Mobilization and Sustainable Development*, 16(2), 381-390. https://www.indianjournals.com/ijor.aspx?target=ijor:jcmsd&volume=16&issue=2&article=009

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

FAO-STAT (2021). Crops and livestock products. https://www.fao.org/faostat/en/#data/QCL

Friedrich, T., Kassam, A. H. and F. Shaxson (2009). Conservation Agriculture. In *Agriculture for developing countries. Science and Technology Options Assessment (STOA) Project*. European Parliament. European Technology Assessment Group, Karlsruhe, Germany. https://www.itas.kit.edu/downloads/projekt/projekt_meye08_atdc_annex2.pdf

Gadi, R. *et al*. (2003). Emissions of SO_2 and NO_x from biofuels in India. *Tellus B: Chemical and Physical Meteorology*, 55 (3), 787-795.

Gul, Chaman *et al.* (2021). Black carbon concentration in the central Himalayas: Impact on glacier melt and potential source contribution. *Environmental Pollution*, 275. https://doi.org/10.1016/j.envpol.2021.116544.

Gupta P.K. *et al*. (2004). Residue burning in rice-wheat cropping system: Causes and implications. *Current Science*, 87(12), 1713–1715.

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. https://acsess.onlinelibrary.wiley.com/doi/abs/10.2134/asaspecpub65.c1

Haq, S. (2019). Competition Commission of Pakistan (CCP) seeks ban on use of wheat straw as fuel. *The Express Tribune*, 25 December. https://tribune.com.pk/story/2124368/ccp-seeks-ban-use-wheat-straw-fuel.

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

Islam, M. S. *et al*. (2020). Utilization of crop residues in rural household of Bangladesh. *Progressive Agriculture*, 31(3), 164-177.

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.

Jalil, X. (2019) Why are farmers resisting a government ban on stubble burning? *Dawn*, 13 November. https://www.dawn.com/news/1516460

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

Kimothi, S.P., Panwar, Sanjeev and Anjani Khulbe. (2020). Creating Wealth from Agricultural Waste. New Delhi: Indian Council of Agricultural Research. https://icar.org.in/sites/default/files/Creating-Wealth-From-Agricultural-Waste.pdf

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?sequenc e=1&isAllowed=y

Kurinji, L. S. and S Kumar. (2021). Is Ex-situ Crop Residue Management a Scalable Solution to Stubble Burning? A Punjab case study. New Delhi: Council on Energy, Environment and Water. https://www.ceew.in/sites/default/files/CEEW-Ex-situ-Crop-Residue-Management-24Dec20_0.pdf

Kuylenstierna, Johan C.I. (2022). Reinvigorating the Malé Declaration offers South Asia the opportunity to improve air quality. *Stockholm Environment Institute*, 5 September. https://www.sei.org/perspectives/reinvigorating-male-declaration/#:~:text=A%20new%20draft%20agreement%20and,promoting%20regional%20cooperation%20in%20Asia.

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

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) (2020). National Agricultural Mechanization Policy 2020. Dhaka: Ministry of Agriculture, Government of the People's Republic of Bangladesh.

Ministry of Agricultural Development (MOAD) (2014). Agriculture Mechanization Promotion Policy. Kathmandu: Government of Nepal. https://www.moald.gov.np/publication/Policy

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 & Farmers Welfare. https://agrimachinery.nic.in/Files/Guidelines/CRM.pdf

Ministry of Agriculture and Farmers Welfare (MAFW) (2019). Report of the Committee on Review of the Scheme "Promotion of Agricultural Mechanisation for In-situ Management of Crop Residue in States of Punjab, Haryana, Uttar Pradesh and NCT of Delhi. New Delhi: Department of Agriculture, Cooperation and Farmers Welfare, Government of India. https://farmech.dac.gov.in/revised/1.1.2019/REPORT%20OF%20THE%20COMMITTEE-FINAL(CORRECTED).pdf

Ministry of Agriculture and Farmers Welfare (MAFW) (2021-22). Second advance estimates of production of food grains for 2021-22. New Delhi: 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, Ministry of New and Renewable Energy, 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.). https://mopng.gov.in/files/TableManagements/AR_2018-19.pdf

Owen, E. and M.C.N. Jayasuriya. (1989). Use of crop residues as animal feeds in developing countries. *Research and Development in Agriculture*, 6(3), 129-138.

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.

Pathak, H., Saharawat, Y.S., Gathala, M. and J. K. Ladha (2011). Impact of resource-conserving technologies on productivity and greenhouse gas emission in rice-wheat system. *Greenhouse Gases: Science and Technology*, 1(3), 261–277.

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

Sarker, N. R., Rahman, S. M. R. and M.Y.A. Khan, (2019). Feeds and fodder trend-in Bangladesh. AHCAB-2017. https://www.researchgate.net/publication/337681662_Feeds_fodder_trend-in_Bangladesh_-AHCAB-2017

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. .

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, J., 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), 483–488. https://doi.org/10.1016/j.biombioe.2009.12.012.

Singh, R. P. *et al*. (2008). Economic assessment 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). https://researchoutput.csu.edu.au/en/publications/economic-assessment-of-the-happy-seeder-for-rice-wheat-systems-in-2

Sustainable Renewable Energy Development Authority (SREDA) (2022). National Database of Renewable Energy. https://ndre.sreda.gov.bd/index.php?id=2&i=6

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

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.

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.

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.

Annex 1: Subregional Framework for Cooperation on Integrated Straw Management

Activity	What is the need?	Countries	What is to be done?	Who could potentially lead?
A. Joint research and analytical studies				
Study on availability, utilization, surplus and burning of crop residues in the subregion.	Sustainable management and use of agricultural crop residues (as straw or stover – stalks, ears, leaves, or cobs) requires accurate data on their availability by crop type as well as their local and annual variability. Improved data can enable a better understanding of location-wise demand and utilization patterns in different areas across countries in the subregion for designing effective interventions. Analytical studies will also help in formulation of evidence-based and synergetic national policies/strategies/programmes/laws/ regulations.	Bangladesh, India, Nepal, & Pakistan	Systematically conduct study on availability, utilization, surplus and burning of crop residues in the subregion following a uniform protocol. Study countries need to carry out surveys and collect data (primary or secondary sources) for calculation of biomass availability and surplus biomass.	Leveraging of existing networks of agriculture research institutions, such as **Asia-Pacific Association of Agriculture Research Institutions (APAARI)** and Consultative Group on International Agricultural Research (CGIAR) centres like the **International Maize and Wheat Improvement Center (CIMMYT)** and **International Rice Research Institute (IRRI) South Asia Regional Centre** to support joint research and analytical studies based on a uniform protocol should be pursued. Departments of Agriculture/Agricultural Engineering of these countries may be engaged in such studies.
Fire mapping studies or collaboration between countries to map and monitor fires		Bangladesh, Nepal and Pakistan	Fire mapping to be done to know the extent of burning of crop residues. Standard procedures and models developed by various researchers can be utilized for the purpose. The use of remote sensing technologies is being leveraged for spatio-temporal monitoring of crop residue burning in the states of Punjab, Haryana and Uttar Pradesh in India under a scheme for promotion of in-situ management of paddy residue. The same approach may be used for fire mapping studies among countries in the subregion to map and monitor incidence of crop residues burning.	A **subregional coordination group** comprising of representatives of line ministries/agencies from interested countries could be established to lead fire mapping studies. Existing regional and subregional networks could be leveraged to support such studies. One of the agriculture research councils, such as the **Indian Council of Agricultural Research,** could facilitate coordination of this work.

Activity	What is the need?	Countries	What is to be done?	Who could potentially lead?
B. Supply chains for aggregation of crop residue biomass				
Development of mechanism for aggregation of crop residue biomass	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. 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. However, the high cost of collection and transportation of residues from the field to the end-user proves to be the prime impediment for scaling up ex-situ management practices. Therefore, entrepreneurs in the supply chain find the economics of handling crop residue unattractive.	Bangladesh, India, Nepal and Pakistan	Ex-situ management of crop residues can be economically viable if good supply chain management exists in the target countries,- including cross-border supply chain management to take advantage of local demand/supply gaps. Policies and coordination are needed that will encourage private investment in crop residue collection and provide options to the farmers in disposing of their crop residues. This will allow the private sector to invest in crop residue valorisation processes such as the production of briquettes, char, paper, tableware, fabric production, etc. The development of supply chains at the local level in respective countries is needed to make ex-situ management practices economically viable. Further assessment on the feasibility of establishing domestic and whereas feasible cross border supply chain mechanisms could be considered. For instance, this could include the development of a mobile app or use of social media platforms for easy trading of crop residues. The sharing of experiences from India and other Asia-Pacific countries on domestic and cross border agriculture supply chains and their application for aggregation of crop residue biomass may be useful to provide policymakers with insights on scaling-up of ex-situ crop residue management practices.	ESCAP could facilitate the sharing of experiences from India and other Asia-Pacific countries on domestic and cross-border agriculture supply chains and their application for aggregation of crop residue biomass.

Activity	What is the need?	Countries	What is to be done?	Who could potentially lead?
C. Sharing and popularization of technologies, equipment and practices for the management of crop residues				
Formation of a common pool for funding collaborative R&D efforts	Farming in future has to be multi-functional and ecologically sustainable so that it can deliver ecosystem goods and services as well as livelihoods to producers and society. Hence farming should effectively address local, national and international challenges of food, water and energy insecurity; issues related to climate change; and degradation of natural resources. The **propagation of conservation agriculture practices** can make efficient use of crop residues that avoids burning while providing many ecological benefits that improve soil health and productivity. This does, however, entail fundamental changes in farming practices which require technical support and awareness raising activities of the benefits of conservation agriculture practices. The decrease in farm workers and	Bangladesh, India, Nepal, and Pakistan	A subregional R&D fund to support development of machinery prototypes as well as other solutions suitable for different agro-ecological zones and their pilot applications should be established.	Agriculture and environment are areas of cooperation in SAARC. **SAARC Agriculture Centre (SAC)** was established in 1989 as the first ever Regional Centre under SAARC to establish network among relevant agricultural research and information agencies in SAARC Member States and disseminate regionally generated technical information to strengthen agricultural research, development and innovations. It has also been mandated to work on crop related issues. **ESCAP** may work with **SAARC** to establish common funds for R&D efforts.
Exchange of technical capabilities and manpower across countries for training and implementation.			Regular knowledge sharing and training programmes such as subregional workshops, study tours and field demonstration on sustainable straw residue management should be organized to exchange technologies, experiences	**CSAM** has a mandate to facilitate regional cooperation, knowledge exchange and capacity building in support of sustainable agriculture mechanization in the Asia-Pacific region. CSAM is already enabling technical exchanges of knowledge and pilots on

Activity	What is the need?	Countries	What is to be done?	Who could potentially lead?
Organization of joint skill development programmes	labourers paves the way for farmers to **adopt and adapt mechanization solutions** for managing crop residues. Accordingly, several technologies have been developed for mechanization of crop residue management in the subregion and are being promoted on a pilot basis. The use of crop residues as fodder for animals or for generation of electricity are ex-situ management practices that can also reduce levels of burning. The **promotion of gasification technology and bio-fuel production from crop residues** have potential to generate electricity with lower emission of pollutants and increase revenues of farmers. However, looking into the adoption of these technologies at the farmers' level, the scenario is challenging. A series of constraints exist in using crop residue management machinery and appropriate funding, R&D, training, scale-up and monitoring interventions are needed to overcome them.		and impact evidence amongst participating countries, especially for the benefit of countries with relatively less experience or capacities for sustainable crop residue management. Such activities should strive to include a diverse range of stakeholders such as government ministries/ departments, research institutions, civil society, private sector, international development partners and lead farmers.	crop residue management. This work should be continued and strengthened in the South Asia subregion. The **SAARC Agriculture Centre (SAC)** also has a mandate to disseminate technical information from South Asia to strengthen agricultural research, development and innovations. SAC may help in organising skill development programme in the subregion.
Establishment of a subregional-level monitoring cell on crop residue burning and management			A joint subregional monitoring cell engaging the target countries may be established to analyse trends, assess emerging challenges, identify interventions suitable for various agro-ecological settings, and monitor progress and gaps.	The proposed subregional coordination group for the fire mapping studies could also be tasked to serve as a subregional monitoring cell on crop residue burning and management. Alternatively, SAC may also lead/coordinate such a monitoring cell.

Activity	What is the need?	Countries	What is to be done?	Who could potentially lead?
D. Harmonization of testing standards and promoting more integrated trade of in-situ and ex-situ agriculture machinery				
Harmonization of test codes of in-situ and ex-situ management agriculture machinery	The test codes for testing of machinery such as super straw management system (Super SMS) attached with combine harvester, Happy seeder, paddy straw chopper, super seeder, zero till seed cum fertilizer drill are being developed for promotion and sale of good quality in-situ crop residue management machinery under an Indian government's financial assistance programme. Some of these machineries are also exported to neighbouring countries. However, testing codes for ensuring the quality of the machinery vary across countries and some countries may also not have a testing system or facilities in place. This creates a trade bottleneck.	Bangladesh, India, Nepal, & Pakistan	Harmonization of testing codes for machinery among participating countries along with a system of mutual recognition of test results/certificates could help to facilitate trade of better quality and more efficient machinery within the subregion, benefiting both producing and importing countries. It could also lower costs by avoiding the need for repeated testing of the machinery in each country.	The **Asian and Pacific Network for Testing of Agricultural Machinery' (ANTAM)** is a CSAM initiative making efforts on the harmonization of testing codes. This work should continue in the subregion as it can facilitate access to quality in-situ and ex-situ agriculture machinery. (https://antam.un-csam.org/)
Establishment of networks and business linkages amongst private sector entities	Private sector agricultural machinery manufacturers and distributors do not have adequate cross-border linkages or institutionalized platforms for networking which hinders trade and investment decisions as well as availability of machinery for farmers.		Improved linkages should be promoted among agricultural machinery enterprises in the subregion in order to further the development of the agricultural machinery market across countries and support the dissemination of more sustainable and efficient technologies based on a demand driven model. One channel for improving such linkages could be via networking amongst national agricultural machinery manufacturer and distributor associations.	CSAM's initiative titled the '**Regional Council of Agricultural Machinery Associations in Asia and the Pacific' (ReCAMA)** is making efforts to strengthen ties between manufacturers and distributer associations. This work should continue in the subregion as it can facilitate access to quality in-situ and ex-situ agriculture machinery. (https://recama.un-csam.org/)