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Review Article

On and Off Farm Crop Residue Management: A brief review on Options, Benefits, Drawbacks, Limitations and Policy Interventions

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Abstract

India ranks as second largest country for agro-based economy having about 1.79 MKM^2 agricultural land that generates approximately 686 Million Tonnes (MT) of gross crop residues including approximately 234 MT surplus residues annually. In 686 MT crop residue, contribution of crop types as well as states is variable. In the present study, the role of crop residue as an important natural and renewable resource along with their on and off farm management options having their own benefits, drawbacks and limitations were discussed. Various terminologies used for crops' residue and methodoloies used to estimate their generation potential were analysed. Different factors regulating the crop residue usage for diverse purposes which affects their end use were identified and listed. As, raw and condensed form of crop residues have different physico-chemical properties and resource value. Various on and off farm crop residue management options including crop residue burning, residue removal, residue retention, residue incorporation, composting, biochar production, livestock feed, mushroom cultivation, biofuel biogas and bioenergy production from different crop residues were compared. Various Government initiatives to minimise and support the unsustainable and sustainable crop residue management options, respectively were reviewed.

Key words: Crop residues, Crop residue generation potential, Crop Residue management option, On and Off farm options.

1. Introduction

In India total agricultural land occupies 1.79 MKM^2 (60.5% of total land area). As per World Bank (2010), agricultural land basically corresponds to the portion of total land which is arable (53.2%). 3.8% and 3.5% arable land is under permanent crops and pasture, respectively. With net area of around 180 Million hectare under the agricultural cultivation and about 140% cropping intensity (Cardoen *et al.,* 2015), India generates huge amount of agricultural residues. Agricultural residues include - livestock residue (both commercial and household livestock) and crop residue (includes non-edible plant parts that are left in the field after the crop being harvested, thrashed or left after pastures grazed including leaves, stalk, stubbles, straws and roots) (FAO, 2014; Lal, 2005).Crop residues are basically the crop parts that remained after all the economic part of the crop has been separated out (Shahane *et. al.,* 2016).

As per the estimations, India generates around 686 Million Tonnes (MT) (Hiloidhari *et al.,* 2014; Singh *et al.,* 2020) of crop residue on farm plus off farm annually. Of total residue generated, field crops such as cereals, pulses, sugarcane and oilseeds contribute 545 MT, 79.8 MT is contributed by fiber crops such as Jute and cotton and 61

MT by horticulture crops such as banana, coconut and areca nut. Under field crops, cereal crops come at the top with 368 MT (i.e. 54%) of residue generation. Among other field crops, sugarcane contributing around 111 MT (16%). 34% of the gross crop residue generated remains as surplus (234.5MT) (Hiloidhari *et al.* 2014) (Table 1).

Table 1. Crop residue generation by different crop types

Crop Name	Quantity of crop residue generated (In Million Tonnes or MT)
Field Crops	
Cereals	367.7
Pulses	17.9
Sugarcane	110.6
Oilseeds	48.8
Total	545.0
Fiber crops	
Jute	3.9
Cotton	75.9
Total	79.8
Horticulture crops	
Banana	41.9
Coconut	18.0
Areca nut	1.5
Total	61.0
Gross total	**686**

The crop residue generation potential of different Indian states depends on the type of crop grown, cropping intensity as well as the productivity level. As per the reports, Uttar Pradesh comes at first position in terms of residue generation by contributing 116 MT followed by West Bengal and Andhra Pradesh by contributing 63.26 MT and 57.44 MT. respectively (Jain *et al.,* 2014). However on comparing generated cereal crop residues, Uttar Pradesh (72MT) is the leading state followed by Punjab (45.6MT), West Bengal (37.3MT), Andhra Pradesh (33MT) and Haryana(24.7MT) (Table 2). The sustainable management of this amount of crop residues generated as well as to understand its importance as a natural resource is necessary to get long term benefits (Jain *et al.,* 2014).

Table 2. Crops' residue generated by different states

State	Cereal crops(MT)	Oilseed crops(MT)	Fiber crops(MT)	Sugarcane (MT)	Total(MT)
Uttar Pradesh	72.02	2.49	0.04	41.13	115.68
West Bengal	37.26	0.95	24.43	0.62	63.26
Andhra Pradesh	33.07	2.5	16.07	5.8	57.44
Punjab	45.58	0.08	9.32	1.76	56.74
Maharashtra	8.75	0.57	19.51	22.87	51.7
Gujarat	8.18	5.06	28.62	5.85	47.71
Haryana	24.73	2.15	7.58	1.93	36.39
Rajasthan	22.19	9.26	2.96	0.15	34.56

Crop residues support diverse ecosystem services (Table 3) and have various competing uses (FAO, 2014) therefore they should not be considered as a waste but as an essential commodity as a natural and renewable resource for providing numerous environmental services and thereby assuring perpetuation of productive agro-ecosystems (Lal, 2004).

Table 3. Ecosystem Services provide by Crop Residues

Type of Ecosystem Services	End use/Example
Regulating services when residues are left on soil	Balancing soil temperature Control Soil Erosion Increase Water holding capacity of soil Carbon sequestration and maintenance of soil structure
Supporting services	Play role in nutrient and water cycling Disease and pest incidence regulation by acting as surface mulch, limits the light and nitrogen availability near soil as well as due to some allelopathic effects supress the emergence of weeds (Singh 2014; Prashanthi and Billa 2020 ;farmpractices.com) The residue mulch prevents the soil which is infected with fungi from splashing up onto the plant foliage(Sinkeviciene et al., 2009; Yordanova and Gerasimova 2016) Protect and promote growth of soil microorganisms and habitat
Provisioning services when crop residues are used as value added products	
If crop residue used as feed	Provide nutrient and energy source to cattle
Nutrient source for plants/crops	After residue decomposition As part of compost As Biochar
Construction materials	Residue based boards, cement material, bricks panels, temporary roof, roof thatching, agrocrete
Energy source	Heat, Electricity, steam
Chemicals	Organic acids, polysaccharides, plastics
Paper pulp	Paper boards

2. Crop residues: Sources and types

The National Agricultural Technology Project (NATP) has placed all Indian agroecosystems under 5 broad categories namely, Arid, Coastal, Hill & Mountain, Irrigated and Rainfed (Saxena *et al.,* 2000) and 14 type of crop production systems. Under each production system, depending upon the cropping system, cropping pattern, cropping intensity and crops productivity, different amount of crop residues being generated. On comparing different production systems, approx. 40%, 15% and 13% of the gross cropped area is under rice - wheat cropping system, other cereal crops(maize, pearl millet and sorghum), oil seeds (groundnut, mustard, soybean) respectively (Figure 1) (Cardoen *et al.,* 2015).

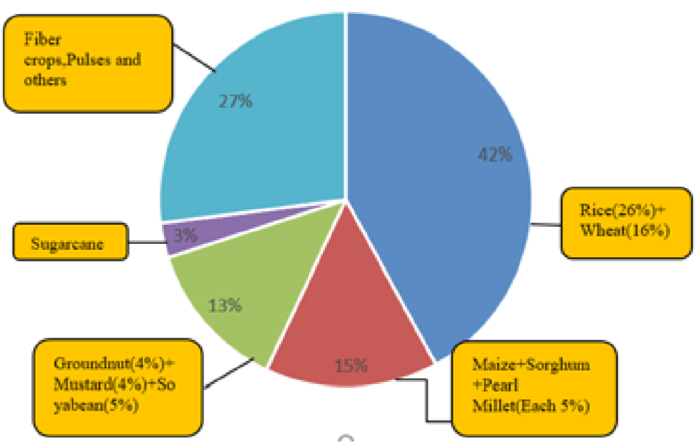

Figure 1. Gross area under cultivation of major crops grown in India

Crop residues generated from different type of crops have been given different names (Hiloidhari *et al.,* 2014) (Table 4). Different crop types (Cereals, oilseeds. Pulses, Sugarcane, horticulture crops and fiber crops) generate variable quantity of on and off farm residues in the states identified as their major producers (Cardoen et.al.,2015) (Table 4).

Table 4. Crop residues: Sources, types, place of generation, quantity and generating states

S.No.	Crop category	Name of Crop Source	Name of residue generated	Place of generation	Quantity of residue generated (MT)	Major producing States
1.	Cereals	Rice/Paddy	Straw	On-Farm	154.0	UP, WB, PB, AP,
		Wheat	Husk	Off-Farm(AtMill)	131.1	OR, HR, TN, CG,
		Maize	Bran	Off-Farm (At Mill)	35.8	BR
		Pearl Millet	De-oiled bran	Off-Farm (At Oil-mill)	24.3	UP, PB, MP, HR,
		Sorghum		On-Farm	17.6	RJ, BR
		Others	Straw	On-Farm	4.9	BR, UP GJ, RJ AP,
			Chaff	Off-Farm (AtMill)		HP, MP, JK, KA,
			Bran	On-Farm		GJ, HR, MH, RJ, UP
				On-Farm		MH, KA, RJ, MP,
			Stover	Off-farm (At Wet Mill)		AP,
			Cobs	On-Farm		TN
			Corn-fibre/Grain	On-Farm		
			hull	Off-farm (At Mill)		
				On-Farm		
			Stalks	On-Farm		
			Cobs	Off-Farm (At Mill)		
			Husk			
			Stalks			
			Cobs			
			Husk			
	Total				367.7	
2.	Oilseeds	Mustard	Stalks	On-Farm	12.7	AS, UP, GJ, RJ, HR,
		and	Seedpod	On-Farm	13.5	JK, MP, , WB
		rapeseed	Meal/Oilcake	Off-Farm(At Oil-Mill)	17.0	MP, MH, RJ, AP,
		Soyabean		On-Farm	3.8	KA
		Groundnut	Stalks	Off-Farm (At Oil -Mill)	1.8	GJ, TN, AP, KA,
		Sunflower	Husk	Off-Farm(At Oil -Mill)		MH
		Others	Meal/Oilcake	On-Farm		KA, AP, MH, BR,
				Off-Farm(At Oil-Mill)		OR, TN
			Stalks	Off-Farm(At Oil -Mill)		
			Shell			
			Meal/Oilcake			
	Total				48.8	
3.	Pulses	Tur(Arhar)	Stalks	On-Farm	7.2	MH, UP, KA, GJ,
			Husk	Off-Farm (At Mill)	6.4	MP, AP
		Gram	Stalks	On-Farm	4.3	MP, UP, RA, MH,
			Husk	Off-Farm(At Mill)		AP, KA
		Others				
	Total				17.9	

4.	Sugarcane	Sugarcane	Tops and leaves Molasses Bagasse Press mud/filter cake Depithed bagasse	On-Farm Off-Farm(Sugar -Mill) Off-Farm(Sugar-Mill) Off-Farm(Sugar -Mill) Off-Farm(Sugar- Mill)	**110.6**	HR, KA, MH, PB, TN, UP
5.	Horticulture crop	Banana Coconut Areca nut	Leaves/ Pseudostems Peels Fronds Husk Shell Meal/Oilcake Coir pith	On-Farm/Plantation Off-Farm(Processing Plant) On-Farm On-Farm Off-Farm (Oil Mill) Off-Farm (Oil Mill) Off-Farm (Processing plant)	41.9 18.0 1.5	MH, TN, KA, GJ, WB, AP, AS OR, BR, AS, KA,GJ KA, KL, TN, AP, OR, MH, GA, AS AS,KR,KA
	Total				61.4	
6.	Fiber crops	Cotton	Stalks Hull/bollshel Gin trash Meal/oilcake	On-Farm Off-Farm (Cotton gin) Off-Farm (Cotton gin) Off-Farm (Oil Mill)	75.9 3.9	AP, GJ, HR, KA, MH, PB, TN WB, AS, OR, BR, AP, TR, MG
		Jute				
	Total				79.8	
	Gross				686.0	

3. Crops' residue generation: Terminologies used and methods for crops residue generation potential estimation

Crop residues are the by-product of crop production system. In literature crops' residue generated on production system is represented throught different terminologies. Similarly crop's residue generation potential is estimated by different methods. The crops residue generated is reported as - Residue to Product Ratio (RPR), Crop to Residue Ratio (CRR), (Gadde *et al.,* 2009; Hiloidhari *et al.,* 2014; Lohan *et al.,* 2018), Gross Crop Residue(CRg), Surplus crop residue (CRs). RPR is also termed as 'yield of crop residue' or straw-to-grain ratio (SGR).It represents the quantity of residue generated for each tonne of crop produced (Equation for calculation of RPR involves the mass of crop residue generated divided by the mass of crop produced) and units are dimensionless(Malik *et al.,* 2019).Inversely CRR corresponds to mass of crop produced divided by mass of residue produced. Some researchers suggested that same crop may have different RPR and CRR value depending upon the portion of crop (Chauhan 2012) (Table 5). For example an RPR range value of 0.416-0.452 for rice is when only top part of rice stem is being cut including 3-5 leaves and leaving the remaining portion in the field (Bhattacharya and Shrestha, 1990) similarly a RPR range value of 1.75-1.87 was reported when the rice stem was being cut at the height of about 2 inches above from the ground (Bhattacharya *et al.,* 1993; Vimal 1979). RPR varies with crop type, varieties, weather conditions, soil fertility, water availability, farming practices, fertilizers, moisture content.

The moisture content of fresh and air-dry crop residue biomass may vary significantly (like the difference of about factor 3 was found in the case of sugarcane bagasse). Estimation of the amount of crop residue generated using a RPR value without considering moisture content may results in inaccurate estimations.

The equation used by Lohan *et al.,* (2018) for the estimation of total residue generated is as follows:

Total crop residue generated (CRR) = The area covered by a particular crop (Ai) Yield of that crop (Yi) Crop to residue ratio of the crop (CRRi)

Table 5. RPR, CRR and Heating values for different crop residues and types

Crop	Residue type	CRR value	RPR value	Heating Value	References
Rice	Straw	1.20	1.5	15.54	Hiloidhari *et al.,* 2011
	Husk	0.16	0.2	15.54	Singh *et al.,* 2008
Wheat	Stalk	-	1.5	17.15	Singh *et al.,* 2008
	Pod	-	0.3	17.39	Singh *et al.,* 2008
	Straw	1.15	-	-	Chauhan , 2012
	Husk	0.16	-	-	Chauhan , 2012
Maize	Cob	0.30	0.2	17.39	Singh *et al.,* 2008
	Stalk	1.88	2	16.67	Singh *et al.,* 2008
Pearl Millet	Cob	0.25	0.33	17.39	
	Husk	0.22	0.3	17.48	Raveendran *et al.,* 1995
	Stalk	1.85	2	18.16	Friedl *et al.,*2005
Mustard and rapeseed	Stalk	1.72	1.8	17.0	Singh *et al.,* 2008
Soyabean	Stalk	-	1.7	16.99	Kis. *et al.,* 2009
Groundnut	Shell	0.26	0.3	15.56	Jekayinfa *et al.,* 2009
	Stalk	1.75	2	14.4	Jekayinfa *et al.,* 2009
Sunflower	Stalk	2.40	3	17.53	
Gram	Stalk	1.08	1.1	16.02	Singh *et al.,* 2008
Tur (Arhar)	Stalk	2.35	2.5	18.58	Singh *et al.,* 2008
Sugarcane	Bagasse	-	0.33	20	Singh *et al.,* 2008
	Top/Leaves	0.06	0.05	20	Singh *et al.,* 2008
Banana	Peel	-	3	17.4	Wilaipon *et al.,*2009
Areca nut	Frond	-	3	18.1	
	Husk	-	0.8	17.9	Pilon *et al.,* 2007
Coconut	Frond	-	4	10	Rahman *et al.,*2006
	Husk	-	0.53	19.4	Minowa *et al.,* 1998
Cotton	Stalk	1.00	3.8	17.4	Jekayinfa *et al.,* 2009
	Husk	-	1.1	16.7	
	Boll shell	-	1.1	18.3	Çağlar *et al.,*2001
Jute	Stalk	-	2	19.7	Asadullah *et al.,* 2008

The **gross crop residue (CRg)** can be defined as the sum total of crop residues produced for a particular crop. CRg for any crop is determined based on three important parameters such as area occupied by the particular crop, crop yield and RPR value for that crop. The formula for calculation using these parameters are as follows:

$$\textbf{CRg} = \sum_{i=1}^{n} A \times Y \times RPR$$

Here 'CRg' denotes the gross crop residue for n number of crops, in tonnes; and 'A' denotes the area covered by crop, in hectares; 'Y' denotes the yield of crop, in tonnes/ hectare and RPR denotes the residue to product ratio the given crop.

Some scientists (Venkatramanan *et al.,* 2021) also used the formula as:

$$\textbf{CRg} = \sum_{i=1}^{n} A \times Y \times RPR \times DM$$

Where DM is the dry matter fraction of the selected crop.

The **surplus crop residue** of particular crop represents the amount of crop residues that are available for energy production after all the other competing uses such as cooking fuel, cattle feed, roof thatching, composting, animal bedding and others. The formula used to calculate CRs is as follows:

$$\textbf{CRs} = \sum_{i=1}^{n} CRg \times SF$$

Here 'CRs' denotes the surplus crop residue for n number of crops, in tonnes. CRs contributed by crops in total is around 209-234 MT/year which is only about 30-34% of gross crop residue (Venkatramanan *et al.,*2021; Hiloidhari *et al.,*2014). $\Sigma_{i=1}$

4. Factors regulating Crop residue uses

Crop residues are used in raw as well as in condensed form for various purposes. However crop residues in raw form are bulky, uneven and have low energy density as well as require more volume for storage and transporting this huge volume is a difficult task. Hence to make their handling, storage, transportation and utilization feasible, they are converted into more condensed briquette form

Figure 2. Loose and condensed(briquette)form of crop residues

(Figure 2). Managing a large amount of residue generated is a tedious task and for this the crop residues need to be converted into bales/briquettes for easy transportation. For making this process effective in practice, bailing and briquetting machines should be planted near the agricultural farms and should be accessible to each farmer. The raw as well as condensed form of crop residues have different physical properties(Pathak *et al.,* 1986; Mythili *et al.,* 2013; Vyas *et al.,* 2015; Sapariya *et al.,* 2016; Ecostan machineries) and are listed in Table 6.

Table 6. Physical properties of raw and condensed (briquette) form of crop resides

Residue names	Bulk Density (Kg/m^3)		Moisture content (%) at (80-100 % relative humidity		Calorific-value (Mj/Kg)		Fixed carbon (%)		Volatile C (%)		Ash content (%)	
	Raw form	Briquette	Raw form	Briquette	Raw form	Briquette	Raw form	Briquette	Raw form	Briquette	Raw form	Briquette
Arhar stalks	180	438.70	20.5	-	18.58	16.74	15.12	10.28	82.9	74.92	1.98	10.30
Sugarcane Baggasse	70	675	34.86	5.42	20	19.66	15.86	19.36	79.2	76.12	4.94	-
Cotton sticks	160	641.20	27.05	-	17.05	16.30	15.30	9.64	81.4	75.56	3.30	14.80
Groundnut shell	100	680	-	9.18	20.1	18.83	11.67	18.88	83.9	77.3	3.27	3.75
Maize stalks	50	-	38.08	-	16.70	15.89	17.10	-	79.6	-	3.40	-
Maize cobs	100	-	28.00	-	17.40	-	15.16	-	83.01	-	1.84	-
Rice straw	50	590	36.70	9.77	14.53	14.64	4.66	16.09	69.70	64.44	19.20	24.44
Rice husk	105	-	29.40	12.00	15.50	15.17	12.50	5.00	71.00	63.00	16.5	20.00
Wheat straw	60	591	34.0	-	17.20	17.15	12.30	-	85.73	75.95	8.80	11.75

Some important physical properties of crop residues are briefly discussed here.

Moisture Content (MC): The level of moisture percentage for any crop residue varies significantly depending on their storage and drying processes. The moisture content of crop residue has an important role in the formation of briquettes and subsequently its combustion also. Moisture content in the crop residues for briquetting must be between 8 and 15 % (Kazi and Mankad., 2020).On an average the moisture content of a briquette is 5.55 to 12.33 % (Kpalo and Zainuddin; 2020) The formula for moisture content is as follows:

MC (%) = (W1–W2/W1) x 100

Here, W1 denotes weight of sample taken before drying (in grams) and W2 denotes weight of sample taken after drying (in grams).

Bulk Density (BD): Bulk density is one of the major physical property playing role in designing the logistic system for crop residue handling. The factors affecting the BD may include particle density, shape, size, moisture content and other surface characteristics .Average density of crop residue briquettes ranges from 0.24-0.37 g/cm^3 (Kpalo *et al.,*2019). Different methods are used to estimate BD of briquettes such as geometric method, wax method and water displacement method. According to Rabier *et al.,* (2006), the formula for calculation of BD of briquettes by geometric method is as follows:

Bulk Density = Mass of briquette material / volume of briquette material

Tumbling Resistance: Tumbling resistance is the measure of per cent loss in weight of condensed crop residue form such as briquette subjected to tumbling action for a period of 5 min. Tumbling resistance is measured with the help of tumbling test in a durability tester using the following formula:

Tumbling Resistance (%) = 100 (Percent weight loss)

and Percent weight loss (%) = (W1–W2/ W1)x100%

Here, W1 denotes the weight of crop residue briquette before the tumbling (in grams) and W2 denotes the weight of crop residue briquette after tumbling (in grams).

Resistance to water penetration: It of percentage water absorbed by a crop residue briquette when immersed in water.

% Resistance to water penetration=100−(water gain%)

Water gain by residue (%)=[(W2−W1)/W1] x 100

Where W1 denotes the initial weight of residue, (in grams) W2 denotes the weight of wet residue (in grams).

Volatile Matter: Volatile matter in crop residues is the combination of short and long-chain hydrocarbons, aromatic hydrocarbons, and some sulphur compounds and it is a combination of CO, H2, H2O, CH4, CO2, N2 and O2. Under some conditions particularly when the air is absent, the volatile matter is driven off on heating the given sample to 950°C. Residue with higher content of volatile matter probably provide a high concentration of bio-oil. The higher percentage of volatile matter contributes to increase in calorific value and also produces long flames**.** The average value of VM for crop residue based briquettes is 68.20 % (Andrew and Gbabo; 2015).

Volatile matter (%) = [(b−c)/a]x100

Where a denotes the initial weight of the sample taken as 1g. b denotes the final weight of the sample after cooling (Heating temperature 107± 3 °C for 1 hour), c denotes the final weight of the sample after cooling (Heating temperature 950 ± 20 °C).

Fixed carbon: The fixed carbon of crop residue represents the amount of char produced during the process of pyrolysis. Fixed carbon in any sample can be determined by subtracting the total percentage of moisture, ash content as well as volatile matter from the initial mass. The formula for the calculation of fixed carbon is as follows:

Fixed Carbon (%) = 100−[Moisture(%)+Ash(%)+VM(%)]

Ash Content: Ash content represents the remaining inorganic residue left after the complete heating of a crop residue sample when all the organic matter and moisture removed particularly in presence of any oxidizing agent**.** Reduction in ash content enhances the calorific value as it is an incombustible matter. Therefore the ash content in any material should be as low as possible. Crop residue briquettes generally have low ash content. The formula for calculation of ash content is as follows:

Ash content (%) = [weight of ash left/ weight of sample taken]/10

Chemical composition of crop residues

Crop residues contains almost one fourth of phosphorus, nitrogen, around three fourth of potassium and half of the sulphur (S) that is up taken by different crops. Besides N, P and K crop residues are reservoir of several other elements also. And this makes the crop residues as a most important and valuable natural resource (Pathak *et al.,* 1986; Sapariya *et al.,* 2016; Singh *et al.,* 2020).The elemental composition of different crop residues are given in Table 7.

Table 7. Selected crops' residues chemical composition

Crop residues	Chemical Composition (%)										
	C	H	N	Na	K	P	Mg	Ca	SiO2	O	S
Sugarcane Baggasse	48.20 57.20 (B)	6.10 3.98 (B)	0.20 1.84 (B)	0.06	0.51	0.04	0.36	0.14	1.30	44.40 37.78 (B)	0.01
Arhar stalks	53.30	4.70	0.60	0.05	0.57	0.08	0.40	0.11	0.68	-	-
Cotton sticks	51.00	4.90	1.00	0.09	0.61	0.08	0.43	0.12	1.33	43.87	0
Groundnut shell	41.10 16.49 (B)	4.80 16.42 (B)	1.60 0.28 (B)	0.05	1.20	0.12	0.40	0.10	2.52	- 68.79 (B)	-
Maize stalks	41.10	4.20	0.60	0.04	0.42	0.05	0.45	0.08	0.90	-	-
Maize cobs	46.20	4.90	0.60	0.03	0.54	0.07	0.28	0.09	2.00	-	-
Rice straw	36.80	5.00	1.00	0.09	2.50	0.06	0.53	0.08	15.60	40.50	0.02
Rice husk	37.80 45.20 (B)	5.00 5.8 (B)	0.30 1.02 (B)	0.02	0.30	0.03	0.17	0.10	15.77	35.45 47.6(B)	0.03
Wheat straw	43.80	5.40	1.00	0.06	0.78	0.04	0.35	0.10	7.08	-	-

Here 'B' stands for briquettes and other values are for raw form of crop residues

5. Crop residue management options in practice

The crop residues management can be categorised based on the site of generation (Figure 3):

1. On-farm

2. Off –farm

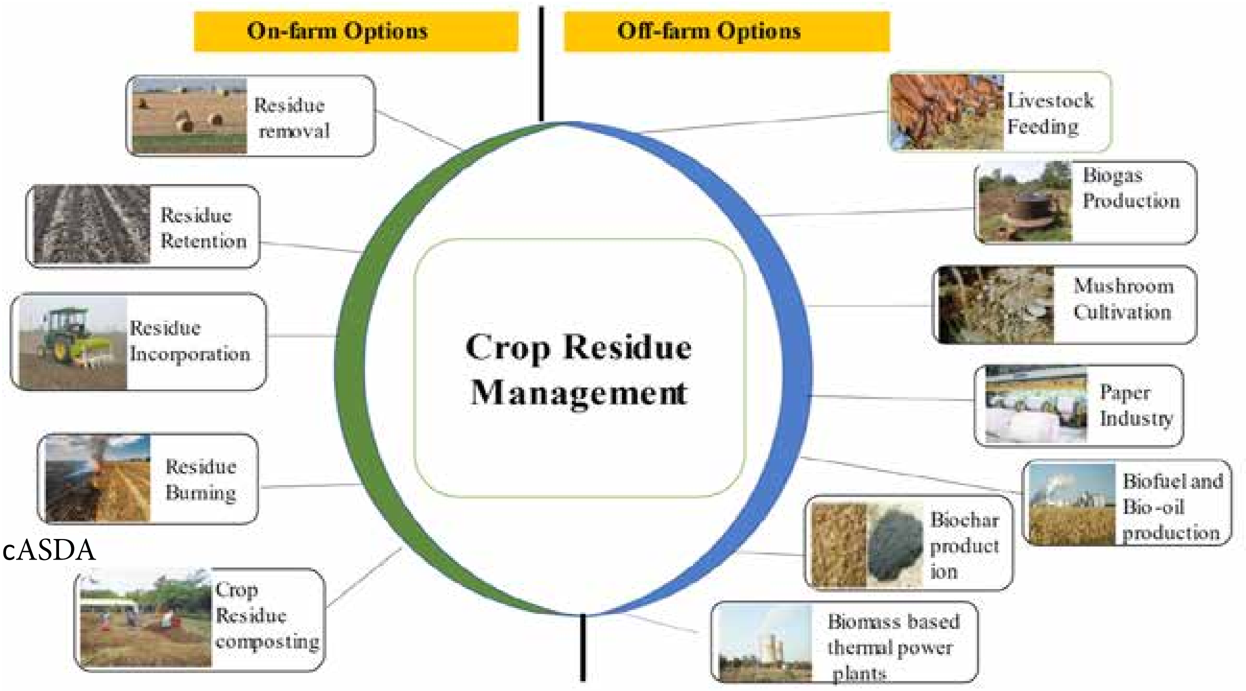

Figure 3. Crop residue management options

5.1. On farm generated residue management options: The management of residues on the point of origin i.e., farmers field itself without the need of transporting them is considered as on farm management. Some common on farm management options are:

- Residue removal
- Residue retention
- Residue uses as mulch
- Residue incorporation
- Residue Burning
- Composting of residues

Residue removal

The crop residues such as straw, husk etc. produced after harvest are removed from the field for various competing purposes. However limited number of studies assessed where, when, and how much of crop residue can be removed without causing serious adverse impacts on soil, NPP, and the environment (Wilhelm *et al.,* 2007). For example it has been reported that in case of corn stover, about 30% to 50% of the total stover produced can be removed without causing severe adverse impacts on soil (Kim and Dale, 2004; Graham *et al.,* 2007). Removal/ bailing/briquetting practice of residues generally being utilised for cattle fodder, as a cooking fuel and stable animal bedding or as raw material in various industrial processes (Lal,. 2008). However residue removal in certain cases can adversely affect soil quality. Hence estimation of sustainable residue removal rates is important to maintain good soil quality (Lal.,2008, Andrews.,2006). For instance, the rates for residue removal should be less when the climate become more warm or humid, when the soil become coarser, when there is more tillage/disturbances in soil (Raffa *et al.,* 2015).

Residue Retention

Leaving the crop residues after harvest as such on the farms ground is called as residue retention. Crop residue retention on the soil surface has been recommended by many agriculture scientists for maintaining soil physico-chemical, and biological properties (Wilhelm *et al.,* 2007). Farming practices that involve reduced/minimum or zero tillage such as conservation agriculture supports a permanent or semi-permanent organic soil covering. Happy seeder and turbo happy seeder machineries are being used to sow the next crop over the surface retained residues in the field (Figure 4).

Figure 4. Sowing of crop seeds through happy seeder in farms having residue retention

Crop residue as surface mulch

Mulching is one of the emerging crop residue management option to avoid burning. It is a conservational management practice in which crop residue (rice/wheat straw) are chopped/shredded into smaller pieces and evenly spread on the ground. For chopping, Super Straw Management System (SSMS) (Figure 5) is attached to the combine harvester and shredding of residues require an added run of mulcher as well as cutter/spreader (mounted onto a tractor) after the harvesting of the field. The field covered with mulch is sown using happy seeder following conservational method that is zero-tillage. It sows wheat in a field covered with mulch.

Figure 5. Super Straw Management System(SMS)machine while chopping and shredding the crop residues in the field creating a surface mulch

Residue incorporation

Residue incorporation can be defined as the use of tillage implements for burying remnant crop residues into soil and has traditionally been used for returning of organic matter back to the soil. This form of tillage buries all superficial crop residues in the soil (Tisdale *et al.,* 1985). Incorporation of residues involve primary tillage by mal board plowing and is the followed by secondary tillage involving disking, harrowing or field cultivating(Figure 6). Another way to incorporate residues is using zero till drill machine or roto- till drill while sowing the wheat crop in rice straw and stubbles. Zero-till which is seed-cum-fertilizer drill has poor efficacy when straw retained on field build up in the seed drill furrow openers that reduces seed sowing efficiency and results in poor seed germination (Sidhu *et al.,* 2015).

Figure 6. Incorporation of crop residues in field through different machineries.
(a. Malboard plow, b. Disk c. Harrow)

Residue burning

Burning of crop residue is an uncontrolled combustion process(Figure 7) which releases CO_2 as a principal component, along with carbon monoxide (CO), un-burnt carbon which has amount of sulphur dioxide (SO_2). Out of 686 MT residue biomass, approximately 16%of crop residues were burnt on fields in which rice and wheat together contribute 62% (Jain *et al.,* 2014). This burning incidents are majorly confined to Indo-Gangetic Plains regions. Studies suggest that Punjab, Uttar Pradesh and Haryana are major potential contributor states for harvesting of cereal crops and on-field burning of their residues. It has been estimated that total 1.95 Million ha area was under paddy residue burning during 2015(Singh *et al.*,2020) in Punjab and Haryana, by different remote sensing agencies in the country (PPCB 2015; Yadav *et al.,* 2015). According to IPCC, over 25% of the total crop residues were burnt on the farm (Jain *et al.,* 2014) and the fraction of crop residue burned ranged from 8–80% for paddy waste across all states. It is the most common and preferred on-farm residue management option for most of the farmers due to cost and time effectiveness as well as shortage of labour, increased mechanisation, destruction of pests and unsuitability of rice straw as cattle feed(Lohan *et. al.,* 2018).

Figure 7. Open burning of crop residues in farmer's paddy fields (a: Before burning, b: After burning)

Crop residues as compost

Composting is a natural process of decomposition by aerobic and anaerobic micro-organisms under controlled conditions and they convert crop residue into a valuable manure or compost with additional advantage in terms of nitrogen, phosphorous sand potassium (NPK) (Mishra *et al.,* 2003). Crop residues are considered as ideal raw material such as animal manure and food waste because of its high organic matter content. It can be made on the farm at very low cost and can be used as organic fertilizer (Bhuvaneshwari *et al.,* 2019; Kaur *et al.,* 2019). Composting involves labour input, but it is not capital intensive and does not require sophisticated infrastructure machinery(Goswami *et al.*,2020).

Researchers have demonstrated successful trials using some microbes (*Aspergillus terreus* MTCC 11778 and *Trichoderma hargianum* MTCC 8230) assisted on-site composting of paddy residues and thereby providing an alternative to most common practice of residue burning(Singh.,2015, Hindustan Times).Other trial demonstrated that bacterial isolate (Pseudomonas) obtained from naturally degrading paddy straw caused the decomposition of paddy straw within 45 days with application of only 5% urea after shortening of straw by using happy seeder machine. In this treatment there was no any requirement to gather the straw in large heap which saves extra space and efforts. Another group of researchers developed and reported microbial consortium based (crop friendly fungi) decomposing capsules known as **PUSA decomposer** for decomposing paddy crop residue (Zaidi, 2021). Four capsules are capable of turning one hectare of farm waste into usable compost. Each capsule costs around 5-10 Rs. Using these capsules, the field retains moisture during decomposition process of agricultural waste, and the soil is enriched with nutrients present in residues and thus minimizing the use of fertilizer.

5.2. Off Farm crop residue management options

There are a number of ways in which the crop residues can be managed ex -situ or off-farm but the common limitations with ex-situ operations are high cost of collection and transportation.

Crop residue for livestock feed

The crop residues are the major feed resources that are available and utilised by smallholder farmers in tropical livestock feeding system. Most of the crop residues are having high nutritional values and are thus suitable for animal feed like wheat straw have high nutritional value and therefore they are collected intensively, stored and then used around the year as feed with sale of surplus. Based on the type of crop, these residues may be either left on the field for grazing of ruminants or may be transported for other livestock feed at market values. In India buffalo are stall-fed with the basal diet called as 'bhusa' that primarily consist of hewed wheat straw. In case of lactating animals this basal diet is given along with supplementation of green fodder and some bi-products of crops. But rice straw is not suitable for livestock feedings because of high silica (6-12%) content and low nutritional contents (Protein 2-7%) (Lohan *et al.*,2018). Also rice straw feeding causes calcium and phosphorous imbalance in cattle (Moellers and Riese,1979). For encouraging the use of rice residue as animal fodder, a pilot project was initiated which involved trials on natural fermentation of rice straw to be used as protein enriched livestock feed and those cattle fed with this feed exhibited a significant improvement in their health and milk production (Kumar *et al.,* 2015).

Crop residue for production of biofuel and bio-oil

Crop residues are rich source of lignin and the production of alcohol from lingo-cellulosic biomass has immense significance. Bioethanol can be blended with petrol and diesel and can thereby reduces the harmful emissions in transport sector. Apart from sugarcane molasses, rice straw can also be the ideal (easily available in plenty amount at cheapest rates) feed stock for biofuel production by converting it into sugary slurries. As per theoretical information the estimates of ethanol production from different kind feedstocks such as corn grain, wheat straw, rice straw, sugarcane bagasse, saw dust etc. vary from 382 to 471 l/t of dry matter (Thorat *et al.,* 2015; Gupta and Dadlani., 2012). This technology is evolving in India but has certain limitations because of some energy and cost intensive conversion steps. Also rice straw is resistant to microbial attacks during the conversion processes because of having phenolic monomers in its structure (Sharma *et al.,* 2018).

Bio-oil is also produced from variety of crop residues by the process involving fast pyrolysis which require temperature of biomass to be raised up to 400-500 ^{0}C within few seconds and it may result a significant change in the process of thermal disintegration. Almost 75% of biomass' dry weight can be converted into condensable vapours. This condensate is allowed to cool quickly and it yields a dark brown coloured viscous liquid which is called as bio-oil. The calorific value of bio-oil ranges from16-20 MJ/kg (Gupta and Dadlani.,2012).

Crop residue for biogas generation

Gasification of crop residues is generally a thermo-chemical process involving the formation of gas due to partial combustion of residues. Crop residues are used in gasifiers for generation of 'Producer Gas'. This gas is being cleaned using bio-filters and then fed into the specially designed engines which are coupled with alternators to produce electricity. One tonne of crop biomass have the capacity to produce 300 kWh of electricity (Koopman *et al.,*1997; Lohan *et al.,* 2018). This technology of gasification can be encountered for successful utilization of crop residues in the form of briquettes and pellets.

Crop residues for mushroom cultivation

Crop residues including rice straw can be used for cultivation of mushrooms. In Punjab rice straw is used as key ingredient for culture of mushroom, but farmers commonly utilize wheat straw as raw material. It is basically used for cultivation of *Agaricus bisporus, Pleuro tusspp., Volvariella and Volvacea*. Around 300, 600,120–150 g of these mushrooms are formed from 1Kg of paddy straw respectively (Kumar *et al.,*2015). Production process involves operations like straw washing and excess water draining, straw cutting and bundle preparations. Presently around 20,000 Metric tonnes of crop residues are being used for cultivation of mushroom solely in Punjab state. Roy *et al.,* (2016) revealed that the estimated cost for using paddy straw as raw material is 7$ per quintal whereas it is 11$ per quintal when using wheat straw as raw material for mushroom cultivation. Thus the use of paddy straw is an economic source for mushroom growers that provides a net saving of 3.75$ per quintal. Paddy straw based mushroom cultivation accounts for 16 % of total production of cultivated mushroom in the world. Straw based mushroom are also a good source of amino acids and can supplement a protein rich diet(Goswami *et al.,*2019). In fact paddy residue mushrooms are easy to grow and require very less space and cost investment.

Crop residues in paper production

Rice and wheat straw are used in combination in the ratio of 40:60 respectively for the production of paper. The sludge thus produced then undergoes bio-methanization process for generation of energy. Paddy residue alone can also an ideal raw material for manufacturing of paper and pulp boards. There are around more than 50 % pulp board mills and paper industries that are utilizing paddy residues as their raw material (Kumar *et al.*,2015).

Crop residues for biochar production

Biochar is a very important C-rich substance which is fine grained and porous product of a thermo-chemical conversion reactions known as 'pyrolysis' which occurs at low temperatures and in an oxygen free (Bhuvaneshwari *et al.*,2019) environment. It has relatively stable biological state that is resistant to microbial decay so it can be considered as one of the important long term carbon sink that can sustain soil productivity, mitigate climate change and can be an emerging option for diverting the residue burning. Biochar produced from crop biomass, when applied to the soil enhances soil fertility,causes reduction in leaching of nutrients and other chemicals to enhance soil carbon, increases fertiliser use efficiency, mitigate soil greenhouse gas emissions and thereby enhances the overall productivity of agricultural system (Chan *et al.* 2008).

Crop residue for energy generation

Crop residues can be utilised to produce energy. In literature it has been reported that currently surplus crop residue is utilized for bio energy generation. The India's bioenergy potential from surplus residues is 4.15 EJ. Among different crops sugarcane bagasse has the potential role in bioenergy generation. Other cereal crops have major role in animal feeding, packaging material apart from energy generation. The bioenergy potential (BE) of any crop is the amount of energy produced by the surplus fraction of crop residues. The formula used for calculation is as follows:

$$\mathrm{BE} = \sum_{i=1}^{n} \boldsymbol{CRs} \times \boldsymbol{HV}$$

Here, 'BE' denotes the bioenergy potential of n crops, in M-Joules; CRs denotes the surplus crop residue, in tonnes and 'HV' denotes the heating value of the crop, in MJ tonnes.

Biomass based power plants prefer to utilise different crop residues like sugarcane trash, cotton stalks, groundnut shell, rice husk, wood chips, mustard stalk and cluster bean straw over the rice straw because of low heating value of rice straw which results in low profit margins (Suramaythangkoor and Gheewala, 2010). Punjab produces around 20–25 Million tonnes rice straw annually which is now a days being utilized in thermal plants. At recent times in Punjab, the boilers using 25–30% rice straw with 70–75% other biomass. A12 MW capacity rice straw power plant demands around 0.12 Million tonnes of straw to produce energy (Singh *et al.,* 2020). It is estimated that on average basis a power industry pays around 900 Rs. per tonne for non-basmati (straw from coarse varieties) and approximately 1500 Rs. for basmati rice (fine grain rice varieties).

Other competing uses of crop residues: Crop residue can also be used for making bedding of cattle, can be used as domestic fuel, cushioning material, packaging of manufactured items such floor tiles, glass etc.

6. Crop residue management options: Benefits, drawbacks and limitations

Though there are diverse on and off farm generated residue management options available at present time for managing the surplus crop residues. But each options have pros and cons both with respect to economic viability, environmental impacts, lack of knowledge, access to machineries to small land holding farmers, costly machineries affecting adoption rate (Table 8 and Table 9).

Table 8. On farm crop residue management options' benefits, drawbacks and limitations

Crops' residue management option (On farm)	Benefits	Drawbacks	Limitations for adoption
Residue Removal	Residue removal from the fields in the form of bales/briquettes make them accessible to various household and industrial uses.	Residue removal sometimes results in low biomass carbon input and decrease in nutrient/elemental cycling (Lal., 2008.)	In some cases logistic issues in transportation of these removed crop residues to longer distances adds to additional costs. (Bhuvaneshwari *et al.*,2019).

		Also it reduces food/energy source as well as habitat for soil biota along with the attendant decline in soil quality((Lal., 2008). Therefore sustainable rates for residue removal should be determined as discussed in section 5.1.	
Residue Retention	Improves soil physico-chemical and biological properties including cation exchange capacity, soil microbial biomass carbon and soil enzyme activities (Wilhelm *et al.,* 1986; Wilhelm *et al.,* 2007; Lohan *et al.,* 2018). Help in carbon sequestration in the soil (Jain *et al.,*2014). With No-Tillage improve water and air quality through reduction in soil erosion (through water and wind), non-point source pollution, sedimentation, and transport of different pollutants into aquatic ecosystems.	Zero till drill has poor efficacy over surface retained residue and thus reduces seed sowing efficiency and results in poor seed germination due to straw build up in seed furrows (Sidhu *et al.,* 2015).	Zero till -drill, happy-seeder consumes high power(> 33.6 kW). Choking of the machine with intense loads of straw(> 7–8 Mg ha−1) occurs sometime. Poor establishment of crops (Sidhu *et al.,* 2015).
Residue Incorporation	Improves soil water retention capacity (Gangwar, et al 2006; Kumar et al 2016). Improves soil structure by reducing bulk density, increasing infiltration rate and soil porosity(Lohan *et al.,* 2018). Enhances soil microbial biomass, alkaline phosphatase and soil dehydrogenase activities (Peter *et al.,* 2014).	Stimulation of CH_4 emissions on short term basis (Singh and Sidhu 2014). Crops suffers N-deficiency due to microbial immobilization of soil and fertilizer N (Singh *et al.,*2005; Goswami *et al.,*2020).	Residue decomposition takes times so significant fallow period is necessary between two successive crops (Goswami *et al.,* 2020). Labour intensive if proper machinery is not available to every farmer (Dobermann and Fairhust 2002). The high C:N ratio of residue needs to be corrected by applying extra fertilizer N at the time of residue incorporation(Singh et al. 2005; Singh *et al.* 2008).
Residue Burning	Controls harmful weeds, soil pest and pathogens (Gupta.,2012; Gupta and Dadlani.,2012). Increases short term availability of exchangeable NH_4^+-N and bicarbonate-extractable P content and Potassium (Gupta and Dadlani.,2012). Easy and time saving option for a narrow window between rice-wheat crops (Jain *et al.,* 2014).	Sudden increase in soil temperature (33.8-42^{0}C) results in death of beneficial microbes(Gupta *et al.,*2004; Gupta and Dadlani.,2012). Long-term burning practice of crop residues decreases total carbon and nitrogen and potentially mineralizable nitrogen in the 0–150 mm soil layer(Gupta et.al., 2004; Singh et.,2010) Degrade air quality and indirectly affects human health.1 tonne of paddy residue burning generates almost 1460 kg carbon dioxide, 3 kg particulate matter, 2 kg of sulphur dioxide ,60 kg carbon mono oxide and 199 kg ash in the air and which consequently (Lohan *et. al.,* 2018). 70%, 7% and 0.66% of C present in paddy straw is released as CO_2, CO and CH_4, respectively upon burning these residues. Around 2.09% of N in straw is emitted as N_2O (Galanter *et al.,* 2000) Support heavy smog problem in adjoining regions during the winter season (Manjeet *et al.,*2019).	No limitations as such.

Composting	Improve soil structure and moisture content and therefore support microbial activity and diversity. Replenish soil carbon stock and restore plant nutrition by adding nutrients from residues to soil.	Results in establishment of suitable habitat for rodent pests and undesirable presence of immobilized residual N(Porichha *et al.,* 2021).	Requires additional chemicals and controlled conditions. Decomposition of residues takes time so more time gap required between two crops (Goswami *et al.,* 2020).

Table 9. Off farm crop residue management options' benefits, drawbacks and limitations

Off farm Crop residue management option	Benefits	Drawbacks	Limitations
Consumption for livestock feed	Source of various nutrients, energy supply and natural support to various food webs.	Enteric fermentation of crop residues in cattle may lead to GHGs emission such as methane(State of Indian Agriculture,2015-16).	Some crop need pre-treatment to be used as fodder which incur extra cost and effort (Kamla *et al.* 2015) Rice straw require extra pre-treatment because it contains silica which has very low digestibility and high palatability (Biswas *et al.* 2006). Rumen micro-organisms' limited ability to digest cell wall polysaccharides (cellulose and hemicellulose)is due to the presence of phenolic and other aromatic compounds such as lignin(Gupta and Dadlani., 2012)in residues.
Biofuel and Bio-oil production	It is best alternative option for fossil fuel consumption and a renewable source of energy. Biomass based biofuels are source to reduce GHGs. By-products of biofuel production such as proteins can be used for animal feed can make a positive contribution to climate change mitigation.	High amount of crop residues are required for biofuel generation and extensive residue removal for this purpose can cause soil losses. Partial removal can be feasible without jeopardizing sustainability provided inputs of K, S, and other nutrients are suitably adjusted to compensate for those removed with residue. (Singh *et al.,* 2014). Also this creates pressure for production of high energy crops That sometimes lead to soil erosion,	The process requires high energy operating conditions, various hydrolytic cellulase enzyme that comes costly,. (Bhagawati *et al.,* 2020). Also lack of natural robust commercial organism which can ferment pentose and hexose sugars simultaneously either individually or in combination with other species poses some basic limitations to this option (Bhagawati *et al.,* 2020).
Biogas production	It's a clean energy source and reduces GHGs emissions. Anaerobic digestion deactivates pathogens and some parasites and reduce the chance of waterborne diseases. Provide healthy cooking alternative in developing areas.	Few studies also reported contradicting facts that in some cases specially during incomplete combustion of biogas some air pollutants such as CO, NO, CH_4 also releases during production. Therefore correct assessment of these emissions is a key point in social acceptance of this technology (Paolini *et al.,*2018).	Process requires purification of gas for removal of impurities and that need special bio filters that is also not cost effective for every kind of farmers.

Biochar production	Potential option to sequester soil carbon, improve soil quality and promote plant growth (Bhagawati *et al.,* 2020). Enhances nitrogen retention in soil by reduction in leaching and gaseous loss. It also increases phosphorus availability by reducing the leaching process in soil. (Hossain *et al.,* 2020) Improves microbial populations, enzyme activity, soil respiration, and microbial biomass.	Negative effects on some important soil properties including soil available water content, soil salinity, soil erosion (Brtnicky *et al.,* 2021).	The biochar production technology is not economically viable as the products and co-products (Heat energy, bio-oil, H2 gas) involved are costly (Bhagawati *et al.,* 2020). Need to develop low-cost pyrolysis kiln (Bhagawati *et al.,* 2020).
io-energy production	The energy generated is used for heat production, electricity generation.	Residue based energy plants generates large amount of ash waste (Hills *et al.,* 2020) if not managed properly affect air quality of the region.	Crop residues are having low bulk density and low energy yield per unit weight basis and transportation of large volume needed for efficient energy production is a major cost barrier. (Thorat *et al.,*2015). Rice straw having low heating value is less profitable for energy generation Suramaythangkoor and Gheewala,2010).

7. Policy interventions for crop residue management options

The Indian Government and the national agencies are continuously taking step to develop policies and other options in order to manage the crop residues in sustainable way.

i. Ministry of Agriculture & Farmers Welfare for have implemented a Central Sector Scheme (which include 100% Central share) for the period of 2018-2019 and 2019-2020 which is further extended for 2020-2021 in order to support the efforts of the Governments of Uttar Pradesh, Punjab and Haryana and NCT of Delhi for addressing air pollution and to subsidize machinery required for in-situ management of crop residues.

The key components of this scheme are:

- Establish Farm Machinery Banks for Custom Hiring of in-situ crop residue management machinery.
- Financial Assistance to the farmers for Procurement of Agriculture Machinery and Equipment for in-situ crop residue management.
- Information, Education and Communication for awareness on in-situ crop residue management.

ii. The Nature Conservancy (TNC), the largest conservation non-profit in the world, launched a project in 2019 to promote sustainable in situ CRM in the states of Punjab and Haryana to complement the efforts of the government.

iii. The Indian Government directed National Thermal Power Corporation (NTPC) for mixing crop residue pellets(approximately 10%) with coal for the purpose of power generation(Patial *et al.*,2020).

iv. Government of India has adopted two ways to curb the open field burning, under NPMCR,2014(National Policy for Management of Crop Residues).

First one is to give emphasis on developing huge awareness among farmers about the ill effects of residue burning and imposing heavy charges on the famers that still practice burning.

And the second approach is promotion of agricultural equipment that are involved in management of crop residues.

v. NPMCR also brought interventions through extending subsidy for the farmers to hire resource conservation machineries from different Custom Hiring Centers (CHS)/Agriculture Service Centers (ASC),and also promoting the establishment of new CHS/ASC for ensuring availability of different machines to the farmers at the time of crop harvesting. (NMPCR, 2014).

vi. In order to motivate farmers to change residue burning practice, rotavator machine/SSMS was introduced in the NICRA (National Innovations for Climate Resilient Agriculture) villages. This machine chops the harvested crop stalks/ stubbles a into small pieces and then incorporate them in-situ into the soil with varying efficiencies depending upon the left over residue.

vii. Punjab government is promoting 100% rice straw-based power plant in order to set a target for using 1 million tonnes rice straw with 200 MW capacity in coming future (PSCST 2013).

viii. Punjab Government and Gramin Vikas Trust signs MoU for establishing biogas pellets plants for ex-situ management of crop residues in sustainable way by incentivizing ex-situ extraction of residues(The New Indian Express report dated on October 12,2022).

ix. As per latest information Punjab Government is going to supply paddy straw to Kerala where it will be used as dry fodder therefore this will solve the problem of paddy straw management in in Punjab to some extent, where paddy straws are not used as cattle feed(The Tribune, November 24, 2022).

8. Conclusion

It can be said based on the benefits of crop residues that they are not a waste but an important natural resource to be used for various purposes. But still many farmers' community is unaware about the potential uses of crop residues and the revenue generation through it which make them find residue burning the easiest and cost effective option. The surplus amount available in India for crop residues is 234 Mt available for energy generation potential of 4.15Ej. Therefore there should be increased awareness programmes for giving idea about alternative options of crop residue management, machineries and resources involved, their cost-effectiveness, their pros and cons, training programmes to use those different machineries, and handholding to make the permanent switch to in-situ crop residue management options .On-farm management options need to be promoted and research should be strengthened to develop fast residue decomposition promoting microbes consortia so that farmers can utilize residue as organic fertilizer. More custom Hiring Centres should be set up under the scheme to provide easy access of farm machinery on rent to small-scale farmers and also should be made popular through these awareness programmes. Though numerous researches have been done in this field but it is important to convey the findings to the farmers in a convincing and understanding ways such as seminars and visual representations, animations for different aspects of each options. There should be introduction of C-credit schemes to benefit the farmers who use crop residue for conservation agriculture for carbon sequestration and greenhouse gas emissions mitigation. Also a community level approach should be there to reach out as much farmers as possible to spread the information related to crop residue management options and a nexus of stakeholders of different fields not only limited to agriculture should be there to deal with the issue

Author's contribution

Conceptualization of research (DS and UM); Designing of the experiments (DS and UM); Contribution of experimental materials (DS and UM); Execution of field/lab experiments and data collection (DS and UM); Analysis of data and interpretation (DS and UM); Preparation of the manuscript (DS and UM).

Declaration

The authors declare no conflict of interest.

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