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Research Article

Crop Residue Burning and its Implications over North-West India

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ABSTRACT

Although the green revolution has boosted production, it is also held responsible for imparting a significant effect on the cropping pattern of Punjab. Out of the total cropped area in Punjab, the area under rice has increased from 5 to 39% and that under wheat from 30 to 43% during 1960-61 to 2019-20. Increased cropping intensity and mechanization of agriculture has resulted in higher production of crop residue and consequently, its management has emerged as a major environmental concern during the recent decades in the region. Crop residue generation in India has increased by 6.25 times (80 to 500 Mt) from 1950 to 2015. Mapping the time and extent of fire incidence is highly important as it affects humans and ecosystem services and this has become possible due to the advent of remote sensing. Crop residue burning severely impacts environmental health, climatic conditions and air quality, leading to various health hazards resulting from emission of greenhouse gases, aerosols, particulate matters and other trace gases. However, this fact can also not be ignored that farmers are hard-pressed to adopt this practice as they don't have economically viable options with them, which they could opt willingly. Retaining the residues as mulch offers the potential benefits of reduced water loss due to the suppression of soil evaporation, reduced runoff, suppression of weeds, increased soil organic C and improved soil structure. The use of rice residue in thermal power plants, mushroom cultivation, bedding material for cattle, bio oil, paper and bio gas production is beneficial for improving agricultural and environmental conditions and ensuring increased crop productivity. The government should facilitate the farmers to avail alternate options for sustainable management of crop residues, such as easy financing of happy seeders, subsidy on incorporation of residues etc. Crop residues should be procured at reasonable price and should be assisted with transportation facilities for generating power. The government should also ensure market availability and reasonable minimum support prices for crops in addition to wheat and rice to promote crop diversification.

Key words: Crop residue burning, north-west India, climatic implications, environmental impacts, soil health

Background

The Indo-Gangetic Plains (IGP) constitute very important agro-ecological region in south-Asia, occupying nearly one-fifth of the total geographical area in four countries, namely Pakistan, India, Nepal and Bangladesh. In India, it covers about 20% geographical area. Punjab is an important part of IGP, popularly known as Granary of India. Punjab covers a geographical area of 5.03 m ha (1.54 per cent of the total geographical area of India), with the total cropped area of 7.84 m ha and net sown area of 4.12 m ha (Anonymous, 2020). It has contributed up to 59.7% of rice and 78.5% of wheat to the central pool of food grains over the last few decades (Fig. 1), whereas, the quantity-wise contribution of Punjab state to central pool increased from 1.3 to 118.3 lakh tones for rice and 5.7 to 129.1 lakh tones for wheat

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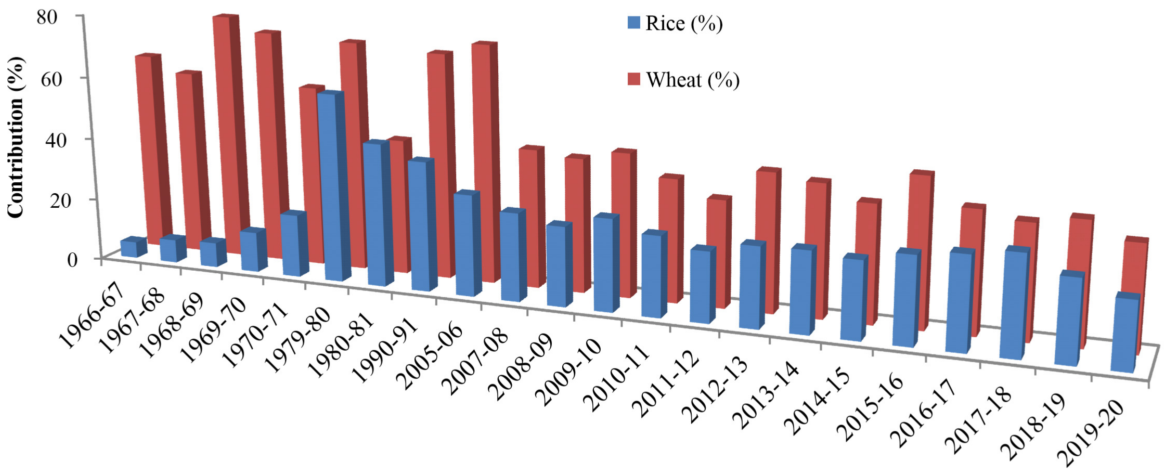

Fig. 1. Contribution of Punjab to central pool of food-grains

during 1960-61 to 2019-20 (Fig. 2). In case of wheat, its marketable surplus is 3rd to Canada and Australia and in case of rice; it is 2nd to Thailand (Vadrevu and Lasko, 2018). Above 95% of food grains that are produced in the state, go out of the state (Kumar *et al.,* 2015). Thus, state agriculture is characterized as the backbone of the public distribution system and a strong base for the country's food security.

Crop residue burning is one of the major concerns that impose potential threat to our ecosystem. Although it appears possible in the short term, it has serious long-term climatic, environmental, and socioeconomic consequences. It leads to increased emission of greenhouse gases (CO_2, N_2O, and CH_4), air pollutants (CO, NH_3, NO_x, SO_2, non-methane hydrocarbons, volatile organic compounds), particulate matter and smoke in the atmosphere, leading to health risks and nutrient depletion in the soil. Various man-made influences, such as the combustion of fossil fuels, increasing mechanization and industrialization, have already deteriorated air quality (Sahu *et al.*, 2011). It additionally prompts expanded illnesses everywhere, severely affecting developed and underdeveloped

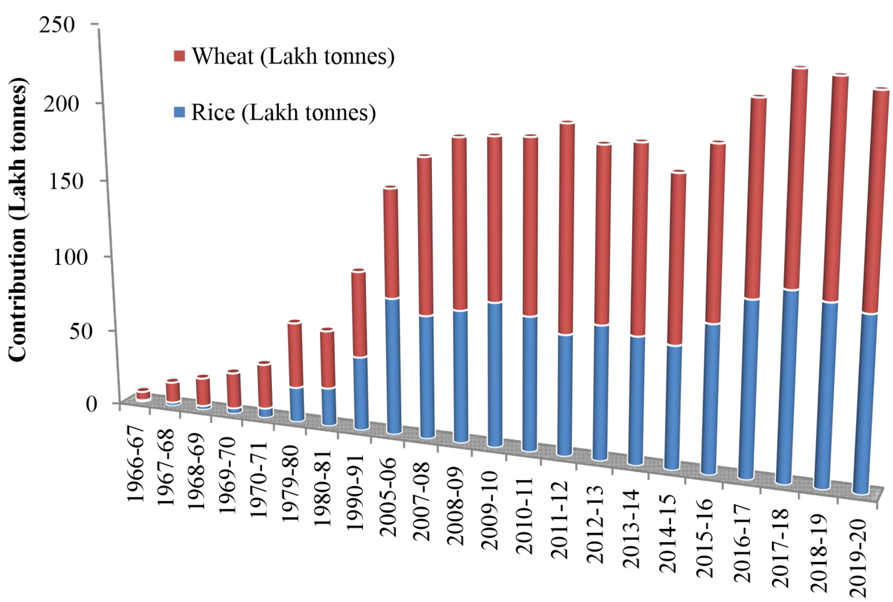

Fig. 2. Quantity of rice and wheat (lakh tones) contributed by Punjab to central pool of food grains

countries (Cohen *et al*., 2015). The issue of air contamination is additionally exasperated altogether particularly in north-west India because of large amount of agricultural residue being left in the field after harvest, which does not degrade fast in the soil. Around one fifth to one fourth of the biomass buildup is burnt by farmers in open fields in India (Ravindra *et al*., 2019a, 2019b). Biomass Burning is leading to excessive depletion of our major natural resources. A study conducted by Yadav and Devi (2018) recorded exhaustion of large areas ranging from 500–1000 mha of open forest and savannas to 1mha of northern latitude and 4 mha of tropical and subtropical areas. A study conducted by Zhuang *et al*. (2018) reported that short term variation of particulate matter concentrations are more strongly affected by intense crop burning than in the long term. The emissions produced by straw burning are so toxic that they induce respiratory difficulties, asthma, cough, bronchitis, skin disorders, and conjunctivitis. They also cause a drop in the number of red blood cells (RBC) and a decrease in the body's oxygen-carrying capacity. As straw burning not only impairs our environment, it adversely affects agriculture and human health, so this paper reviews the recent scenario of stubble burning quantitatively and qualitatively.

Historically, Punjab was never a paddy-growing area. India was on the brink of mass famine in the early 1960s. Because of rapidly growing population, the country was importing food grains. During 1964-65 drought conditions, India imported 13 million tons of food grains, which put heavy drain on the nation's foreign reserves. To strengthen national food security, a need was felt to adopt agricultural practices which promoted grain production. The government of India invested more than Rs. 70 million to promote agriculture in Punjab, Andhra Pradesh, Tamil Nadu and Gujarat, etc. However, Punjab emerged as a front-runner. The introduction of high yielding varieties and increased use of chemical fertilizers and irrigation led to phenomenal production increase. With phenomenal growth in agricultural production, Punjab became the showpiece of India's successful green revolution strategy. However, over time, the state started suffering from the side-effects of input-intensive green revolution technologies. Increased cropping intensity and mechanization of agriculture resulted in higher production of crop residue and consequently, its management has emerged as a major environmental concern during the recent decades in the region.

Rice-wheat monocropping and mechanization – a major driver

Green revolution on one hand, boosted production, but on the other hand, it had a significant impact on the cropping pattern of Punjab. Due to Minimum Support Price (MSP) for grains, subsidy for chemical fertilizers and improved irrigation facilities, in the interest of national food security (NFS), farmers in the state continued to bring more and more areas under paddy and wheat. In addition to this the policy of free electricity to farmers, encouraged the cultivation of water-guzzler crops like paddy. These policies encouraged the farmers to over use their land, as a result the cropping intensity in the state increased from 126% in 1960-61 to 190% in 2020 (Annonymous, 2020) along with the adoption of paddy-wheat mono-cropping. The area under paddy increased fourteen-fold from 227th ha in 1960-61 to 3141th ha in 2019-20, whereas, that under wheat increased by two and a half times from 1400th ha in 1960-61 to 3508th ha in 2019-20 (Annonymous, 2020). Out of total cropped area in the state, area under rice has increased from 5 to 39% and that under wheat from 30 to 43% during 1960-61 to 2019-20, which has led to significant decline in the area under other major crops like maize, bajra, jowar, sugarcane, groundnut, pulses, etc. (Fig. 3).

Under the rice-wheat cropping pattern, rice has to be harvested early in order to accommodate the wheat crop. However, due to Preservation of Subsoil Act of 2009, which was enacted to save depleting groundwater, farmers cannot transplant paddy before June 10 or 15, which results in delayed harvest. Thus, very little time is left with the farmers to turn around for planting the wheat crop. With the increase in area under paddy and wheat, various modern implements were introduced in Punjab to harvest these crops, one such implement being 'combined mechanized harvester'. The number of combine harvesters in the country, particularly in the IGP increased dramatically from nearly 2000 in 1986 to 13,800 in 2012-13 (Lohan *et al*., 2018). Similarly, in Punjab,

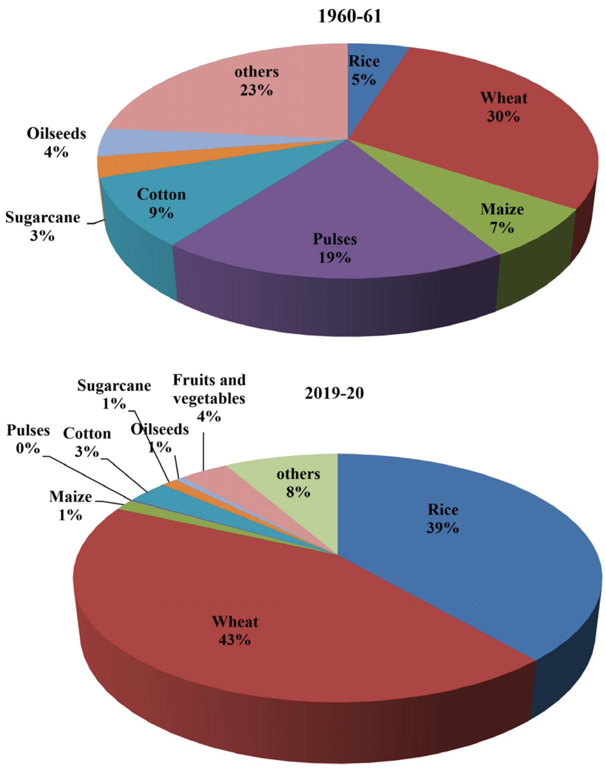

Fig. 3. Temporal variation in cropping pattern of Punjab

the number of tractors increased from 4935 in 1960-61 to 4,50,213 in 2019-20. In 2019-20, there were 7980 self-propelled and 4200 tractor driven combine harvesters in the state (Annonymous, 2020). As mechanical harvesting is more economical and efficient, thus about 90% of paddy area in Punjab and 75% in Haryana is harvested by combine harvester (Sidhu *et al.*, 2007).

However, the combine harvesters cut the paddy crop a certain height above the ground, thus leaving the standing stubble residues and the windrows of loose crop residues in the fields. It is particularly the latter that are a nuisance for establishing the subsequent crop which we call as crop residue. During 1950, its amount in India was approximately 80 Mt, which increased to over 500 Mt (6.25 times) in 2015 (Mathur and Srivastava, 2019). Although a considerable part of this crop residue is used as fodder, fuel for other domestic and industrial purposes, however, there is still a surplus of 140Mt out of which 92 Mt is burned each year, which is much larger than the entire production of agricultural waste in other countries in the south-Asia (Bhuvneshwari *et al.*, 2019). Among different states, the generation of crop residues is highest in Uttar Pradesh (60 Mt), followed by Punjab (51 Mt) and Maharashtra (46 Mt) (Lohan *et al*., 2018). Among the crops, its production is 110 Mt of wheat, 122 Mt of rice, 71 Mt of maize, 26 Mt of millets, 141 Mt of sugarcane, 8 Mt of fiber crops and 28 Mt of pulses (Devi *et al.,* 2017). Kaur (2017) reported that 95% of paddy straw and 25% of wheat straw are burnt every year in Punjab.

Why residue burning?

Farmers prefer residue burning because of many reasons. Farmers are left with only a few days (15-20 days) to clear fields of paddy straw before planting wheat and, also, these days are not enough to biologically decompose the residue. Paddy straw as animal feed is not considered good as it contains high silica content, which reduces its palatability among the milch animals and reduces milk yield. In addition to this, the rural households in Punjab mainly use LPG cylinders for fuel purposes and, hence paddy straw is not used as even fuel. Its market availability is also poor as the demand is less. Even if market is available, the cost of getting the stubble removed is very high (Fig. 4). Thus, farmers go for burning of crop residue, which has turned out to be a severe problem in the rice–wheat cropping system of north-western states (Punjab, Haryana and western Uttar Pradesh etc.) of India, where mechanized harvesting of rice using combine harvesters is a common practice, and management of leftover residue in the short window of 10–15 days for timely sowing of wheat is a formidable task (Kumar *et al.*, 2019). It has been estimated that every year 21.92, 19.65 and 9.08 Mt of crop residue is burnt in Uttar Pradesh, Punjab and Haryana, respectively (Fig. 5) (Ministry of Agriculture, GOI, 2014).

Assessment through satellite remote sensing

Remote sensing has played a major role in stubble fire detection. Mapping the timing and extent of fire incidence is highly important as it is a prominent disturbance factor affecting humans and ecosystem structure. Satellite data have been used to monitor biomass burning at regional to global scale using algorithms that detect the location of active

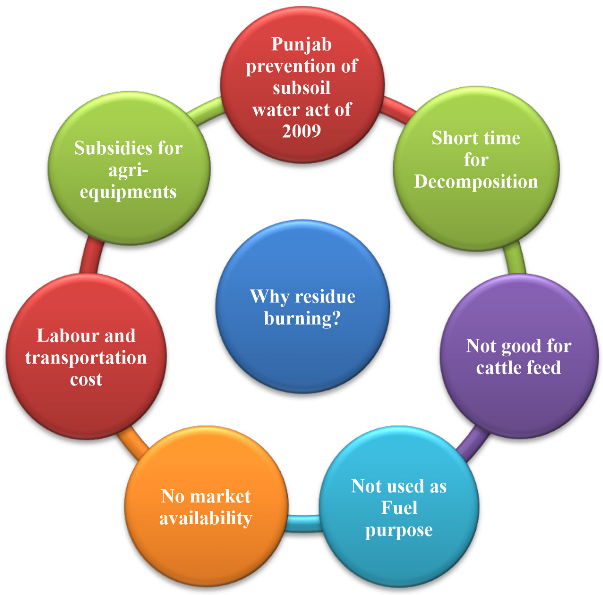

Fig. 4. Reasons of crop residue burning by farmers

fire at the time of satellite overpass and the burnt area mapping algorithms that map directly the spatial extent of the areas affected by fire. The NASA Moderate Resolution Imaging Spectro-radiometer (MODIS) on the Terra and Aqua satellites has specific features for fire monitoring and has been used to systematically generate global MODIS land products (Justice *et al*., 2006). The burnt area product contains burning and quality information on a per-pixel basis. Produced from both the Terra and Aqua MODIS-derived daily surface reflectance inputs, the algorithm analyses the daily surface reflectance dynamics to locate rapid changes, and uses that information to detect the approximate date of burning and mapping the spatial extent of recent fires. Nair *et al.* (2020) analyzed the contribution of stubble burning in air quality of Delhi during October and November 2017. Both remote sensing and ground observations showed similar results. Chawla and Sandhu (2020) estimated the burnt area for the year 2014-2018 for Patiala and Ludhiana by using Normalized Burn Ratio (NBR) Index and statistical threshold techniques and revealed that burnt area was reduced by 32 and 40% in Patiala and Ludhiana, respectively. An increase in pollutants (such as RSPM, NO_X and SO_2) was also observed, in which RSPM and NO_X were higher than emitted SO_2 in case of stubble burning.

Yang *et al.* (2020) analyzed the satellite and ground observations and developed a regional air quality modeling system to estimate the contribution of open biomass burning to surface $PM_{2.5}$ concentration during a severe haze episode. Using the differences in active fire spots as detected by the Visible Infrared Imaging Radiometer Suites (VIIRS) aboard the Suomi-NPP, it was estimated that the burning ban enforced in 2018 caused the $PM_{2.5}$ concentrations to decrease from the 2015 level by 67.10%, 53.23%, and 10.06% in the Heilongjiang,

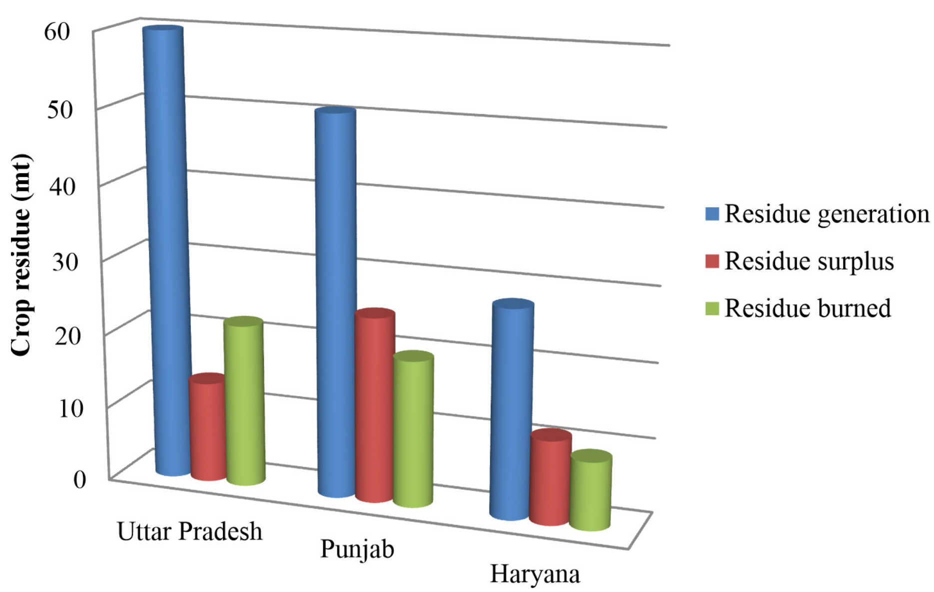

Fig. 5. Crop residue generated, surplus and burned in Uttar Pradesh, Punjab and Haryana

Jilin, and Liaoning provinces respectively. Vadrevu and Lasko (2018) compared fire products from the Visible Infrared Imaging Radiometer Suite (VIIRS) 375 m active fire product (VNP14IMG) and Moderate Resolution Imaging Spectro-radiometer (MODIS) 1 km fire product (MCD14ML) in an agricultural landscape of Punjab, India. They used an inter-comparison of three different approaches for estimating total particulate matter (TPM) emissions which included the fire radiative power (FRP) based approach using VIIRS and MODIS data, the Global Fire Emissions Database (GFED) burnt area emissions and a bottom-up emissions approach involving agricultural census data. On the basis of their results they showed a range of 2.56–63.66 (Gg) TPM emissions per month, with the highest crop residue emissions during November of each year. Results, on TPM emissions for seasonality matched the ground-based data.

Chabbra *et al.* (2019) monitored the fire emissions from three states Punjab, Haryana and Uttar Pradesh by recording the thermal datasets from three sensors VIIRS, MODIS, AVHRR. Comparative analysis shows that the burning till 30th November 2018 was 85 per cent of 2017 and 58 per cent of 2016. According to the study there was 11%, 29%, 24% reduction in Punjab, Haryana and UP respectively as compared to 2017 and 41%, 42%, 32% reduction in Punjab, Haryana and UP respectively as compared to 2016. They concluded that burning was at its peak in 2016 and decreased substantially afterwards due to various state and central government schemes. Similar results were reported by NASA (2018). However, a critical perusal of these research studies indicate that the intensity and extent of crop residue burning are very high in the region, which has severe impacts on the environment, air quality, climatic parameters, soil health and nutrient availability and severe health hazards.

Implications of crop residue burning

Crop residue burning has manifold implications as it severely impacts environmental health, climatic conditions and air quality leading to various health hazards. Air quality deteriorates significantly during the period of crop residue burning due to emission of greenhouse gases, aerosols, particulate matter and other trace gas emissions. The liberation of soot particles causes smog in the environment leading to health hazards to humans, animals and birds. In addition to this, crop residue burning also results in the loss of beneficial soil nutrients and adversely affects soil micro-organisms (Fig. 6).

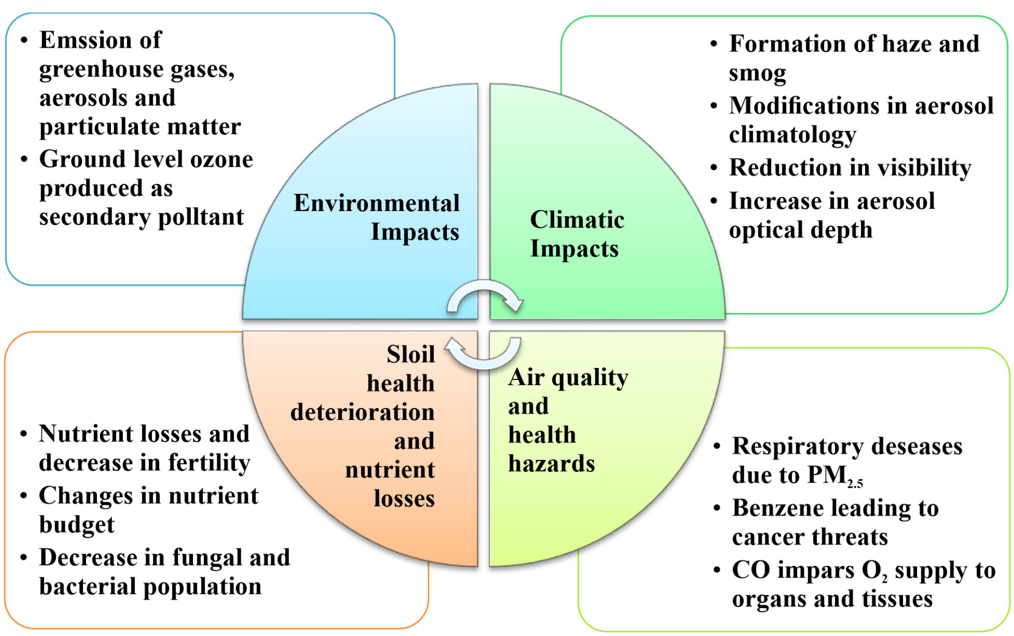

Fig. 6. Major impacts of crop residue burning

Environmental implications

Crop residue burning releases large quantities of particulate matter into the air. $PM_{2.5}$ ranged between 146 and 221 µg/m^3 in critically affected areas and average PM_{10} values were found 300 µg/m^3, against a permissible limit of 60 µg/m^3 for residential rural areas (PPCB, 2007; Kumar *et al.,* 2015). Sahu *et al.* (2021) quantified the high-resolution seasonal emission of air pollutants from crop residue burning in India. $PM_{2.5}$ and PM_{10} crop burning emissions were estimated for India as 990.68 and 1231.26 Gg/yr in 2018. The maximum emission was found to be generated in winter months (~50%) followed by summer months (~48%). In $PM_{2.5}$ emission, rice contributed maximum (45%) followed by wheat (27%), sugarcane (14%), maize (8%) and coarse cereal (7%). $PM_{2.5}$ has greater stability timing in air when contrasted to PM_{10} because of the balance between the downward force of gravity and aerodynamic drag force. Chanduka (2013) in Gobindgarh showed that there is more increase in PM_{10} concentration as compared to $PM_{2.5}$ due to stubble burning. During harvesting there was an increase of 86.65% in PM_{10} concentration and 53.2% in $PM_{2.5}$ concentration as compared to pre-harvesting. The substantial increase in PM concentration was due to stubble burning. Even in the post-harvesting season, the PM concentration was seen higher than pre-harvesting this indicated that the effect of burning is not only in the season but prevails in other seasons.

Crop residue burning is also responsible for forming ground-level ozone, which is a colorless and highly irritating gas that forms just above the earth's surface. Ozone is formed as a secondary pollutant when two primary pollutants (nitrogen oxides (NO_x) and volatile organic compounds (VOCs)) react in sunlight and stagnant air. According to Gadde *et al.* (2009), the annual contribution from crop residue burning in Asia is estimated to be 0.10 Tg of SO_2, 0.96 Tg of NO_2, 379 Tg of CO_2, 23 Tg of CO and 0.68 Tg of CH_4. It was also reported that paddy residue burning produced more emissions and is more harmful as compared to wheat. The comparison of the average total emission between rice and wheat from 2002-03 to 2012-13 revealed that burning of rice residue produced more GHGs and aerosols than the burning of wheat residue (Acharya *et al.,* 2016). Kumar *et al.* (2015) reported that the crop residues contains about 6.0 million tonnes of carbon that on burning could produce about 22.0 million tonnes of carbon dioxide in a short span of 15–20 days. CO appeared to be the most critical as concentrations of 114.5 mg/m^3 or more were observed at 30 m distance from burning fields and 20.6 mg/m^3 CO was recorded at residences even 150 m away. Given that the permissible limit of CO in ambient air is 4.0 µg/m^3, this was a major health hazard for residents and road travellers in the area.

Soil health deterioration and nutritional losses

Residue burning affects soil as nutrient loss by volatilization, ash convection, runoff, wind and soil erosion and leaching of fire-released nutrients (Schoch and Binkley, 1986). Kumar *et al.* (2015) estimated that burning of straw raises the soil temperature up to 33.8–42.2°C up to 3 inches depth. The fungal and bacterial population are decreased immediately up to 2.5 cm depth of soil. The burning of straw raises the temperature of the soil in the top 3 inches to such a high degree that the carbon-nitrogen equilibrium in soil changes rapidly. The carbon as CO_2 is lost to atmosphere, while nitrogen is converted to nitrate. This leads to a loss of about 0.824 million tonnes of NPK from the soil. Heat from burning residues also cause death of beneficial soil organisms. Frequent residue burning leads to complete loss of microbial population and reduces level of N and C in the top 0-15 cm soil profile, which is important for crop root development (Ministry of Agriculture, GOI, 2014).

Lohani *et al.* (2020) observed the phenomenal alterations in the quality of soils due to stubble burning in Amritsar, Punjab. Kumar *et al.* (2019) observed considerable reduction in the population of micro-organisms after burning, but was normalized after 30-60 days. Microbial enzymes and soil health properties also declined after burning and these could not be recovered most probably due to the lack of substrates. Turmel *et al.* (2015) analyzed residue management practices, its advantages and disadvantages in cereals based agro ecosystems in developing countries. Surface retention and incorporation showed varied effects on various soil properties and improved soil health. Sarkar *et al.*

(2020) also mentioned that ecosystem services from crop residue improved soil health status and supplement necessary elements in plants.

Climatic implications

The large-scale emissions of airborne particulates from burning of agricultural residues particularly over the upper Indo-Gangetic Plain (IGP) have often been associated with frequent formation of haze, adverse health impacts, modification in aerosol climatology and thereby impact on regional climate (Singh *et al.,* 2018). Haze refers to an aggregation of very fine, widely dispersed, solid or liquid particles in the atmosphere, giving the air an opalescent appearance which may include atmospheric moisture, fine dust, smoke and vapor etc. which diminish visibility, which usually arise from complex chemical reactions that occur as sulfur dioxide gas emitted during combustion is converted into small droplets of sulfuric acid. It has been observed during past few years that haze events during the straw burning period has led to reduction in visibility and degradation of air quality. Kumari *et al.* (2021) showed that the concentrations of Ozone (O_3), carbon monoxide (CO), sulphur dioxide (SO_2) and nitrogen oxides (NO_x) increased during the haze event whereas temperature, wind speed and relative humidity decreased. Cheng *et al.* (2016) found that sulphate production increased as $PM_{2.5}$ level increased. Under heavy haze conditions ($PM_{2.5} \geq 300$ mg m^{-3}), the sulphate production rate of the NO_2 reaction pathway was much higher than the reaction rates involving other important aqueous oxidants such as O_3 and H_2O_2. According to FAO (2020)**,** smog (which is a combination of several types of pollutants such as NO_x and SO_2 etc. with fog) has residue burning as one of the major contributors. Study showed that biomass burning affected distribution of troposphere ozone and acid depletion and is also a major source of greenhouse gases.

Black carbon is another essential constituent of particulate matter, which is often emitted as a product of incomplete combustion of fossil fuel and burning biomass. It is an important constituent (90% in $PM_{2.5}$) of airborne particulate matter (PM). It has typical lifetime ranging from 1 week to 10 days in the absence of precipitation and hence is amenable for long-range transport. On a global basis, however, approximately 20% of black carbon is emitted from burning of bio-fuels, 40% from fossil fuels, and 40% from open biomass burning, which has severe climatic implications (Tiwari *et al.*, 2013). Black carbon warms the earth by absorbing sunlight and heating the atmosphere. When deposited on snow and ice, it reduces albedo, may cause a significant positive radiative forcing and hastening melting. By interacting with clouds, it affects the cloud albedo and changes the hygroscopicity of cloud condensation nuclei. It also affects the reflectivity, stability and duration of clouds and alters precipitation (Fig. 7). Depending on how much soot is in the air and where black carbon is present in the atmosphere, it has different effects. If it absorbs heat at the level where clouds are forming, it will evaporate. When it lies above lower stratocumulus clouds that block the sun, it stabilizes them and thus has a cooling effect as it interacts with other components of particulate matter, such as sulphates and nitrates that reflect sunlight and cool the atmosphere. Biomass burning is considered one of the main causes of dense “brown clouds” in South Asia.

Usually urban haze, smoke particles, desert dust and sea salt etc. constitute aerosols. The measure of distribution of aerosols within a column of air from the instrument/earth’s surface to the top of the atmosphere is quantified as Aerosol Optical Depth (AOD), which is measured by using multi-wavelength radiometer (MWR). It is the natural logarithm of the ratio of incident to transmitted spectral radiant power through aerosol. Aerosol optical thickness is based on the fact that the particles change the way the atmosphere reflects and absorbs visible and infrared light. An optical thickness of less than 0.1 indicates a crystal clear sky with maximum visibility, whereas a value of 1 indicates very hazy conditions. MWR takes measurements of the spectral extinction of ground reaching solar ûux as a function of the solar zenith angle at ten wavelengths, centered at 380, 400, 450, 500, 600, 650, 750, 850, 935 and 1025nm. Sharma *et al.* (2017) observed day-to-day increase in AOD_{500} values during October 2006 and 2007 suggesting additional loading of aerosols over the region associated with agriculture crop residue burning practices.

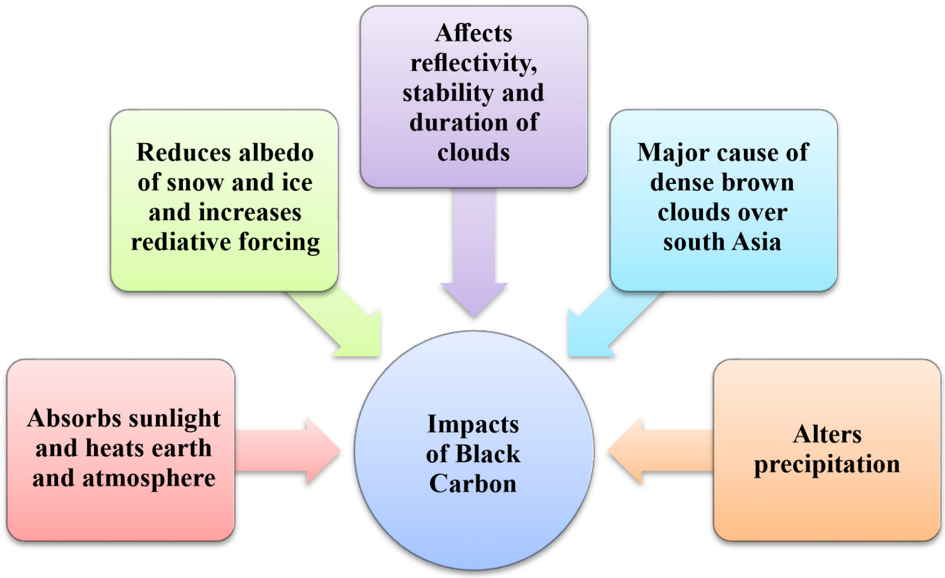

Fig. 7. Climatic impacts of black carbon

The Aerosol Radiative Forcing (ARF) is the change in the net (downward minus upward) radiative flux. The negative value of ARF indicates decrease of flux with aerosols and positive indicates increase of flux. Positive radiative forcing means earth receives more incoming energy from sunlight than it radiates to space. Aruna *et al.* (2016) also observed that ARF of atmosphere showed higher fluxes in the winter seasons due to increase in relative humidity. Beig *et al.* (2018) measured the share of biomass burning in impairing the air quality using the SAFAR chemical transport model. They showed that the impact of biomass burning on Delhi's $PM_{2.5}$ varied on day-to day basis (peaking at 58%) as it is highly dependent on transportation pathway of air mass, controlled by meteorological parameters from source to target region. Climatic influences also play a significant role in transporting the soot emissions region-wide. The smoke mixes with industrial pollution, dust and fog to form a thick haze (NASA, 2017). High air pressure, high relative humidity (61–79%), lower air temperatures (daily minima around 10–12°C) and nocturnal radiative inversions create relatively stable boundary layers preventing vertical mixing and thereby trapping pollutants and stagnant air close to the ground. The average wind speed required to cause turbulence in the air particle is estimated to be about 2 km/hr.

Air quality and health hazards

Stubble burning has emerged as the major source of increased pollution specially in South Asia. Abdurrahman *et al.* (2020) observed that it lead to increase in the concentration of greenhouse gases in the atmosphere. Their analysis showed that the burning of 63 Mt of crop stubble releases 3.4 Mt of CO, 0.1 Mt of NO_x, 91 Mt of CO_2, 0.6 Mt of CH_4 and 1.2 Mt of PM into the atmosphere which is even worse than India. The AQI is calculated for four major air pollutants regulated by the Clean Air Act: ground level ozone, particle pollution, carbon monoxide and sulfur dioxide. The AQI is divided into six levels of health concern and ranges from 0 to 500. The higher the AQI value, the greater the level of air pollution and the greater the health concern. AQI values at or below 100 are generally thought of as satisfactory. When AQI values are above 100, air quality is considered to be unhealthy. Air pollution leads to increased diseases worldwide, severely affecting the developing and under developed countries (Cohen *et al.,* 2015).

In crop residue burning there is no stack duct, no vent, thus all emissions are fugitive. We can refuse to consume adulterated and polluted water and food for a reasonable period of time, however, we cannot afford to stop breathing even for a minute, although we may know it is polluted. Particulate matter of size less than 2.5 µm ($PM_{2.5}$) are not entrapped by the respiratory filtration system and enter deep inside the lungs. Particles entering the pulmonary tract, reside for longer duration than that of gases. The main effect is narrowing of the airways called broncho-constriction. This may be accompanied by wheezing, chest tightness, and shortness of breath. Smoke from residue burning aggravates existing respiratory diseases, such as asthma and chronic bronchitis. Agarwal *et al.* (2012) reported that SO_2 and NO_2 have less adverse effects on pulmonary functions than different size particulate matter. Inhaling of fine particulate matter of less than $PM_{2.5}$ µg triggers asthma and can even aggravate symptoms of bronchial attack. Extreme lifetime cancer threat due to benzene has also been estimated.

Chakrabarti *et al.* (2019) also reported that respirable aerosol particles released by agricultural crop-residue burning (ACRB), practised by farmers in all global regions, are potentially harmful to human health. Carbon monoxide enters the bloodstream through the lungs and binds to hemoglobin, thus reducing the amount of oxygen reaching the body's organs and tissues. It reduces the RBC count in humans and adversely affects the oxygen carrying capacity in the body. Singh (2018) reported a 10% increase in the number of patients within 20–25 days of the burning period every season in rice-wheat belt of Punjab. Kumar *et al.* (2015) concluded that stubble burning aggravates health problems. Tiwari *et al.* (2013) also showed the temporal association between incidence of agricultural crop residue burning and acute respiratory infection. Inhaling fine particulate matter (FPM) adversely affects animal health too. It causes corneal irritation and temporary blindness and chronic bronchitis leading to asthma like conditions. Severe exposure leads to potential decrease in milk yield, and sometimes death of animal due to conversion of normal haemoglobin to deadly haemoglobin because of high level of CO_2 and CO in the blood.

Solutions /management options

It is evident that crop residue burning is resulting in severe environmental, climatic and health implications along with loss of nutrients and soil health deterioration. However, this fact cannot be ignored that farmers are hard pressed to adopt this practice since they don't have viable economical options with them. Hence, there is a dire need to bring out some viable options for crop residue management to opt those willingly. No tillage with residue retention and appropriate crop rotation is gaining more attention in the recent years due to the rising concern over degradation of natural resources, mainly soil and water, and to offset the production cost (Ladha *et al.,* 2009; Saharawat *et al.,* 2012). Conservation agriculture can be a potential alternative to the conventional agricultural practices for managing soil health and improving soil C stock, and thereby sustaining productivity and mitigate climate change (Maity *et al*., 2021). Retaining the residues as mulch also offers the potential benefits of reduced water loss due to the suppression of soil evaporation, reduced runoff, suppression of weeds, increased soil organic C and improved soil structure (Singh *et al.,* 2005). Thus, to achieve the desired objectives in both short- and long-term scenarios, various strategic interventions might be followed for promoting 'Earn, Don't Burn' concept (DST, 2014). Reddy *et al.* (2019) suggested that use of rice residue in thermal power plants, mushroom cultivation, bedding material for cattle, in bio oil and paper production, bio gas production is beneficial and helps in betterment of both agricultural and environmental conditions and ensures increased crop productivity (Fig. 8).

Innovative technologies / implements

Various resource-conserving technologies such as zero or minimum tillage in wheat, direct seeding in rice and simultaneously mulching rice residue while sowing wheat with happy seeder (Sidhu *et al.,* 2007) provide the option of surface-applied rice residue rather than incorporation and burning. Straw management system developed by Punjab Agricultural University, Ludhiana, is attached to the rear side of the combine harvester, which chops the loose paddy straw and spreads it uniformly in the field (Singh *et al.,* 2010) for better sowing of succeeding crops. Similarly, tractor mounted straw chopper cum spreader chops the standing stubble left after combine harvester operation and spreads in the field in a single operation (Singh *et al.,* 2011). The

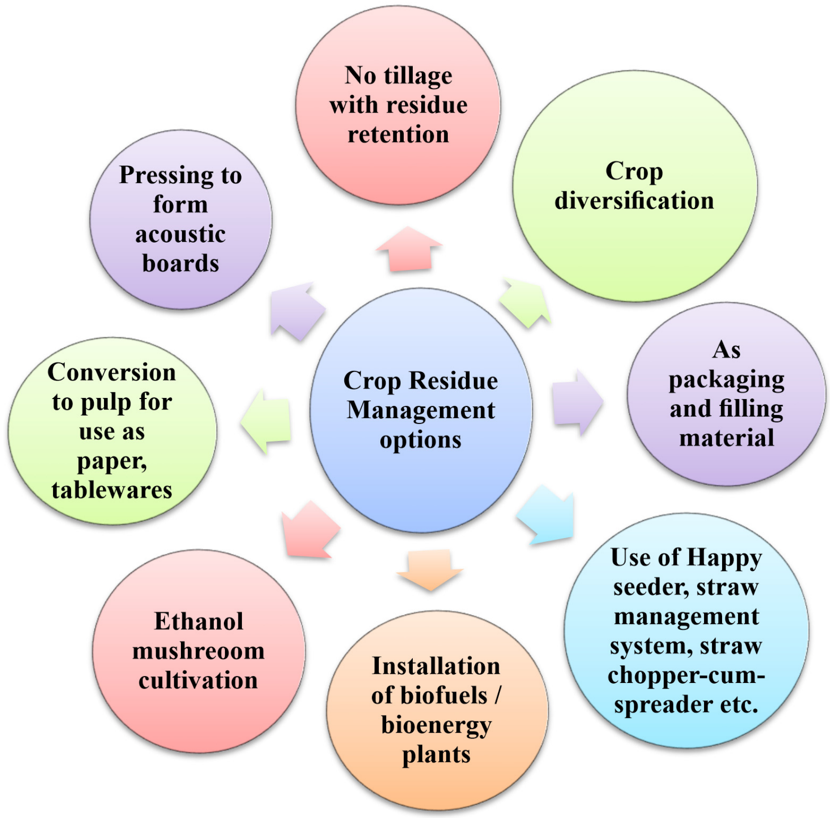

Fig. 8. Crop residue management options

leftover straw can also be chopped by using a paddy straw chopper-cum-spreader into small pieces. The chopped straw can be mixed into the soil by tillage operations without any adverse effect on the yield of next wheat crop and the succeeding crop can be sown using "Happy Seeder". PUSA decomposer, another very recent technology developed by scientists at Indian Agricultural Research Institute (IARI) is proving to be one such potential solution to avoid stubble burning. It is in the form of a capsule and converts stubble into compost in about 25 days and has 70-80 % efficacy. Most importantly this technology complies with the objectives of Swachh Bharat Mission. On 25th September, Delhi government launched preparation of bio-decomposer solutions which when sprayed on stubble left on the field results into decomposition and converts residue into fertilizer in just 15-20 days. Also, Takachar, an Indian company has developed a cheap machine by using oxygen-lean torrefaction concept which converts residues into sellable bio-products (fertilizer, solid fuels, other chemicals).

Creation of transportation facilities

Bhuvneshwari *et al.* (2019) suggested that agricultural landowners predominantly handle agricultural waste with little public sector involvement. Based on the needs of the community or the region, the Government agencies should offer different options such as to collect and transport the crop residue from the fields to the places where it is needed/utilized as a raw material such as a composting, biogas, biochar manufacturing plant etc.

Use for paper/board making and packaging/ filling material

Rice straw is a lignocellulosic material (the lignin in the straw being sufficient to act as a binder). The agricultural waste can be processed to convert to pulp. The transformation of straw into pulp has stronger effect on our environment than wood-based pulp (Sun *et al.*, 2018a, 2018b). The pulp can be converted into other value-added products like paper, table wares etc., aiming to facilitate rural entrepreneurs, NGOs and government in setting up of the process integrated machinery and providing the required technical and operational training. The advent of new packing material like thermocole has its adverse environmental implications including disposal problem. Use of paddy straw as a packing and filling material, as an alternative to thermocole and other materials such as plastic or paper needs to be promoted, wherever feasible. By pressing, the straw can be converted into expensive acoustic boards that are at presently imported in India and cost too much. These acoustic boards are used for sound reduction in auditoriums, theaters, sound studios etc.

Installation of biofuel / bioenergy plants

Biomass based power plants are an effective alternative. The calorific value of coal is 4200 Kcal/Kg and that of paddy straw is 3590 Kcal/Kg, which are comparable. But another advantage of paddy straw over coal is that they are available at low cost and their ash content is much less as compared to 36% ash content of coal. Biofuel generation industry should be installed to generate biofuels from crop residues, which can solve the purpose of income generation for the farmers and improve environmental health by stopping residue burning and bio-fuel energy generation, which can further help to reduce the use of fossil fuels. In rural China, biomass accounted for over 70% of total energy use in 2003 (Wu et *al.,* 2019). The production of electricity has been observed as more beneficial even than straw incorporation as it utilizes the energy better, although both these alternatives are much better options than open burning of straw in field (Yodkhum *et al.,* 2018).

Bedding material for animals

Bedding material for animals which helps improving the quality and quantity of milk as it contributes to animals' comfort and health. It keeps them warm and maintains reasonable rates of heat loss from the body. The paddy straw used for bedding can subsequently be used in biogas plants.

For cultivation of mushrooms

Paddy straw is also being used for the cultivation of mushrooms such as *Agaricusbisporus*, *Volvariella volvacea*, and *Pleurotus spp*. One kg of paddy straw yields 300, 120–150 and 600 g of these mushrooms, respectively. Paddy straw mushroom accounts for 16% of total production of cultivated mushroom in the world.

Availability of machines at subsidized rates

The various machineries that have been developed for harvesting and straw management should be made available along with optimum subsidy. If subsidy is already there, it should be ensured that it is accessible for all the farmers.

Creating awareness among farmers

There is need to improve farmers interest and participation in "No-burning" activity through trainings / information dissemination /campaigns / printed material (poster, leaflets etc.), electronic (sms, e-mail) and broadcasting media including Whatsapp groups. There is a need to educate willing farmers so that they can set as an example for others and set up workshops where innovative farmers can interact with other farmers.

Practical concerns

In the recent years, government, scientists, environmentalists have become more aware and concerned about the consequences of harmful effects of stubble burning. Steps are taken by the government every year, but it seems difficult to check this problem unless there is availability of user-friendly, cost-effective and economically viable options with the farmers, so that they opt them willingly. In addition to this, non-availability of machine for purchasing as well as on custom hiring basis, high cost of the machine, requirement of a big tractor to operate Happy Seeder as compared to seed drill, inappropriate seed depth while sowing, no substantial yield increase, more spacing requirement, clodding in the field at the time of operation and more rodent infestation are some of the constraints as mentioned by the farmers leading to its low adoption in Punjab. Also subsidies for agricultural equipments, such as happy seeder or rotavator did not reach most of the farmers.

Thus, inspite of the options available, many practical problems are being experienced at farmers' end, which need to be addressed for real solution of the problem. Roy *et al*. (2018) studied the problems faced by farmers regarding paddy straw management and found that the farmers were compelled to opt for crop residue burning due to the non-availability of any economically viable option. As a result, about one fifth to one fourth of the bio mass residue is burnt by farmers in open fields in India (Ravindra *et al.,* 2019a, 2019b). The government should facilitate the farmers to avail alternate options recommended for sustainable management of crop residue, such as easy financing of happy seeders, subsidy on incorporation of residues etc. Crop residue could be procured for generating power with good price and transportation facilities. The government should also ensure market and costs for crops to promote diversification.

Conclusion

It is evident that our environment is being polluted at alarming rates, which has long-term socio-economic impacts. Alternatives need to be provided to farmers so that they perceive their agro-waste as an agro-asset. As crop residues are a renewable resource for improving soil health and are good sources of plant nutrients, thus recycling of these residues improves the soil physical, chemical and biological properties besides stabilizing the agricultural ecosystem. But rice residue management through direct incorporation of straw in soil is associated with certain problems such as immobilization of plant nutrients, particularly nitrogen and reduces germination of subsequent crops. But, still there are a number of unexplored opportunities to use this bio-resource. There is an urgent need to find ways to prevent burning of paddy straw and manage it by other means. The development of a comprehensive interdepartmental policy is the need of the hour. There is a need for a thorough assessment of available resources in local ecosystems and market demand for specific bio-energies. Region-specific policies can be framed for making agro-waste to agro-asset.

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