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Stubble burning: Effects on health & environment, regulations and management practices

Muhammad Isa Abdurrahman, Sukalpaa Chaki, Gaurav Saini*

Department of Civil Engineering, School of Engineering and Technology, Sharda University, India

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ABSTRACT

Stubble burning has been reckoned among the major contributors of air pollution especially in South Asia. It is a significant source of gaseous pollutants such as, carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), and methane (CH_4) as well as particulate matters (PM_{10} and $PM_{2.5}$) causing serious damage to human health and the environment. It was reported 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. The situation is more austere in India due to the intensive rice-wheat rotation system which generates large amount of stubble. It was estimated that about 352 Mt of stubble is generated each year in India out of which 22% and 34% are contributed by wheat and rice stubble respectively. About 84 Mt (23.86%) of the stubble is burnt on-field each year immediately after harvest. The disastrous haze observed over India during the winter season has been linked to stubble burning as it coincides with the burning periods (October-November). During this time, most Indian cities, especially within the National Capital Region (NCR) experience harsh pollution often reaching the severe levels of the air quality index (AQI). In November 2019, Delhi recorded a peak AQI of 487, Ghaziabad reported an AQI as high as 493, and Greater Noida recorded 480. The health effects of air pollution ranges from skin and eyes irritation to severe neurological, cardiovascular and respiratory diseases, asthma, chronic obstructive pulmonary disease (COPD), bronchitis, lung capacity loss, emphysema, cancer, etc. It also leads to an increase in mortality rates due to the prolonged exposure to high pollution. The Energy and Resources Institute (2019) reported that in 2012, air pollution had led to about 5 million deaths in South Asia which is around 22% of the total deaths in the region. In addition to its effects on air quality, stubble burning also affects soil fertility (through the destruction of its nutrients), economic development and climate. The crop stubbles (if managed properly) could provide immense economic benefits to the farmers and protect the environment from the severe pollution. Some of the alternative management practices include the incorporation of the stubble into the soil, use of stubble as fuel in power plants, use as raw material for pulp and paper industries, or as biomass for biofuel production. It can also be used to generate compost and biochar, or as blend for the production of cement and bricks. Most of the farmers in North India are not aware of the prolific alternatives for managing stubble and, therefore, consider burning as the best option. This necessitates the need for immense awareness programs to enlighten the farmers about the availability of economically feasible options and the composite effects of stubble burning.

Abbreviations: AERMOD, Atmospheric dispersion modeling; AOD, Aerosol Optical Depth; AQI, Air quality index; BC, Black Carbon; BrC, Brown Carbon; DALY, Disability-Adjusted Life Year; DESA, Department of Economic and Social Affairs.; EIA, Environmental Impact Assessment; EPIC, Energy Policy Institute at the University of Chicago; FRP, Fire Radiation Power; HC, Hydrocarbon; HYSPLIT, Hybrid Langrangian Integrated Trajectory; IARI, Indian Agricultural Research Institute; IGP, Indo-Gangetic Plain; IPCC, Intergovernmental Panel on Climate Change; ISCT3, Industrial Source Complex Short Term; MNRE, Ministry of New and Renewable Energy, Government of India; MoEF & CC, Ministry of Environment, Forest and Climate Change, Government of India; Mt, Million tonnes; NAQMS, National Air Quality Monitoring Scheme; NCAP, National clean air program; NCR, National Capital Region; OC, Organic Carbon; TERI, The Energy and Resources Institute, India; Tg, Terra grams; U.P., Uttar Pradesh; WRF, Weather Research and Forecasting.

* Corresponding author.
E-mail address: gauravsaini@gmail.com (G. Saini).

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1. Introduction

Stubble burning is one of the major contributors to atmospheric pollution in the world releasing particulate and gaseous pollutants that have severe effects on human health and the environment (Sharma et al., 2010). It is a significant source of air pollution in many parts of the world being only the 3rd after industrial and vehicular emissions (Gurjar et al., 2016; Krishna et al., 2011). Stubble burning can be defined as the intentional incineration of stubbles by farmers after crop harvest. Stubbles are the cut stalks left on the field after the grains of cereal plants or stems of sugarcane are harvested. Other biomass burning activities such as wood burning for domestic cooking, open field incineration of municipal waste, and wildfire also contribute to the emissions, however; in Asian countries such as China, around 60% of the total biomass emissions comes from the burning of stubble (Zhang et al., 2015). On a global scale, stubble burning constitutes about one-fourth of the total biomass burning (inclusive of forest fires) (Yadav and Devi, 2019; Zhang et al., 2016).

The harsh haze observed over South Asia during the winter season has been linked to biomass burning as it coincides with the stubble burning periods (Ghosh et al., 2019; Khwaja et al., 2012). In India, New Delhi and the other NCR (National Capital Region) cities have been experiencing harsh pollution from smog and haze caused by various anthropogenic activities and lower temperatures during the winter especially during October to December months every year. Since 1990, Delhi has been listed among the most polluted cities in the world. Recently, in 2019, the global air quality report showed that 14 out of the 20 most polluted cities in the world are from India with the most polluted being the city of Ghaziabad in Uttar Pradesh (U.P) (Sikarwar and Rani, 2020). Greater Noida and Delhi were ranked the 5th and 9th on the list. Most of the cities on the list fall under the Northern region of India especially the state of Uttar Pradesh (Sikarwar and Rani, 2020).

The common farming system in the Indo-Gangetic Plain (IGP) is the rice-wheat rotation system. The IGP is an important region located in South Asia blessed with fertile agricultural farmlands and a diverse ecosystem. Geographically, it occupies about 20% of the total land area of India, Pakistan, Bangladesh, and Nepal. In India, it consists of about 40% of the country's total population occupying around 20% of its total geographical area. This region provides 41% of the annual food production in India most of which are grains. Out of approximately 66 million hectares (total area of the IGP), about 12 million hectares are utilized for the wheat-rice (Crop rotation) production system (Sharma et al., 2010). An estimated 9.6 million hectares of land are utilized annually for the rice-wheat cropping system in India (Sharma et al., 2010). Most of the farmers in this region use combine harvesters for planting and harvesting the crops thereby generating a significant quantity of stubble. The use of Combine harvesters for harvesting grains is common among Indian farmers especially in the northern parts of the country. This machine can combine three different tasks, i.e. Reaping, Threshing, and Winnowing into a single operation. They are reported to be efficient in harvesting different types of grains, however; they generate a huge amount of stubble consisting of tall stalks, about 15cm high, which are difficult to be incorporated into the soil (Mittal et al., 2009; Pratika and Sandhu, 2020).

A significant amount of the stubble generated is set to fire on the field. According to the Indian Agricultural Research Institute (IARI), approximately 14 million tons (Mt) out of the 22 Mt of the rice stubble (about 63.6%) generated each year in India is set to fire (IARI, 2012). Haryana and Punjab, two of the key agricultural states of India, alone contribute 48% to this amount (Gadde et al., 2009). In the Punjab region, rice and wheat account for about 85.91% of the total cultivation with other crops produced in relatively minor quantities. Rice is usually planted in the summer season, around May/June, and harvested around October/November. On the other hand, wheat is normally planted during the winter, mostly in December and harvested during the summer of the subsequent year, around April/May. The burning takes place immediately after harvest in each season. This time may, however, vary in other parts of the world (Kapil, 2019).

From the farmers' perspective, it is easier to burn the crop stubble after harvest to quickly prepare the farmland for the next sowing (of rice or wheat as the case may be). The farmers' eagerness to quickly prepare the farmland for the next planting compels them to simply burn the stubble on-field thereby emitting a large number of hazardous pollutants (Krishna et al., 2011). Another rationale behind the burning of the stubble is the shortage of time between the harvest and the sowing of the next crop (Ravindra et al., 2018). The average time interval between the harvest of rice and sowing of wheat was reported to be 15 days, and that of rice sowing after wheat harvest was relatively higher, up to about 46-48 days. The farmers, therefore, do not have sufficient time to appropriately manage the crop stubble especially after rice harvest (Krishna et al., 2011).

Burning of firecrackers during Diwali, a major festival in India, was suggested by some (Arora et al., 2018) as the cause of poor winter air in India. For example, in 2019, Delhi, Noida, Gurugaram, and Ghaziabad reached the hazardous AQI levels during the Diwali festival. Diwali is, however, not the major cause of air quality problems during the winter due to the presence of harsh pollution even before the event (Barman et al., 2008; Ghei and Sane, 2018). The Diwali activities coincide with the crop stubble burning periods and thus results in further deterioration of the air quality. Ghei and Sane (2018) reported that the burning of firecrackers during the Diwali ceremony results in a quantitatively small and statistically significant rise in air pollution. They compared the stubble burning periods with and without Diwali and found an increase of about 40 $\mu g/m^3$ $PM_{2.5}$ (Particulate matter with aerodynamic diameter less than 2.5 microns) concentration during Diwali days in 2018.

It is worth noting that stubble burning is not the only cause of post-monsoon deteriorated air across the IGP; meteorological conditions such as ambient temperature, relative humidity, wind speed, wind direction and ambient pressure also play important roles (Ravindra et al., 2019). A number of studies have established a link between the post-monsoon poor quality of air in India and the variation in meteorological conditions (Banerjee et al., 2011; Guttikunda & Gurjar, 2012; Krishan et al., 2019; Resmi et al., 2020). Sembhi et al. (2020) asserted that the variations in $PM_{2.5}$ concentrations is dependent upon specific meteorological parameters. In other words, the post-monsoon meteorological conditions favor more stable atmosphere rendering the pollutants to accumulate and reside longer in the atmosphere leading to severe levels of pollution.

The impact of stubble burning is more severe during the rice stubble burning season as the lower winter temperature leads to a more stable atmosphere (Inversion conditions) (Ghei and Sane, 2018). The fact that pollutants stay longer in the atmosphere during this time, and that the amount of rice stubble burned is quite higher than that of wheat results in a harsh level of pollution often obstructing visibility. It was reported that the air pollution level in Delhi during October 2017 was six-fold as compared to that during July of the same year . The atmospheric inversion provides greater residing time for pollutants, poorer dispersion, and lesser rate of smoke diffusion. The smoke generated, therefore, accumulates in the atmosphere exerting more damage to the environment (Pratika and Sandhu, 2020).

Air pollution poses a grave threat to human health and wellbeing leading to a rise in mortality and morbidity rates in many parts of the world. According to WHO, toxic air, as a result of pollution, results in the death of about 7 million people in the world annually (WHO 2008). The Energy and Resources Institute (TERI) reported that in 2012, air pollution had led to about 5 million deaths in South Asia which is around 22% of the total deaths in the region. The report added that more than 51% of the total population in South Asia has been under continuous exposure to $PM_{2.5}$ above the WHO limits (Ghosh et al., 2019). India contributes 26.2% to the total global Disability-Adjusted Life Year (DALY) rate while constituting only 18% of the world population. The northern region of the country has the highest rate of DALY especially in the U.P, Punjab, Haryana, and Rajasthan (Ghosh et al., 2019).

Air pollution also affects economic development both on the local and regional scale. It claims approximately 5 trillion dollars from the global economy annually (Ghosh et al., 2019). The poor visibility in the NCR as a result of air pollution has caused many people to migrate out of the region especially during severe pollution episodes which conversely affects tourism, especially in Delhi. A survey on tourism, in 2018, reported that the inflow of tourists into Delhi has decreased by about 25-30 % as a result of air pollution (Sharma et al., 2019). Air pollution, therefore, has a great impact on tourism and economic development.

The states most affected by the severe pollution are Delhi, Uttar Pradesh (U.P), Punjab, Haryana, Bihar, and West Bengal. These states are also the most agriculturally productive in India (Khrishna et al., 2011). Punjab, for example, is sometimes regarded as the country's breadbasket and provides about 30% of the country's grain supply (Saggu, 2018). Survey has shown that U.P has the highest number of farmers counting to about 23.8 million (Sharma et al., 2010).

The impact of stubble burning may increase in the coming years with the increase in population and food demand. A report by the United Nation pointed out that the world population may rise to 10 billion by 2050, which will in turn lead to increased food demand. In India, crop production is projected to increase by 45% by 2050, i.e. from 619 Mt (million tons) in 2017 to 899 Mt in 2050 (United Nations, 2015). This will necessitate the production of more food and consequently the generation and burning of more stubble.

Several efforts have been made by the government to provide alternative management techniques for the farmers to manage their crop stubble. Despite strict policies, the practice of outdoor crop stubble burning in India continues to be a threat to human health and wellbeing. However, in 2018, the Ministry of Environment, Forest and Climate Change (MoEF&CC), Government of India, reported a reduction in the number of stubble fires in Haryana and Punjab by about 38.93% and 20.3% respectively as compared to 2016 (Singh, 2018).

This review aims to comprehensively cover the existing literature and current status of stubble burning in India, including; (1) the generation and burning of crop stubble (2) the composition of emissions from stubble burning (3) the transport and dispersion of emissions from stubble burning (4) the effects of stubble burning (5) the legislation and policies on stubble burning and (6) the alternative techniques for managing crop stubbles. The review also recommends some approaches that (if used appropriately) will profoundly assist in arresting the issues of burning agricultural stubble in the country and beyond.

2. Crop stubble generation and burning

A huge amount of waste is generated after harvesting crops like wheat and rice, most of which are burned after the valuable constituents have been removed. Some of these wastes are used as animal feeds, for making cattle sheds, rural houses roofs, or as fuel for domestic cooking. In rare cases, they serve as raw materials for small scale industries, such as pulp/board industries, biogas generation, etc (Ravindra et al., 2018, Singh et al., 2016). Nonetheless, a significant portion of the stubble is left on the field with no specific usability, and therefore it is simply burned to clear the farm for next planting (Singh et al., 2018). About 352 Mt of agricultural stubble are generated each year by cereal crops out of which 22% and 34% are contributed by wheat and rice stubbles respectively (Singh et al., 2018). Uttar Pradesh generates the highest quantity of stubble, about 72Mt, followed by Punjab (46Mt), West Bengal (37.3Mt), Andhra Pradesh (33Mt), and then Haryana (24Mt) (IARI, 2012). These values may increase in the future with increased population and food demand. There is also a potential likelihood of their reduction with the development of technological methods and machinery for managing agricultural stubble and/or governmental policies. The maximum stubble is generated by cereal crops constituting about 58% of the total annual crop production. For most of the grains, the amount of stubble generated is higher than the grain produced. In the case of rice and wheat, the stubble is approximately 1.5 times the grain produced (Gupta et al., 2004; Sahai et al., 2007).

Table 1
Amount of crop stubble burned in India

Type of Crop	Quantity of Stubble burnt (Mt per year)	Reference
Rice	13.9	(Kumar et al., 2015)
Rice	44	Thumaty et al. (2015)
Wheat	24	Thumaty et al. (2015)
All Crops	98.58	Jain et al. (2014)
All Crops	131.9	IPCC (2006)
All Crops	127	Mehta (2004)
All crops	133.14	Garg (2008)
All Crops	84	Pratika and Sandhu (2020)
All crops	70.8	Badarinath et al. (2006)
All crops	133.14	Garg (2008)
All crops	350	Mandal et al. (2004)
All crops	347	Gupta et al. (2004)
All crops	184.9	Agarwal et al. (2008)

The burning of biomass has been reportedly increasing over recent years with most of it caused by human activities. It was estimated that about 90% of biomass burning is attributed to human practices with the remaining smaller percentage being linked to natural fires (Kaskaoutis et al., 2014). After domestic and other utilizations, an excess stubble of 84Mt is normally burnt in the field out of which 24Mt comes from wheat and 44Mt from rice harvests in India (Thumaty et al., 2015). In Punjab, more than 90% of the farmers burn their stubble in the field. Most of the farmers in this region practice mechanized farming, and only 7% of wheat and 2% of rice were reported to be harvested manually resulting in the generation of a large quantity of crop stubble. The stubbles are generated as stalks, straws, and sugarcane leaves (Ravindra et al., 2018).

Many regions in the North including Punjab have banned this practice through their state pollution control boards since 2005. However, satellite fire hotspot data have shown an increased occurrence of agricultural fires through the subsequent years (Csiszar et al., 2014; Jain et al., 2014, Ghosh et al., 2019). Thumaty et al. (2015) used MODIS satellite data and observed the continuous occurrence of fire in about 60% of the total agricultural areas in Punjab and Haryana.

There are various hypotheses on the total percentage of crop stubbles burned in the field ranging from the very low 6.6% to the modest 43%. Table 1 presents the quantities of stubble burnt in India according to different studies. The Intergovernmental Panel on Climate Change (IPCC), reported that 25% of stubbles generated in the farm are burned by the farmers, while Jain et al. (2014) suggested 23% for wheat and rice, and 10% for other crops. Cao et al., 2008 reported that about 6.6% of the crop stubble generated in the farm is burnt in-situ immediately after harvest. Another study pointed out that about 43% of the total crop stubble generated in India is burnt on the field (Singh and Kaskaoutis, 2014).

2.1. Types of crops cultivated in India

The crops mostly cultivated in India include; rice (*Oryza sativa*), wheat (*Triticum aestivum*), sugarcane (*Saccharum officinarum*), cotton (*Gossypium hirsutum*), jute (*Corchorus olitorius*) and mesta (*Hibiscus cannabinus*), Coarse Cereals (Sorghum (*Sorghum bicolor*), maize (*Zea mays*), millet (*Panicum miliaceum*), pearl (*Pinctada margaritifera*), and barley (*Hordeum vulgare*)), total pulses (gram (*Cicer arietinum*), moong (*Vigna radiate*), urad (*Vigna mungo*), pigeon-pea (*Cajanus cajan*)), and the other cereals (Soybean (*Glycine max*), sunflower (*Helianthus annuus*), rapeseed (*Brassica napus*) and Mustard (*Brassica nigra*), groundnut (*Arachis hypogaea*), castor seed (*Ricinus communis*), and sesame (*Sesamum indicum)*) (Jain et al., 2014). The highest stubble is generated from rice production as illustrated in table 2.

Table 2
Types and quantities of crops commonly generated in India (Jain et al., 2014).

Type of Crop	Quantity of Crop Produced (Mt/year)	Quantity of Stubble generated (Mt/year)	Ratio of Stubble to Crop
Rice	153.35	188.98	1.23
Wheat	80.68	120.07	1.49
Jute	18.32	31.51	1.72
Sugarcane	285.03	107.50	0.38
Maize	19.73	26.75	1.36
Cotton	37.86	90.86	2.40
Millet	17.62	21.57	1.22
Rape seed	7.20	17.28	2.40
Groundnut	7.17	11.40	1.59
Total	627.96	620.43	

3. Emission composition

Stubble burning is a significant source of carbon dioxide (CO_2), volatile organic compounds (VOCs), nitrogen oxides (NO_x) and hydrocarbons (HC) accounting for about 10% of the total emissions in the world (Liu et al., 2019). The emission contains particulate matter and harmful gases such as Nitrogen dioxide (NO_2), N_2O (Nitrous oxide), Sulfur dioxide (SO_2), Carbon monoxide (CO), Carbon dioxide (CO_2), and Methane (CH_4), all of which severely affect human health. Sahai et al. (2011) gathered that upon burning of 63 Mt of the stubble, 3.4 Mt of CO, 0.1Mt of NO_x, 91 Mt of CO_2, 0.6 Mt of CH_4, and 1.2 Mt of particulate matter are emitted. Another study established that burning 1 ton of stubble emits 199 kg of fly ash, 1460 kg of CO_2, 60 kg of CO, 2 kg of SO_2, and 3 kg of suspended particulate matters (SPM) (Gupta et al., 2004). Jain et al. (2014) demonstrated that emissions from stubble burning are mostly CO_2 accounting for about 91.6% of the total emission. The remaining percentage is composed of 66% of CO, 11% of VOCs, 5% of hydrocarbons, and 2.2% of NO_x. About 40% of the total stubble burning related emission comes from rice stubble burning, while the burning of wheat and sugarcane stubble contributes 22% and 20% respectively (Jain et al., 2014). In 2009, an estimated 153.4 Mt of various pollutants were emitted from stubble burning. Burning of stubble converts around 70% of the carbon inside the stubble to CO_2, 7% to CO, and 6.6% to methane (CH_4). It also transforms about 20% of the stubble nitrogen to NO_x and 2.1% to N_2O, while 17% of the stubble sulfur is released as SO_x (Carlsen et al., 1992). Another study by Yevich and Logan (2003) reported that the burning of stubble emits approximately 91 terragram (Tg) CO_2, 4.1 Tg CO, 0.6 Tg CH_4, 1.2 Tg particulate matter, and 0.1 Tg NO_x in India annually.

The smoke particles generated during stubble burning are reported to be of different particle sizes depending on the combustion phase. For example, smoke particles released during the smoldering phase were reported to be coarser than those released during flaming phase (Ordou & Agranovski, 2019). Wardoyo et al. (2007) investigated the size distribution of smoke particles in varying burning modes for some species of grass and found that the emitted smoke particles range in diameter between (30 nm and 60 nm) for flaming phase and around (60 nm to 210 nm) for smoldering phase. The particles size of smoke particles released during agricultural burning were reported to be around 150 nm for cereal crops and 200 nm for wet fuels (e.g. montana grass) (Zhang et al., 2011).

The aerosols from biomass burning generally comprise of two main chemical components namely, Black Carbon (BC) (which strongly absorbs solar radiation) and Organic Carbon (OC) (which scatters solar radiation) (Ryu et al., 2004). Black carbon is mostly produced under flaming conditions when oxygen supply is limited leading to an incomplete combustion. Organic carbon is the major component of aerosol particles formed primarily by the incomplete combustion of organic matter inside the biomass having a strong light scattering ability (Huang et al., 2015). However, there is a portion of the OC that can also absorb light (similar to the BC) known as the Brown Carbon (BrC) (Laskin et al., 2015). The BrC differs from the BC in the sense that it has a stronger light absorbing capacity and can absorb radiation ranging from the visible to ultraviolet spectrum. Stubble burning emissions also comprise of ionic species such as chloride (cl^-), nitrate (NO_3^-), ammonium ion (NH_4^+), potassium ion (K^+), calcium ion (Ca^+), and magnesium ion (mg^{2+}) (Ryu et al., 2004) and inorganic salts such as sulphates, oxalate etc. (Saarikoski et al., 2007).

Globally, biomass burning is the major source of OC and approximately 33.9 Tg of OC and 8 Tg of BC are emitted each year out of which about 74% and 42% for OC and BC respectively are contributed by biomass burning (Saarikoski et al., 2007). Jung et al. (2015) reported that, in 2012, the OC and EC emissions released by biomass burning activities in China contributed about 45% and 12% to OC and BC loadings, respectively. Ryu et al. (2004) reported a high OC/BC ratio during rice post-harvest stubble burning episodes indicating higher quantity of OC as compared to BC (aggregately 20.5 and 2.6 μg/m^3 respectively). They inferred that OC was dominant throughout the entire period comprising of approximately 44% of the overall fine mass. Li et al. (2015) used a chamber-simulation technique to determine the chemical composition of stubble burning aerosols in China and found that about 50% of the aerosol mass is made up of organic carbon while only 11% is black carbon. The remaining percentage is comprised of water-soluble inorganic salts (23.8%), inorganic ions and other minor constituents.

4. Transport and dispersion of stubble burning emissions

It is a common practice to burn crop stubble in India since it requires minimum labor, claims no cost, and takes lesser time. The resultant emissions can travel a very long range in the air via complex atmospheric processes determined by the prevailing meteorological conditions (Ghosh et al., 2019). Air quality is significantly affected by the regional transport of the pollutants across state and national boundaries. Studies show that pollutants travel from the Punjab region of India to Pakistan and vice-versa (Ghosh et al., 2019, Shabbir et al., 2019). It was reported that even though levels of emissions are declining in Europe, the rate of premature deaths will not decrease in the coming 15 years due to trans-boundary transport of pollutants from neighboring regions (WHO, 2008). Masud et al. (2016) found that pollution from Bangladesh enters India (Gazipur) and contributes about 150 μg/m^3 of PM_{10} (Particulates matter with aerodynamic diameter less than 10 microns) concentration to the air pollution in the region. Ghosh et al. (2019) conducted a 5-day back trajectory analysis of air and concluded that a trans-boundary transport of pollutants exists among India, Bangladesh, Nepal, and Pakistan with little impacts from other neighboring countries. Therefore, information about the sources and properties of the emission is required to effectively assess the impacts of stubble burning and to study the transport and residence times of pollutants in the air (Guoliang et al., 2008).

4.1. Air pollutants transport modeling

Air quality modeling is essentially important in understanding the behavior of pollutants and estimating the relationship between the sources of the pollutants (e.g. open fires) and their effects on the ambient air quality. Open fires are generally estimated from the temporal and spatial distribution of fire hotspots or burned areas detected through satellite observation platforms or via ground-based measurement of emission factors (Li et al., 2015). Air quality modeling can be conducted by using a statistical or deterministic approach depending on the context (Sharma et al., 2019). The use of modeling techniques saves the cost, time, and energy of conducting real-time field measurements. Before 2003, the most common model used for assessing the transport & predicting the ambient air concentration of the pollutants in India was the Gaussian dispersion model which assumes a steady-state transport of pollutants over a limited region (Ghosh et al., 2019). This model, however, is only applicable to a small geographical range within a few kilometers. In 2003, the Central Pollution Control Board (CPCB) provided a standard procedure and guideline for air quality control throughout the country and proposed the use of atmospheric dispersion modeling (AERMOD) system for Environmental Impacts Assessment (EIA) purposes. Since then, AERMOD and Industrial Source Complex Short Term (ISCT3) models have been the most commonly used air pollution dispersion models in India (Ghosh et al., 2019).

Some institutions in the country such as The Energy and Resources Institute (TERI) have adopted the use of more advanced models that incorporate complex chemical reactions and can cover a wider range of pollutant transport. Such complex models include weather research and forecasting (WRF-Chem) models for atmospheric chemistry and transport. The models were reported to be accurate and efficient in their predictions. For example, Sharma and Dikshit (2016) studied the formation of ozone in the atmosphere using the WRF-Chem model and found that NO_x concentration plays an important role in the formation of ozone. The results strongly correlated with the ground-based measurements for NO_x and ozone. The model was also used to project the future concentrations of ground-level ozone and detected a significant increase in the level of ozone during the burning periods under a business-as-usual scenario (Chatani et al., 2014).

Other studies were conducted using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to evaluate the effects of burning stubble on the quality of air both in India and other parts of the world (Begum et al., 2014; Liu et al., 2018; Sahai et al., 2007), while others used satellite data and analyzed Aerosol Optical Depth (AOD), Fire Radiation Power (FRP) and other related properties to assess the impact of the crop stubble burning on the air quality of India (Kumar et al., 2015; Lohan et al., 2018; Nair et al., 2020).

4.2. Impacts of meteorological parameters on the transport of pollutants

Air pollution varies spatially and temporally depending on the sources and prevailing atmospheric conditions. The pollutant concentration is, therefore, dependent on meteorological parameters such as temperature, wind speed and direction, humidity, precipitation, and atmospheric pressure (Gupta and Cheong, 2006). The assessment of the stubble burning impacts would require the measurement of these parameters alongside the pollutant concentration of the region under study. Several air quality modeling studies using meteorological conditions were conducted over the years ranging from simple mathematical analysis to complex computational models (Cusworth et al., 2018; Jethva et al., 2018; Kumar et al., 2018; Lei et al., 2012; Nair et al., 2020; Singh, 2015). Cao et al. (2008) have demonstrated that wind direction and wind speed influence the transport and dispersion of air pollutants. Lei et al. (2012) modeled the impacts of biomass burning on the air quality of Mexico City and found that the change of air quality is more sensitive to the change in meteorological parameters when compared to variations in altitude and diurnal properties. Liu et al., 2018 inferred that changes in temperature greatly affects the transport and dispersion of air pollutants. Therefore, effective assessment of stubble burning impact and air pollution, in general, requires the incorporation of meteorological parameters of the region under study.

5. Effects of stubble burning

5.1. Effects on air quality

Burning of stubble poses a serious threat to the air quality of the exposed environment. Kaskaoutis et al. (2014) pointed out that air quality is considerably affected by agricultural burning due to the emission of aerosols and gaseous pollutants. $PM_{2.5}$ and PM_{10} are reported to have the highest effect on the health of the exposed population. In 2001, the World Bank conducted a source apportionment study (1st of its kind) on $PM_{2.5}$ for several Indian cities. They discovered that biomass burning contributes 9-28 %, 23-29%, 24%, 37-70% to the $PM_{2.5}$ concentrations in Delhi, Mumbai, Chandigarh, and Kolkata respectively. In 2011, $PM_{2.5}$ concentration, in Delhi, increased by 78% and 43% during the rice and wheat stubble burning periods, respectively (Awasthi et al., 2011). Singh (2015) compared the burning and non-burning periods in Delhi and found a 300 mg/m^3 increase in the hourly concentration of PM_{10} during the burning episodes. In 2015, PM_{10} and $PM_{2.5}$ concentrations increased by 86.7% and 53.2% for rice and wheat burning periods respectively in Mandi-Gobindgarh city, Punjab (Singh, 2015). Kumar et al. (2015) conducted a source apportionment study in Patiala city and discovered that stubble burning contributes about 100-200 μg/m^3 of PM_{10} to the air pollution of the city.

Table 3
Central pollution control board, India's AQI and particulate standards (Central Pollution Control Board, 2014)

AQI Ranges	PM_{10} (24-hr)	$PM_{2.5}$ (24-hr)	Category
0-50	0-50	0-30	Good
51-100	51-100	31-60	Satisfactory
101-200	101-250	61-90	Moderate
201-300	251-350	91-120	Poor
301-400	351-430	121-250	Very Poor
401-500	430+	250+	Severe

Despite not being the main source of pollution, stubble burning is a significant source of air pollution in India. A combination of point and nonpoint sources constitute the composite emissions. These sources include; industries, power plants, vehicles, construction, and indoor emissions (Sharma and Dhiskit, 2016). Guttikunda and Gurjar (2012) found that emissions from industrial sources comprise 15% of CO, 14% of $PM_{2.5}$ and 23% of SO_2, while transportation emissions contain 17% of $PM_{2.5}$, 13% of PM_{10}, 53% of NO_x and 18% of CO. On the other hand, stubble burning emissions are relatively lower comprising of 14% CO and 12% $PM_{2.5}$.

The air quality becomes austere mostly in November of each year across the north Indian states (figure 1) (Mishra, 2019). The air quality of the urban areas is more affected by stubble burning emissions because of the presence of the accumulated pollutants from vehicular and industrial emissions leading to a severe air quality conditions (Mishra, 2019).

The air quality of a region can be categorized in terms of a parameter termed as the air quality index or AQI, which is a range of categorical measurements of the pollution level which helps in interpreting the quality of air in a region on a scale of 0-500 (Table 3) (Central Pollution Control Board, 2014). Most of the regions in North India have AQI beyond the safe limit, especially during the burning episodes. For example, in November 2019, Delhi recorded a peak AQI of 487, Ghaziabad reported an AQI as high as 493, and Greater Noida recorded 480. These AQI values are clearly in the "severe" region as the CPCB AQI (Table 3). This prompted the government of Delhi and other northern states to close schools at primary levels and warned citizens against early morning outdoor exercises (Kapil, 2019).

5.2. Effects on soil fertility

Apart from the effects on air quality, stubble burning also affects soil productivity by burning the essential nutrients inside the soil (Singh et al., 2018). It also raises the soil temperature to about 42 °C, thus displacing or killing the important microorganisms in the soil at a depth of about 2.5 cm (Jain et al., 2014). This generates an additional expense of regaining back the soil fertility through the application of fertilizer or compost. Stubble burning strips the soil of the essential nutrients, i.e. Nitrogen, Phosphorus, and Potassium (NPK) as well as other micro-nutrients. For instance, the burning of rice stubble leads to a loss of about 0.445 Mt of NPK, 0.144 Mt in the case of wheat stubble burning,

A

B

Fig. 1. Pollution in Delhi before and during stubble burning periods; (A): Image of New Delhi during July, 2019. https://www.shutterstock.com (B): Image of New Delhi during November, 2019. https://theenglishpost.com/public-health-emergency-declared-delhi-ncr/

and 0.84 Mt in the case of sugarcane waste burning each year (Jain et al., 2014).

5.3. Effects on agricultural productivity

The effects of burning crop stubble extend to the agricultural sector. There is convincing empirical evidence that air pollution affects food production. The pollutants may affect agricultural productivity directly or indirectly. Direct effects entail injury to leaves, grains, or assimilation of heavy metals. For example, Nitrogen oxide can damage the tissue of plants and cause discoloration. SO_2 may lead to the formation of acid rain which has severe effects on plants and soil, and may lead to plant mortality (Augustaitis et al., 2010). Prolonged exposure of plants to particulates pollution may lead to Chlorosis or Bifacial Necrosis (Ghosh et al., 2019). Indirect effects include the provision of favorable conditions for the growth of pests or diseases. For example, the growth of aphid pests is favored by high concentrations of SO_2 and NO_2 (Ghosh et al., 2019).

Stubble burning releases VOCs and NO_x which combine to form ground-level ozone. Ozone is formed in the immediate atmosphere by the reaction of nitrogen oxide and volatile organic compounds in the presence of solar radiation. Ground-level ozone affects plant's metabolism, penetrates, and destroys leaves causing serious effects on crops in the northern parts of India. Ozone was reported to greatly affect the performance of some crops such as wheat and soy, while crops like barley were known to possess some resistance to the same. Rice and maize were reported to be moderately affected (Sharma et al., 2019). Hence, stubble burning negatively impacts agricultural productivity and needs to be dealt with appropriately to improve agricultural production to meet the increasing food demand.

5.4. Mortality rates

The rates of death as a result of air pollution have been gradually increasing over recent years. For example, in South Asia, the number of deaths attributed to air pollution had increased from 1.1 million to 1.2 million between 1990 and 2015 (Sharma et al., 2019). Dwellers of the Indo-Gangetic Plain (IGP) regions were reported to have lesser life expectancy compared to the other Indian regions with about seven (7) years difference (Kapil, 2019). It was reported that air pollution had increased by about 65% from 1998 to 2016 in the IGP, and the particulate matter concentration in the region was also twice the average levels for other regions in the country (Energy Policy Institute at the University of Chicago (EPIC) 2020)). Particulate matter especially $PM_{2.5}$ is reported to be the most lethal of all the pollutants, and about 50% of India's population is exposed to a high level of the $PM_{2.5}$ with a concentration above the WHO limit (35 $\mu g/m^3$), while about 49% of the exposed population do not have access to good healthcare (Liu et al., 2018). This is why the South Asian countries are characterized by the highest number of premature deaths due to prolonged exposure to high concentrations of particulate matter emissions.

The first and primary target of toxic substances inhaled through the air is the respiratory system causing disorders, cancer, or even death in extreme cases. Prolonged exposure to particulate emissions may lead to an elevated rate of cardiovascular mortality (Saggu et al., 2018).

Estimates on global effects of air pollution have shown that in India, more than 600,000 people die prematurely each year due to exposure to polluted air (Lelieveld et al., 2015; Ghude et al., 2016). The life expectancy of the Delhi inhabitants has decreased by about 6.4 years due to exposure to a high level of pollution (Ghude et al., 2016). Delhi populace could live 9 more years if the WHO standards are met, and 6 more years if the national ambient air quality standards are met (EPIC, 2020). In Pakistan, the air pollution problem is the leading cause of diseases and premature deaths causing the deaths of some 135,000 people each year (Sarfraz, 2020). In India, air pollution had claimed the lives of about 1.24 million people, in 2017, out of which 0.67 million were attributed to particulate matter emissions (Balakrishnan et al., 2011). Also, 51% of the total deaths in India were caused by air pollution most of which were people under 70 years of age (Liu et al., 2018). Cropper et al. (1997) argued that the rate of trauma death increases by about 2.3% when suspended particulate matter concentration rises by 100 $\mu g/m^3$.

5.5. Effects on human health and wellbeing

Many studies have established a link between air pollution and the risk of several health problems especially among children, pregnant women, elderly persons, and people with pre-existing health issues. The harmful effects of exposure to air pollution range from skin and eyes irritation to severe neurological, cardiovascular, and respiratory diseases. In some cases, it may also lead to lethal effects especially when the exposed victim is having pre-existing respiratory problems (Saggu et al., 2018). In chronic cases, exposure to a high level of air pollution may cause permanent health injuries such as the development of lung diseases like asthma, Chronic Obstructive Pulmonary Disease (COPD), bronchitis, lung capacity loss, emphysema, cancer, etc. (Ghosh et al., 2019). Most of the farmers exposed to stubble smoke complain about eye and lung irritation and had spent a considerable amount of money on medical expenses (Kumar et al., 2015).

Fine particulate matter ($PM_{2.5}$) has more effects on humans than the larger sizes, for the former can penetrate through the trachea into the lungs and subsequently to the bloodstream (Ghosh et al., 2019). An epidemiologic study conducted by Saggu et al. (2018) reported a decline of pulmonary and lung function especially in children exposed to a high level of particulate pollution. $PM_{2.5}$ pollution alone accounts for about 21% of the total deaths in the southern part of Asia. Its effects range from a runny nose, coughing, and difficulty in breathing to chronic effects such as asthma and coronary diseases (Ghosh et al., 2019). A study showed that exposure to a high level of particulate emissions may lead to a decrease in the functionality of the human lungs. The effect is more austere in children as prolonged exposure may lead to asthma or chronic pulmonary diseases (Ghosh et al., 2019). Other effects of exposure to polluted air include; tuberculosis, stroke, lung cancer, cardiac arrest, and acute infections in the respiratory system (Saggu et al., 2018).

5.6. Effects on the economic development

Apart from its effects on health and the environment, air pollution also affects the growth of a country's economy. The effectiveness of air pollution management in a country is dependent on the economic and technological development of the country, which implies that increased pollution affects the country's economy in many ways. In recent years, tourists' inflow has decreased in Delhi by about 25-30% due to the increase in the level of air pollution. Ghosh et al. (2019) inferred that the accumulated effects of air pollution cost the economy of India about 4.5 to 7.7 % of its GDP in 2018, and when projected to 2060, the percentage rose to about 15%. The productivity of workers in different disciplines is also affected by air pollution through sickness and poor visibility (Sharma et al., 2019). The World Bank reported that air pollution cost the global economy about $225 billion in 2013 most of which came from the developing countries (World Bank, 2016). The Indian government had delineated the cost of air pollution management and welfare to be around $14 billion annually (Kumar et al., 2015).

The cost of air pollution management and welfare also has an impact on a local scale. For example, the economic benefit of maintaining air quality at a safe limit in a typical household in Kolkata and Delhi was measured to be 950 (about 12.7 USD, assuming 1 USD = 75 rupees) and 2086 rupees (about 27.8 USD) per annum, respectively (Kumar et al., 2015). A similar study was conducted for the city of Kanpur and the rural areas of Punjab, and economic benefit/loss of about 255 and 76 million rupees were reported, respectively (Gupta, 2008; Kumar et al., 2015).

5.7. Effects on climate

Emissions from stubble fires have a direct effect on weather and climate through the release of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) which may potentially lead to global warming (). About 17% to 32% of the total annual greenhouse gas emissions in the world are contributed by the agricultural sector (Bellarby et al., 2008). Ravindra et al. (2018) reported that in 2017, crop stubble burning had resulted in the emission of 171.37 Tg of CO_2, 0.706 Tg of CH_4, and 0.073 Tg of N_2O. Marseni and Qu (2016) stated that India contributes about 12.2% to the global greenhouse gas emissions, which is about 658.823 Tg CO_2 equivalent. It was reported that India lost about 36% of its expected annual wheat yield in 2018, which was linked to the poor quality of air and change in the weather patterns (Ghosh et al., 2019).

6. Legislations and policies

The core administrative bodies regulating emissions and promoting air quality in India are the Ministry of Environment, Forest and Climate Change (MoEF&CC), the Central Pollution Control Board (CPCB), and its subsidiaries at the state level. The board coordinates with the MoEF&CC and other institutions to provide efficient monitoring and control of air pollution-related problems. The major air quality legislation in India is the Air (prevention and control of pollution) Act established in 1982, under which the guidelines for air quality control were clearly outlined. The Air (prevention and control of pollution) Act together with the environmental (protection) Act provides the basis for monitoring air quality across the country. Other guidelines were stated by the Environment (protection) rule, 1986.

In 1994, the Indian government, through the Ministry of Environment and Forest, implemented an Environmental Impact Assessment (EIA) process which covers air quality and other environmental resources and compelled the conduct of the EIA before the execution of medium and large scale projects (including air quality control projects). In 2000, the Government of Delhi under these legislations, compelled the use of compressed natural gas as fuel for public transport vehicles, for it emits lesser pollutants as compared to the gasoline (also known as petrol) (Foster and Kumar, 2011). In 2006, a remediation plan was initiated encompassing 17 cities to mitigate and control air pollution which was reviewed in 2009 to include all the regions in the country. Under this scheme, the CPCB labeled out about half of the industrialized cities as critically polluted areas (Ghosh et al., 2019).

The Indian air quality monitoring program was initiated in 1967 and later established as the National Air Quality Monitoring Scheme (NAQMS). Under this scheme, the number of air quality monitoring stations was increased from 28 (in 1985) to 731 (in 2016) (Ghosh et al., 2019). The stations were designed to measure sulfur dioxide (SO_2), NO_x, $PM_{2.5}$, PM_{10}, and meteorological parameters such as wind speed, wind direction, ambient temperature, ambient pressure, and relative humidity. Other pollutants like lead, ammonia, CO, H_2S, and aromatic hydrocarbons were later added. The national air quality index AQI in India was established on the 17th of November, 2014 by the MoEF&CC under the Swachh Bharat Abhiyan (Clean Air Campaign). It constituted 8 main criteria pollutants namely; PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, O_3, NH_3, and lead (Ghosh et al., 2019).

Delhi high court, on October 8, 2016, compelled the states of Uttar Pradesh, Delhi, Punjab, Haryana, and Rajasthan to execute an exhaustive policy to curb the issue of outdoor stubble burning at their respective provinces. Following this directive, the above states immediately enacted strict policies including fines on the burning of any stubble in their respective states. For example, in Haryana, on 26th November 2016, 1406 farmers were fined a total of 1.375 million rupees after been caught violating the policy (The Indian Express, 2017). In 2017, the Punjab government distributed direct seeders to many farmers which helped in easily incorporating the paddy straws into the soil (Kamal, 2017). The government also proposed to reduce the cultivated area for paddy farming by about 7 Lakh acres by 2020, which is about 10% of the total paddy area cultivated in 2019 (Hindustan Times, 2020).

The Indian government in 2019, established the national clean air program (NCAP) to be implemented in the coming 5 years. The program was focused on bringing down the particulate matter emission to 20-30 % by 2024 taking 2017 as the base year. The program mandates a collaborative and participatory approach between agencies at various levels and all the stakeholders . It was also planned to address the transboundary transport of pollutants, by planting trees, worth 2.3 billion tons of CO_2 equivalent by 2060. Kapil (2019) reported that successful implementation of this goal would increase the average life expectancy of the country's populace by up to 2 years for the IGP residents.

Male' declaration (1998) was focused on the promotion of clean air through the control and prevention of air pollution especially at the trans-boundary level in the southern part of Asia which covers the countries of India, Pakistan, Bangladesh, Nepal, Iran, Srilanka, Maldives, and Bhutan. After about 22 years of establishment, several policies were made by the Indian government but were, however, ineffective in tackling most of the pollution issues (Ghosh et al., 2019).

Table 4
Loss of nutrients due to rice stubble burning in Punjab, India (Kumar et al., 2015).

Nutrient	N	P	K	C
Nutreint Content in Stubble (g/kg)	6.5	2.1	17.5	400
Percentage Lost due to burning (%)	90	25	20	100
Amount lost per hectare (kg/ha)	35	3.2	21	2,400

Fig. 2. A Happy seeder operated for stubble management in Haryana. https://krishijagran.com/farm-mechanization/happy-seeder-tractors-two-seeders-to-stop-crop-burning/

7. Management practices

The best management approach is to tackle the problem at its base through the adoption of precautionary and preventive techniques. Some management practices are presented in the subsequent sections.

7.1. Incorporating the stubble into the soil

The inclusion of the agricultural stubble into the soil is one of the best strategies for managing them. It increases soil fertility and helps in maintaining its organic matter content (Ravindra et al., 2018). Li et al. (2016) reported that incorporating straw into the soil improves its nutrient levels (which would have been otherwise burnt) and enhances its productivity (see Table 4). Another study suggested that incorporating the crop stubble into the soil for 3 weeks before new planting significantly boosts the productivity of crops like wheat. It also increases the carbon content of the soil by about 14-29% (Singh et al., 1996). In some parts of Punjab, about 14% and 9% of rice and wheat stubbles, respectively are incorporated into the soil each year (Kumar et al., 2015). The stubble straws contain the vital nutrients essential for plant growth, i.e. nitrogen, potassium, and phosphorus. Kumar et al. (2015) reported that rice straw in Punjab contains an average of 0.61% nitrogen, 0.18% phosphorus, and 1.38% potassium. Wheat stubble was reported to be better than rice and other cereals as it contains more nutritive constituents beneficial to the plants. However, Ravindra et al. (2018) stated that the same amount of yield as in wheat stubble is obtained when the rice waste is mixed with some quantities of inorganic nitrogen. Additionally, the rice straws may be inoculated with microorganisms to enhance their nutrient levels. Microbial inoculants such as *Azotobacter chroococcum* or *Saccharomyces cerevisiae* have been reported to significantly improve the nutritive value of rice stubble to a level higher than that of the wheat stubble. *Azospirillum brasilense* and *Bacillus megaterium* when inoculated with rice straw, increases the crude protein content in the straw by 13.71% (Zayed, 2018).

The use of mechanized tools such as happy seeders (figure 2) for straw incorporation into the soil has proven effective especially in tilling operations (Singh et al., 2008). These machines can conduct mulching of straw and tillage without significantly disturbing the topsoil (Ravindra et al., 2018). The process of straw incorporation generally boosts soil fertility and increases carbon sequestration. However, the technique requires mechanized tools and/or additional labor, the cost of which cannot be handled by many farmers, especially in the underdeveloped regions within the IGP (Ravindra et al., 2018).

Table 5
Different management techniques for rice and wheat stubble in Punjab, India (Kumar et al., 2015)

Management method	Rice (Percent Total stubble)	Wheat (Percent Total stubble)
Incorporation into soil	1	<1
Fodder	7	45
Rope making	4	0
Burnt	81	48
Miscellaneous	7	7

7.2. Composting

Composting produces nutrient-rich substance (compost) which contains nitrogen (2%), phosphorus (1.5%) and potassium (1.4-1.6%). The compost from agricultural stubble is rich in nutrients and therefore improves the productivity of the soil (Ramasanta et al, 2017). It can improve crop yield by about 4-9 % (Sood, 2013). A popular composting method is the Vermicomposting that generates compost using earthworms which significantly improves the productivity of the soil (Singh et al., 1996). Vermicomposting involves using earthworms and microorganisms to biologically oxidize and stabilize the organic material in the stubble. The vermicompost is a stable and finely divided substance having high porosity and good water holding ability with high nutrient contents that are easily assimilated by the plants (Nghi et al., 2020). Stubble composting is conducted in two stages; anaerobic followed by aerobic process, each conducted for about 40 days (Gummert et al., 2020). The earthworms are introduced during the aerobic stage to effectively condition the substrate and help alter its biological activity. It was found that that stubble from wheat, millet, sugarcane, and pulse generates especially valuable vermicompost when mixed with cow dung (Ravindra et al., 2018).

Another composting technique is the mechanized windrow composting method. This technique uses mechanical aeration with a windrow turner to enhance aeration and speed up the composting process. The compost from this process is also rich in nutrients and was reported to be especially good for vegetables (Gummert et al., 2020).

7.3. Biochar production

Another alternative approach is the production of Biochar from the crop stubble through the process of pyrolysis (Ravindra et al., 2018). Biochar is a finely-divided, carbon-rich, porous substance obtained by subjecting the biomass to a thermo-chemical conversion process with little to no oxygen (pyrolysis) at a temperature of about 350–700°C (Jyothsna, 2019). Biochar can be used for soil sequestration and conditioning which improves the carbon content in the soil and helps remove atmospheric carbon dioxide (Ravindra et al., 2018). Mohammadi et al. (2016) argued that a 38-49% reduction in emissions could be achieved by adopting the local production of biochar from crop stubble in India. The technique of biochar production from agricultural stubble is, therefore, a viable and sustainable option for managing agricultural stubble.

7.4. Use as animal feed (fodder)

This technique has been quite common in India especially with wheat stubble due to its higher nutritional value. It was reported that only around 7% of the rice stubble and about 45% of wheat stubble generated in some parts of Punjab are used as feed for animals (Table 5). The most commonly used crop stubbles are wheat and maize. Rice stubble

Table 6
Power generation potential of crop stubble in South Asian countries (Rahman and Paatero, 2012)

Country	Thermal energy potential from generated crop stubble (PJ/annum)	Electricity generation potential (TWh/annum)
India	1570	113
Pakistan	282	20.4
Bangladesh	230	16.7
Nepal	53	3.83
Sri-Lanka	22	1.56

is not always used because of its lower digestibility and lesser nutrient content (Na et al., 2014). Therefore, the use of wheat stubble as animal fodder could be a sustainable and economically viable technique that, if efficiently used, could potentially mitigate the outdoor burning of stubble.

7.5. Biofuel production

Recently, developments have been made for the utilization of agricultural stubble for biofuel production (Singh et al., 2018). This is a viable option for managing crop stubble which promotes cleaner air and greener environment by directly preventing the release of toxic emissions from stubble burning, and indirectly reducing the use of fossil fuel-based energy. India ultimately depends on imports for automobile fuel spending huge amount of money in its purchase and transportation into the country. A shift from the fossil fuel energy to biofuel produced from lignocellulosic materials such as agricultural stubble is an economically and environmentally viable alternative. Biofuels have recently been gaining global interest due to their lower carbon footprint as compared to fossil fuels. With the first generation (produced from food crops) biofuel having the potential of causing food crisis, lignocellulosic biomass are now gaining the upper hand as a potential feedstocks for biofuel production. These feedstocks have relatively less use and are abundantly available in a substantial quantity (Hiloidhari et al., 2014). The agricultural stubble is a valuable lignocellulose feedstock that can provide substantial raw material for biofuel (bioethanol) production. Hiloidhari et al., 2014 reported that agricultural stubbles, if utilized efficiently, have the potential of fulfilling 17% of the total energy demand in India.

The crop stubble can also be used to generate biogas via anaerobic digestion benefiting the producer with bio-methane and a solid effluent that can be used as compost for plants (Sun et al., 2016). The biogas can be used as fuel for domestic heating, thus reducing emissions from the indoor burning of biomass.

7.6. Energy generation

Agricultural stubble can effectively generate energy via combustion, gasification, or methanation (Shafie, 2016). The stubble can be combusted directly or co-fired with other biomass in a combustion chamber to generate electricity and heat. Air is discharged into the combustion chamber to maintain an appropriate air-to-fuel ratio to achieve complete combustion. The bye-products (bottom ash and fly ash) from this process have economic value as they can be used as blends in the manufacture of cement and bricks or the construction of roads (Kumar et al., 2015).

The agricultural stubble generated in India has the energy potential of 1570 petajoules (PJ) per annum (Table 6). The Ministry of New and Renewable Energy (MNRE), Government of India has installed about 500 power plants across the country fueled either completely or partially by biomass (MNRE, 2016). These power plants contribute about 11.5% of the total renewable energy generation in the country and have a total installed capacity of 8,700.8 MW (MNRE, 2018). Agricultural stubbles form a significant portion of the biomass used in many of these plants. For instance, the 10 MW thermal power stationed at Jalkheri, Fatehgarh Sahib District (established in 1992) is India's first plant focused on the use of biomass for power production. The plant has an estimated total biomass requirement of 82,500 Mt annually at 100% capacity. The farmers (within the plant's vicinity) sell their crop stubble to be used in the plant at 350 rupees/ton (around 5 USD) (Kumar et al., 2015). This plant uses rice husk, waste wood chips, the straw of different plants e.g. paddy, wheat, etc. The project offers additional revenues, through the sale of biomass stubbles, to thousands of farmers and also lessens the discharge of particulates and other gases resulting from the waste burning.

Another plant with an installed capacity of 7.5 MW was established by Malwa power Pvt Ltd. in 2002 at Gulabewella in district Mukatsar, Punjab. The plant was set up to utilize the crop stubble (available in the area) such as mustard and cotton stalks, rice husk, and sawdust. It was designed with an estimated biomass requirement of 72,270 Mt annually to supply 465.1 GWh to the grid within 10 years (2005-2015) (Kumar et al. 2015).

7.7. Bacteria and fungi straw decomposition

Effective decomposition of the crop stubble can replace straw burning. Microorganisms are effective for the degradation of cellulose and lignin present in the straw. The rice straw decomposition restores the fertility of the soil by recovering biomass, nitrogen, and other nutrients and returning them to the soil (Zhao et al., 2019). The aerobic mechanism is of greater significance for most soils than the anaerobic one. Besides rice stubble, other agricultural wastes such as coir pith, banana sheath (dried), sugarcane waste, maize, pulse waste, and cotton stubbles are being decayed by the white-rot fungus (*Pleurotus sp.*). Other commonly used white-rot fungal species are the *Platypus, Djamor*, or *Sajorcaju* (Su et al. 2020).

7.8. Other uses

Scientists have proposed other alternative methods such as the use of stubble as raw material for alcohol refineries, as fodders for mushroom farming, or as fuel for gasification in boilers (Gummert et al., 2020; Kumar et al., 2015; Ravindra et al., 2018). Other approaches that could potentially serve as an alternative to stubble burning and help mitigate the effects caused by the practice include; the production of bio-lubricants, production of nano-silica, and pulp and paper manufacturing (Zhang et al., 2017). The Nano silica can be further used to produce solar cells, nanomedicines, cosmetics, etc. (Zhang et al., 2016).

The use of the crop stubble in the building sector is also a feasible approach as it can be used in making various types of concrete and bricks (Bories et al., 2015; Liu et al., 2017). Bories et al. (2015) asserted that using agricultural stubble in concrete production enhances its compressive strength, bending strength, and hardness. They added that substantial improvement in the thermal properties of fired bricks could be achieved by proportionally using biomass in its production.

7.9. Recommendations

- An extensive awareness program is required to enlighten the farmers on the environmental and economic benefits of using alternative approaches for managing the crop stubble. A survey conducted by Kumar et al. (2015) pointed out that about 90% of the farmers are aware of the health effects of stubble burning, however, they burn it anyway. This may be due to a lack of manpower or incentives from the government or even the farmers' ignorance of the availability of more economical and environmentally friendly alternatives. Most of the farmers who adopted alternative approaches to managing their crop stubble were not incentivized by the government and were not supplied with the materials or machinery to be used in managing the stubble (Kumar et al., 2015). Awareness programs should be developed with an effective means of disseminating information and integrating modern mass media techniques.

- Furthermore, the pulp and paper, construction, biomass, and power industries should be compelled by the government to use the crop stubble as a proportion of their raw materials. This will provide motivation to the farmers as selling the stubble will generate additional income for them.
- Different pollutants may behave distinctly under a unique condition, and a single pollutant may behave differently under various conditions. The development of the appropriate strategy to effectively control air pollution requires a profound understanding of the chemical and physical processes governing the transport, deposition, and dispersion of the pollutants. This brings forth the applicability of air pollution models to simulate the pollutants' behavior under distinct scenarios. Therefore, there is a need for exhaustive and comprehensive models to be used for more accurate and reliable air pollution simulations.
- To efficiently control trans-boundary transport of air pollutants, there is a need for collaboration and effective communication between the national governments of the neighboring countries. International committees should, therefore, be formed comprising members from the concerned countries to discuss and tackle any international air pollution issues that may arise.
- Even though air quality control programs have been more successful in India compared to other south Asian countries, there is still a need for effective enforcement of policies to ensure appropriate compliance among the intended populace.
- There is also a need to expand the NAMP because most of the rural areas (where stubble burning takes place) have not been assessed as most of the stations are situated in urban regions. Exposure to a high level of pollution in these areas proves fatal due to the non-availability of quality health care facilities.
- Another challenge is the lack of enforcement on the existing rules rendering the policies ineffective in most places. This may be associated with the lack of follow-up, insufficient funding, and the non-availability of incentives. Effective enforcement and follow-up should be exhibited by government agencies to ensure intended compliance. Incentives should also be provided to the farmers that adopt sustainable management practices at all levels.
- The lack of collaboration among various institutions involved in the control of air pollution within the country and beyond contributes to the non-attainment of success in the fight against pollution. There is a need to facilitate communication, cooperation, and partnership among national leaders and decision-makers, and to promote the execution of the national action plan, as well as encourage the sharing of knowledge and expertise and recognize opportunities for joint action and cooperation.

Conclusion

The large-scale rice-wheat crop rotation system practiced in India has resulted in the generation of significant quantity of crop stubble often more than the quantity of grains harvested. A considerable portion of these stubbles is usually burnt on-field to clear the farm for the next planting, thus releasing toxic pollutants to the atmosphere which leads to the deterioration of air quality. It may be concluded (based on the existing evidence) that the combined effects of stubble burning emissions and meteorological conditions are the cause of the severity of air quality especially during rice stubble burning episodes in north Indian cities.

The pollutants from stubble burning pose a grave risk to the health of the exposed population as they are linked to several health issues and even death, in severe cases. In addition to atmospheric pollution, stubble burning may also lead to climate change, global warming, and the destruction of soil nutrients. It is, therefore, the need of the hour to implement exhaustive policies to curb this menace at its base.

In contrast to burning, the stubbles can be exploited to yield economically valuable and environmentally friendly substances such as compost or biochar. They can also be used as fuel in power plants, as biomass for biofuel production, as blends for cement/brick production, or as raw materials for the production of pulp and paper. Most of the farmers in North India are not aware of these prolific alternatives and, therefore, consider burning as the best option. This necessitates the need for immense awareness programs to enlighten the farmers about the availability of economically feasible options and the composite effects of stubble burning.

Despite the strict policies and legislations put in place by the Indian government at the federal and state levels to ban the burning practices, the activity continues in most parts of northern India especially in Punjab, Haryana, and Uttar Pradesh. Patriotic compliance with these policies requires effective follow-up with timely and continuous monitoring at all places.

Declaration of Competing Interest

The authors declare no competing interests.

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