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Published in:
Journal of Environmental Management

DOI:
https://doi.org/10.1016/j.jenvman.2022.115104

First published: 15/07/2022

Journal of Environmental Management 314 (2022) 115104

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Crop residue burning in South Asia: A review of the scale, effect, and solutions with a focus on reducing reactive nitrogen losses

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ARTICLE INFO

Keywords:
Biomass
Fire
Soil
Greenhouse gases
Environment
Pollution

ABSTRACT

This paper reviews the literature on crop residue burning - a widespread practice in many regions in South Asia. Specifically, we examine evidence from studies highlighting the scale of the practice in South Asia, the environmental implications, the drivers of the practice and the remedies to the problem. The studies provide evidence that the Indo-Gangetic Plain (IGP) is a hot-spot for atmospheric pollutants, with seasonal crop residue burning being a major contributor. The burning of crop residue is reported to degrade the soil, increase the risk of erosion, and increase the soil temperature, consequently decimating soil microorganisms. This subsequently impacts the monetary cost involved in recovering the soil fertility and the potential for further pollution through the increased use of fertilizer. The review shows that farmers' reasons for burning crop residues are mainly the high cost of incorporating, collecting, transporting, and processing crop residues in South Asia. Labour shortages, the marketability of the crop residue and the short time interval between harvest and next cropping seasons also influence farmers decision to burn crop residue. To address this problem, there is the need to encourage the use of agricultural machines capable of sowing crops in standing stubble, adopting in-situ practices and changing crop varieties to those with short duration. In addition, education and awareness are needed to change beliefs and perceptions on crop residue burning. Crucially, when promoting alternative sustainable uses of crop residue, the economic benefits should be prioritized, and support towards initial investments that accompany the adoption of alternative practices should be provided.

1. Introduction

Most countries in South Asia grow rice, wheat and maize as the main food crops (Gathala et al., 2017). As a result, every year after the harvest season, a huge quantity of crop residues [1] is produced. Some crop residues are often used as animal feed, building materials for houses, cooking fuel for the population and industrial dyes (Hiloidhari et al., 2014; Adhikari and Denich, 2019). However, a large quantity of crop residue which has the potential to be put to alternative sustainable uses is burned across the region (Singh and Kaskaoutis, 2014; Azhar et al., 2019; Das et al., 2020). This practice has a long-term negative impact on the soil, environmental and human health.

1.1. Rationale for the study

The effect of fire on soils differs between soil types. However, there is evidence that the total nutrient pool on agricultural land can be decreased by fire. Fire enhances soil erosion and has a detrimental effect on soil microbes, soil porosity, soil organic matter (Andreu et al., 2001; Santín and Doerr, 2016; Goswami et al., 2020). Across South Asia, several soils-related sustainability issues have consequences for the long-term productivity of agricultural soils (Lal, 2010; Nawaz et al., 2021). For example, the organic matter content of the soil in many areas in Bangladesh and Nepal is below 2%, which is substantially lower than the ideal 4–5% required to sustain productivity over time (Cook et al., 2016).

Also, the Indo-Gangetic Plain (IGP) of South Asia, covering 13.5 million hectares across India, Pakistan, Nepal, and Bangladesh, is a hot-spot of atmospheric pollutants (The Energy and Resources Institute, 2019), with seasonal crop residue burning being a major contributor by up to 70% in PM2.5 and over 40% increase in black carbon concentrations in peak period (Kumari et al., 2021; Ravindra et al., 2021). The Health Effect Institute (HEI) (2020) report ranks South Asia as the global highest population-weighted pollution concentration due to numerous

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https://doi.org/10.1016/j.jenvman.2022.115104
Received 21 October 2021; Received in revised form 16 April 2022; Accepted 16 April 2022
Available online 21 April 2022

combustion sources, including agricultural burning. Also, in Pakistan, the Punjab and Sindh provinces have higher emissions due to intensive agricultural activities (Azhar et al., 2019). Currently, most research is either targeted at local regions or examines crop residue burning problems in individual countries, e.g., Bangladesh, India, Pakistan, and Nepal. However, the consequences of pollution are not always localized. For example, crop residue burning in India affects air quality in Pakistan and vice versa. In a study by Ghosh et al. (2019), a 5-day back trajectory analysis of air was simulated. They found the tendency for transboundary dispersion of pollutants across India, Bangladesh, Nepal, and Pakistan. Similar findings on the transboundary transport of polluted air in South Asia is reported in Yousaf et al. (2021).

Further, the air quality in Nepal, previously ranked 177th in 2016, has dropped to 180/180, making it the worst among the examined countries in 2018. Pakistan, India and Bangladesh ranked 176/180, 178/180 and 179/180, respectively (Environmental Performance, 2020). These statistics also justifies the need for synthesizing the findings of the extant literature.

The objective of the paper is to determine why farmers burn crop residue, highlight the implications, identify sustainable methods of managing crop residue and provide evidence on interventions. The paper addresses the following questions (i) How widespread is crop burning in South Asia? (ii) What are the implications? (iii) What challenges prevent farmers from recycling crop residue? (iv) What are the possible remedies to the problem? (v) What policies, laws, and regulations exist, and how have they performed?

1.2. Why focus on reducing reactive nitrogen losses?

South Asia is one of the hotspots of reactive nitrogen (N) losses, especially from agriculture [2] which has caused severe environmental pollution across the region (Adhya et al., 2016; Rasul, 2016). Although the substantial increment in N pollution from the low levels in the 1960s is mainly from the increase in the use of synthetic fertilizers (Xu et al., 2018), however, crop residue burning also results in substantial loss of reactive nitrogen N (Nitrogen Oxides (NOx), Peroxyacetyl nitrate (PAN), Nitric acid (HNO_3), and nitrate) which otherwise would have been retained in the soil (Kondo et al., 2004; Dey et al., 2020). The removal of crop residues by burning is an unsustainable practice that may increase the need for synthetic fertilizer in subsequent growing seasons (Chen et al., 2014; Chivenge et al., 2020). Besides, there are implications for soil health and productivity and soil water conservation, as discussed in Section 3.2 (Goswami et al., 2020).

In terms of N emissions, for every tonne of rice straw burned, approximately 5.5 kg of Nitrogen is lost (Kaur et al., 2021). Also, 2.09% of N in rice straw is emitted as Nitrous oxide (N_2O) (National Policy for Management, 2014). This loss contributes to Green House Gases (GHGs) emissions from agriculture. It has also been reported that when crop residues are burned frequently, it results in loss of N and carbon (C) up to 15 cm below the topsoil (Bhuvaneshwari et al., 2019). In Punjab alone, the loss of 0.7Mt N year^{-1} is attributed to rice residue burning (Bimbraw, 2019). Notably, among the soil macronutrients, the losses of N from crop residue burning are considerably larger (up to 80%) compared to phosphorus (P) (25%) and potassium (K) (21%) (Mandal et al., 2004).

2. Methodology

The paper is based on a narrative review. However, we followed a protocol to locate all relevant literature. We searched databases (Google Scholar, Scopus and Web of Science) for existing literature using a combination of specific search terms (e.g., crop residue, crop waste, harvest waste, leftover crop, burning, bush burning, farm burning, stubble burning, field fire, South Asia, India, Nepal, Pakistan, Bangladesh, Bhutan, Sri Lanka, Maldives, Bhutan). The search terms were keyed-in individually or in combination using Boolean operators. We screened papers using an inclusion criterion (studies that highlight the scale of the practice in South Asia, the environmental and health implications, the drivers of the practices and the remedies to the problem). The search returned 1960 papers, and after the title, abstract and full-text screening, the 77 papers that met the criteria constituted the review presented in this paper.

Although the country-specific literature is limited in some South Asian countries (for example, Bhutan, Maldives, and Nepal) compared to others (for example, India and Pakistan), this is not necessarily equivalent to crop residue burning practised less in the countries where such studies are scarce. One could postulate that the lack of papers in some countries could be that environmental pollution from crop burning does not take centre stage in discussions in such countries. Or it could be the existence of regulations that led to the assumption that the practice has been curtailed (which may not necessarily be the case). It could also be that the assumption is that the contribution of crop residue burning to environmental pollution within the country is low, and those from neighbouring regions are localised (i.e., failing to consider the transboundary transport of pollutants).

3. Review of empirical findings

3.1. How widespread is crop burning in South Asia?

In India, rice, wheat and sugarcane are the major crops residues burnt (Jain et al., 2014), with rice residue as high as 80% of the total produced (Kumar and Singh, 2021). According to Jain et al. (2014), in 2009, 0.620 Gigagrams (Gg) of crop residue was generated, and approximately 16% was burnt across farms. This is corroborated by Bhuvaneshwari et al. (2019) report that about 0.092 Gg of crop residue is burned in India each year. Rice straw made up 40% of the total residue burnt, while wheat straw and sugarcane residue constituted 22% and 20%, respectively. In Pakistan, wheat constituted 48%, rice straw and sugarcane residue 23% each, while maize straw accounted for 6% of crops residues burnt (Azhar et al., 2019).

Between 2000 and 2014, the total quantity of crop residue from these four crops was 757000 Gg, of which about one-third, i.e., 228000 Gg, was burnt in the field. Over this period, 52% of the total residue generated was from wheat, 24% from rice, 20% from sugarcane and 4% from maize. In 2014 alone, the total crop residue of maize, rice, sugarcane and wheat in Pakistan was 62470 Gg, of which 20000 Gg was burned. (Azhar et al., 2019). In Nepal, the total crop residue open burning was estimated at 2280 Gg in 2003/04, which increased to 2908 Gg by 2016/17, indicating that up to 25% of crop residue was burnt in the period (Das et al., 2020). In Bangladesh, rice residue comprises 70% of the total yearly crop residue produced and mostly the Aman rice burned (ASB, 2008; Haider, 2013).

The peak is usually during the post-monsoon season, when large scale crop residue burning takes place in the Indo-Gangetic Plains (IGP) (Kaskaoutis et al., 2014; Anjum et al., 2021). Azhar et al. (2019) studied the spatial and temporal patterns of crop residue burning across Pakistan and found emissions increased in June, February and November following harvest. Similarly, Das et al. (2020) found that in Nepal, over 80% of air pollutants (CO_2, CO, CH_4, SO_2, PM2.5, NOx, NMVOC, NH_3) were produced between February and May, mainly from the burning of crop residue.

The emission of the different air pollutants attributed to crop residue burning is non-uniform across states in India as it depends on the type of crop residue burnt. However, Punjab, Uttar Pradesh, Haryana and Maharashtra were on top of the list of regions with a high incidence of crop burning (Jain et al., 2014; Shyamsundar et al., 2019; Kaushal and Prashar, 2021). Similarly, in Pakistan, the heterogeneity that exists in each crop residue generation across regions results from varying cropping patterns, cropping intensity and productivity (Azhar et al., 2019). The Indian agriculture sector accounts for 12.2% of the total global GHG emissions (CO_2, N_2O, CH_4) from agriculture (Maraseni et al., 2018). The estimated emission from the crop residue burning was 73.35 Gg/yr for

N_2O in 2017 (Ravindra et al., 2019).

The two groups of pollutants from crop residue burning are gaseous (SO_2, NO_X, CO_2, CO, CH_4, N_2O etc.) and particulate matter (PM10, PM2.5, and PM1.0, BC, OC). In Pakistan, Azhar et al. (2019) found that between 2000 and 2014, there was a rise in CO emissions in Pakistan by 40% at an average annual rate of 2.7%, i.e., from 1160 Gg to 1630 Gg. Pakistan has also witnessed a rise in emissions of between 37% and 63% of CO_2, CH_4, NMVOCS, N_2O, NH_3, SO_2, NOx, PM2.5, PM10, OC and BC between 2000 and 2014 (Azhar et al., 2019).

In India, it is estimated that of the 488 Mt of crop residue produced in 2017, 24% was burnt on the farm. This resulted in emissions of 211000 Gg of CO_2 equivalent GHG (CO_2, CH_4, N_2O) (Ravindra et al., 2019). Following current trends, there are predictions that crop residue burning emissions will increase by 45% in 2050 (Ravindra et al., 2019). In Nepal, the total emissions from crop residue burning for 2016/17 were approximately 4140 of CO_2 (56–144%), 154 of CO (4–196%), 6.5 of CH_4 (7–193%), 1.2 of SO_2 (60–140%), 24.5 of PM2.5 (30–170%), 8.6 of OC (38–162%), 2.2 of BC (-1-201%), 7 of NOx (54–146%), 22.5 of NMVOC (8–192%) and 2.7 of NH_3 (3–197%) Gg yr^{-1}. Over 86.16% of the total emissions coincided with the period just after harvest (Das et al., 2020).

In summary, Fig. 1 highlights the scale of crop residue burning in South Asia in the past five decades. Compared to other regions globally, the practice has increased over the period, with the statistics suggesting that South Asia is a major hotspot for pollution from crop residue burning. This finding is corroborated by Sarkar et al. (2018), who used both satellite and ground-based sources and reported an increasing impact of crop residue burning in the Indo-Gangetic Basin.

3.2. *The implications of crop residue burning*

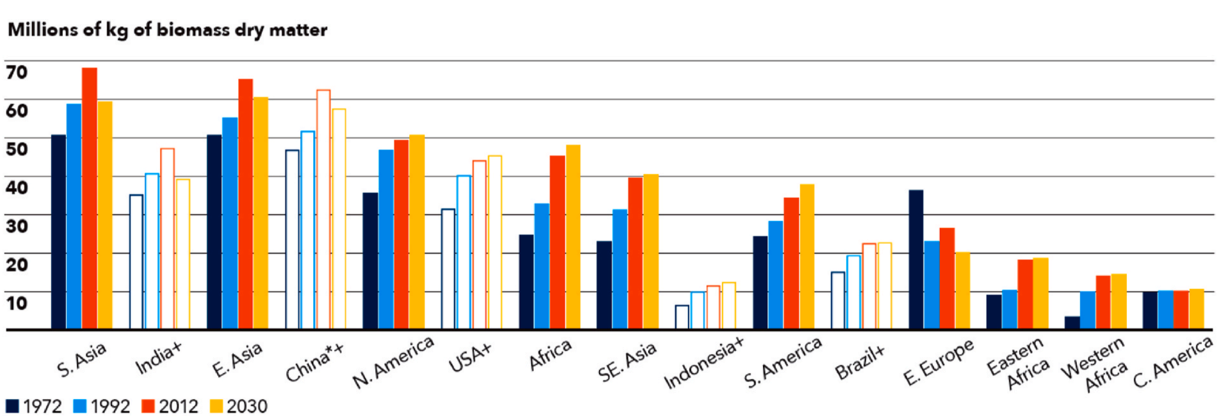
This paper does not delve into reviewing the science of how crop residue burning affects the environment, as this has been discussed in previous studies (e.g., Kumari et al., 2018; Mathur and Srivastava, 2019; Kumari et al., 2020). Rather we focus on the negative environmental impact of the practice on the soil. Burning of crop residue increases the soil temperature to about 42 °C, consequently decimating soil micro-organisms up to a depth of about 2.5 cm (Jain et al., 2014). This subsequently impacts the monetary cost involved in recovering the soil fertility, as well as the potential for further pollution through the increased use of fertilizer.

Burning of rice residue results in a loss of almost all C, leading to a drop in C sequestration (Singh et al., 2020), a loss of 90% of N, 60% of S and 20–25% of P and K as well as other micro-nutrients (Dobermann and Fairhurst, 2002). In India, the burning of rice straws, wheat and sugarcane stubble results in a loss of about 0.45 Mt, 0.144 Mt and 0.84 Mt of NPK annually, respectively (Jain et al., 2014). The burning of crop residues degrades the soil structure and increases the risk of erosion (Sarkar et al., 2020). Gupta et al. (1994) assessed soils with residues burned, retained, and a combination of burned and retained residue in respect to their ability to improve soil organic matter and carbon and nitrogen availability. The results showed that residue retention significantly increased the amounts of mineralizable C and N compared to the alternatives, and soil organic matter, total nitrogen, carbon/nitrogen ratios were affected by the long-term burning of crop residues.

The VOCs and NOx produced from burning crop residue create ground-level ozone, which affects the metabolism of crops and destroys leaves, causing crop losses (Abdurrahman et al., 2020). Besides, it alters the ecosystem by providing suitable conditions for the growth of pests or diseases. For example, the increase in concentrations of SO_2 and NO_2 from burning are suitable for aphid pests to thrive (Ghosh et al., 2019).

In South Asia, the second most important risk factor for ill-health is exposure to air pollution (Krishna et al., 2017). Considering the increased risk to ambient air quality and spatiotemporal extent of pollutants since 2010, it poses a severe health threat to the population of these regions. Across South Asia, air pollution is reported to contribute to exacerbating asthma, bronchitis, emphysema, cardio-pulmonary disorders and lung cancer (Ahmad, 2002; Saggu et al., 2018; The Energy and Resources Institute, 2019). According to Chakrabarti et al. (2019), residing in regions in India where crop residue burning is prevalent increases the risk of acute respiratory infection by three times. Besides, the effect of crop residue burning on respiration health is heightened among children (Chakrabarti et al., 2019; Gupta, 2019). Gupta (2019) conducted an epidemiological study on 150 children across India and found that the short-term rise in suspended PM from crop residue burning results in a significant deterioration in health after exposure and is likely correlated with triggering disorders like cognitive impairments and neurological complexity in children. This aligns with the findings from Awasthi et al. (2010) study examining the effects of agriculture crop residue burning on children on pulmonary function tests in Northwest India.

Also, evidence suggests that the increase of up to 10% in hospital visits in the north Indian province of Punjab during the harvest season is linked with the burning of crop residue (Singh et al., 2008). Region-wise, it is estimated that exposure to air pollution accounts for between 13% and 21% of all deaths in South Asia (Krishna et al., 2017). The limited number of studies examining the health effects of air pollution in other South Asian countries has been highlighted in several reviews (e.g., Kurmi et al., 2016). Nevertheless, there is data that suggests that in Nepal, respiratory diseases is one of the main reasons for outpatients' consultations in 2013/14 (Ministry of Health and Population, 2014a), and chronic obstructive pulmonary disease is one of the leading causes of mortality among inpatients (Ministry of Health and Population,



Source: Based on FAOSTAT data. ***Note:*** Burning of residues, as measured by kilograms of biomass dry matter from rice paddy, maize, wheat, and sugarcane production. *Mainland China. +Overlaps with other categories shown in chart.

Fig. 1. Burning of crop residues measured as biomass dry matter (Cassou, 2018).

2014b). Prolonged exposure to air pollution results in an increased risk of mortality. As of 2012, the estimated death from air pollution in South Asia was 5 million, which constituted about 22% of the region's total deaths (Abdurrahman et al., 2020).

In monetary terms, Kumar et al. (2015) study on the health effects of air pollution in rural Punjab in India reveals that the total annual welfare loss with respect to health damages arising from exposure to pollutants from crop residue burning is approximately Rs 76 million. This excludes other costs such as productivity losses due to being sick. It is estimated that the annual economic cost of exposure to air pollution from crop residue burning in Punjab, Haryana and Delhi alone at US$ 30 billion (approximately Rs 2 lakh crore) (Businesstoday, 2019). Regarding the reduction in yield and nutrient loss, Bimbraw (2019) reports that it is approximately Rs 500 crore per year in India.

3.3. What challenges prevent farmers from putting crop residue to sustainable use?

With increased mechanization of harvesting, such as combined harvesters, crop residues are unevenly spread across the harvested plots and left in the field, making residue recovery difficult (Gupta, 2010). Besides, combined harvesters leave behind taller crop residue (about 1–2 ft tall) compared to manual harvesting, where the crops are cut close to the base (leaving behind stalks of less than 6 inches) (Mohanty, 2020). Farmers are also time-constrained between harvesting one crop and sowing the next. Specifically, this could be as small as 7–10 days as this cropping pattern maximize economic returns (Kumar and Singh, 2021).

The cost involved in collection and transportation, and recycling crop residues is a concern for many farmers. This is increasingly the case as crop production, and the subsequent volume of excess residues has increased over the years. Given the volume of residue post-harvest, off-site residue management is currently not economically viable (Lohan et al., 2018). In Pakistan, it is estimated that removing the crop stalks and stubble manually increases the farmer's costs up by over a third (Irwin, 2015). Ahmed et al. (2015) estimate crop residue removal cost to be up to 35% higher than burning. Similarly, Haider (2012) found that the farmers' profit can fall by up to US$ 111 per hectare when the cost of removing the residue is taken into account. Besides the costs of labour and machinery to retain and incorporate in-situ, the crop residue is beyond the reach of many farmers.

Farmers also believe that crop residue burning is crucial to controlling weeds and pests through direct destruction or by altering their natural habitat (Pathak et al., 2011; Satyendra et al., 2013). Also, farmers believe that the soil nutrient gains in terms of potassium in the ash for the next crop cycle (Irfan et al., 2014). Although this may be true in the short term, the consequences of loss of other important nutrients and organic carbon outweigh the short-term benefit. Crop residue burning is also credited to improving plough preparation for the next crop.

Rice straw had low nutritional value and high silica content, so it is not used as animal feed (Bisen and Rahangdale, 2017; Kaushal, 2020). Besides, the conversion and loss of common grazing lands result in fewer farmers keeping animals that would otherwise use the straw as fodder or bedding (Joshi, 2020). Other reasons for burning crop residue are the lack of or unreliable market for the stalks and stubble (Kaur, 2017). In addition, the low financial returns from the crop residue have been reported to negatively influence crop residue burning decisions (Haider, 2012). Besides the seasonal shortage of labourers or cost of wages (Gupta, 2014) and the lack of understanding of the adverse effects of residues burning or unawareness about specific air pollution-related health implications and GHG pollution also drive the practice (Grover et al., 2015; Bajracharya et al., 2021).

Other farm and farmer characteristics have been identified as drivers of crop residue burning in South Asia. Larger farms tend to produce more residue. Farmers with no (of few) livestock cannot use residues as feed or bedding. Those farmers whose farms are further away from their homes are less likely to collect residue for biofuel. All these factors influence the decision to burn crop residue (Ahmed et al., 2015; Rafiq et al., 2019; Ahmed and Ahmad, 2019; Bajracharya et al., 2021).

Also, there are findings that suggest crop residue burning decreases among older farmers and farm owners. In addition, a farmer's wealth and neighbourhood effect [3] increases the tendency to burn crop residue (Lopes et al., 2020). In other words, farmers have been found to burn crop residue because their neighbours do so. The effect of wealth on crop residue burning may be correlated with larger farm size. Other important factors are education and having a better understanding of environmental consequences or experiencing health problems related to pollution (Raza et al., 2019).

3.4. Possible remedies to the problem

Agricultural machines such as Zero till seed drill and Happy Seeder can sow crops in standing stubble. Also, rotavators are useful in incorporating crop residue in the soil. Similarly, the Paddy Straw Chopper reduces the stalk and stubble to sizes that are quicker to compost. Some studies suggest that the Happy Seeder can increase profit on average by US$85–160 per hectare while reducing GHGs that would otherwise arise from crop burning by more than 78% (Shyamsundar et al., 2019; Keil et al., 2020). However, the cost of owning and operating these machines is prohibitive for many farmers in South Asia. Therefore, reducing rental costs, subsidizing fuels and having more machines available is necessary to encourage its use.

Adopting in-situ practices such as No-till conservation agriculture or simply incorporating crop residues into the soil is highly sustainable and eco-friendly (Badarinath et al., 2006). Soils benefit from nutrients, i.e., nitrogen, phosphorus, and sulphur, topsoil formation and organic materials improvements when crop residue is returned to the soil through decomposition. This, in turn, prevents runoffs and erosion, which reduces the risk of nutrient losses and the need for synthetic fertilizer. Also, producing biochar from crop residues is sustainable. Biochar applications improve soil fertility, sequester carbon, increase biological nitrogen fixation (BNF) when combined with legumes, and improve fertiliser use efficiency (Rondon et al., 2007; Mohan et al., 2018). It is estimated that in India alone, up to US$ 10 M in fertilizer value could be saved annually by converting paddy residue to biochar (Charvesting, 2016). Besides, biochar from crop residue nutrients can produce nitrogen between 0.3 and 3.2 g/kg (Khare et al., 2021).

Kashif et al. (2020) highlighted the potential for generating renewable energy from crop residue in the region. This includes the production of biogas, bioethanol and alternative fuel (Kumar and Singh, 2021). In addition, there is the potential for briquettes and pellets made from rice straw to substitute coal in thermal power plants. Crop biomass accounts for 10% of the total energy production of India (Ravindra et al., 2019); hence there is scope for its use to be expanded. In Pakistan, Kashif et al. (2020) estimate that about 11,000 MW of electricity could be generated using crop residue derived biomass.

More short-duration varieties need to be introduced to address the issue of time between harvest and sowing. This will allow the crop residue to decompose or be incorporated into the soil. The private sector could also take the lead on linking farmers with markets where they can sell crop residue. This linkage will prove that crop residue can be a profitable and valuable source of additional income.

Currently, there are eco-friendly and economically viable methods of converting rice straw into pulp that can be used in producing paper (Rodríguez et al., 2010; Kaur et al., 2017) or for bioplastics and sustainable packaging materials (Sain, 2020). Furthermore, scaling such use on crop residue will address the lack of market for crop residues and provide financial returns to farmers. Thus, generating a circular production chain from crop residue has previously been treated as waste.

Either laboratory or home formulated bio-decomposer solutions containing microorganisms that stimulate and enhance in-situ composting of the crop residue (Srinivasan and Abirami, 2020) need to be made available and affordable. One example is a crop-residue decomposer available to farmers in India at approximately ₹20 in solution, which can potentially decompose about 10,000 metric tons of crop residue in 30 days after spraying (Wangchuk, 2019).

It has been recommended that there be some sort of reward or recognition for farmers who voluntarily quit the practice of crop residue burning. Rafiq et al. (2019) suggest that farmers that completely remove or incorporate crop residues should benefit from a compensation mechanism similar to Payment for Ecosystem (PES), considering that these alternatives involve high cost. Ahmed and Ahmad (2013) found that in Pakistan, PKR 674–908 (US$ 8–11) per acre is the amount of subsidy required to incentivize farmers to end the practice of crop residue burning.

Education and awareness are needed to change beliefs and perceptions on crop residue burning. This can be in increased awareness of alternative methods, highlighting the public and private gains from adopting these alternatives. In some cases, farmers feel that their singular action has no significant impact. According to Lopes et al. (2020), farmers take into consideration the private costs and benefits of crop residue burning but not its external social costs. There may be a need for group sensitisation to help farmers grasp the scale of the consequences of continued crop residue burning. Giving farmers tangible evidence, e.g., by organising field visits to farms that have visibly benefited from using crop residues sustainably, could also be useful. Highlighting the economic case for better crop residue management is crucial.

In Fig. 2, we summarize the drivers, effect and solutions to crop residue burning that we have discussed in section 3.

3.5. Where laws and regulations exist, how have they performed?

Governments have not ignored the poor air quality across countries in South Asia. In 1998 a declaration on control and prevention of air pollution and its likely transboundary effects for South Asia was adopted by the Governing Council of the South Asia Co-operative Environmental Programme (SACEP). The declaration stimulated discussions on the need for countries to carry forward or initiate studies and programmes on air pollution in each country of South Asia. Since then, several policies have been put into action by governments across South Asia.

In terms of policies specific to crop residue management, none of the South Asian countries (except for India) has formulated a National Policy for Management of Crop Residue (NPMCR) (SAARC, 2019). In India, this policy was formulated in 2014 to promote the technologies for optimum utilisation and in-situ management of crop residue and encourage diverse uses of crop residue. Much recently, the Indian government rolled out a crop residue management scheme costing US$164 million to incentivize farmers in the northern states to quit the practice of burning crop residue. Individual farmers and cooperatives benefit from 80% to 50% financial assistance respectively towards purchasing machines for in-situ management of crop residue. However, there are concerns those small and marginal farmers may not benefit even after the subsidies as the cost remains well beyond their reach (Kumar and Singh, 2021). The Indian government has also established the national clean air program (NCAP), which will include an extensive drive against open burning to reduce PM2.5 pollution by 20–30% by 2024 compared to 2017 across several cities (Ganguly et al., 2020).

In some regions, fines or stiffer penalties such as jail terms have been introduced for non-compliance. For example, in Rajasthan, Punjab and Haryana, fines ranging from (US$35 to 210) was imposed on those that

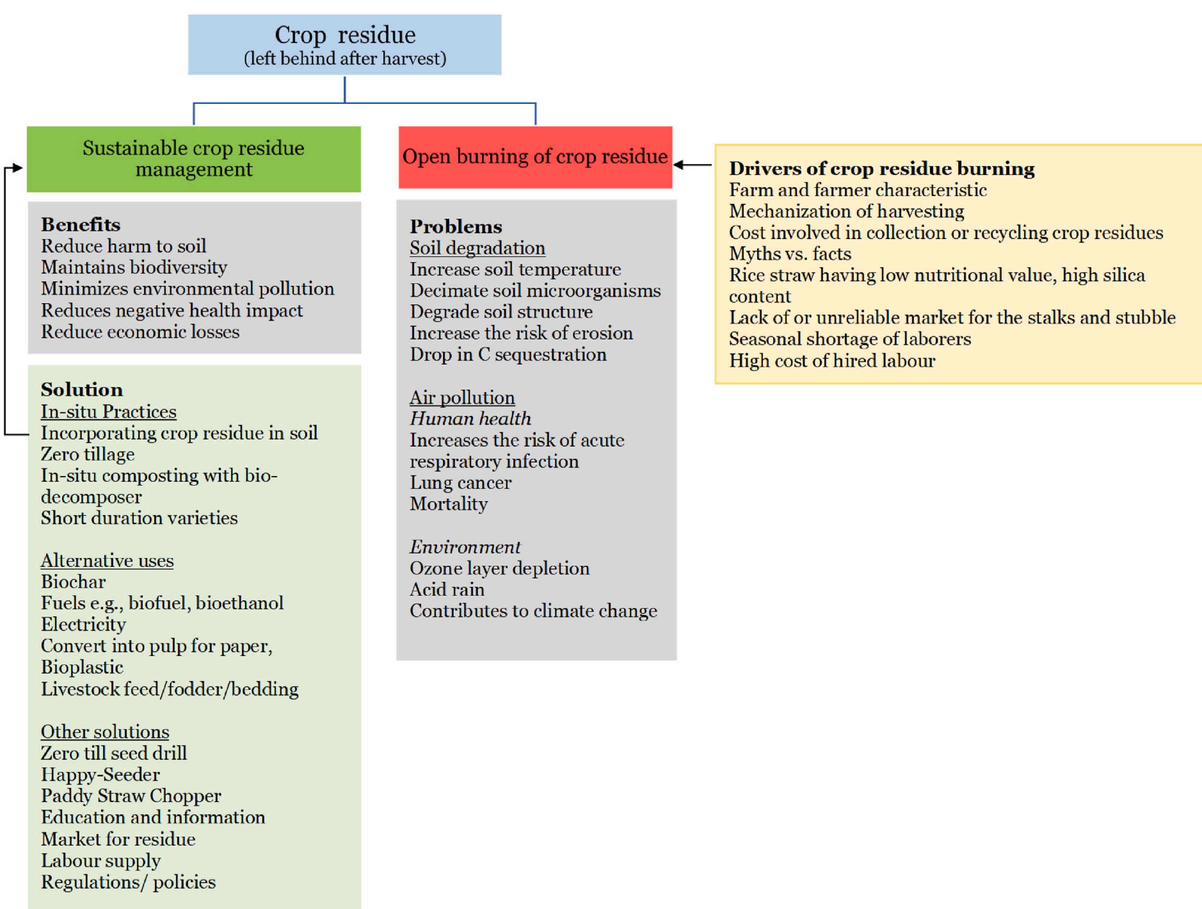


Fig. 2. Summary of the drivers, effect and solutions to crop residue burning.

engaged in crop-burning (Bhuvaneshwari et al., 2019). However, penalties have not been effective either as many of the poorer farmers prefer to take the risk of burning their crop residues. In Pakistan, there are indications that from the government's point of view, stubble burning is next to non-existent as there has been a ban, which is reportedly fully implemented (Jalil, 2019). As such, the consensus is that the air pollution from crop residue burning is from the transboundary dispersion of pollutants.

Overall, the evidence suggests that these policies have not fully met their goals of addressing air pollution (Ghosh et al., 2019; Abdurrahman et al., 2020). Despite the existing regulations, the burning of crop residue has not ceased. This is partly due to uncertainty regarding policy implementation, partial enforcement, and issues around access to and concerns about returns to alternative technologies (Shyamsundar et al., 2019). Further, Shyamsundar et al. (2019) postulate that the reluctance to enforce existing policies could be attributed to the lack of affordable and profitable alternatives to burning crop residue. Besides, the alternatives were not feasible and capable of scaling to adoption by a huge farming population. Crucially, for policies to be efficient, the farmer - main stakeholder, must be involved in the design and implementation. Besides, the lack of a database or scant specific guidelines and policies for the proper management of the residue (as highlighted in Haider, 2013) needs to be addressed.

3.6. Summary of identified gaps and suggested research agenda

Understanding the scale and effect of agricultural fires is crucial to preventing further harm to soils and reducing pollution in South Asia. This review highlights some research gaps. To attain a more profound understanding of the effect of agricultural fires, there is the need for more studies that analyse the air pollutant concentrations during post-monsoon and winter seasons in the IGP and investigate the extent to which the high episode during these seasons is caused by crop residue burning. In addition, more studies should focus on providing further evidence and clarity on the solutions to the problem, for example, examining the impact of the duration of incorporating residue before planting has on N immobilisation. Similarly, a deeper understanding of farmers soil management attitudes and environmental perceptions is required. We also find evidence of regulatory issues in addressing agricultural fires. With the increase in regulations, more studies should focus on mapping the trend of crop residue burning to the duration when regulations are implemented to provide a holistic picture of its impact. Overall, there is a need for more studies on the topic in Bhutan, Maldives, and Nepal, considering that the country-specific literature is limited.

4. Concluding comments

In most South Asian countries, the main source of biomass burning is from crop residues which have significant environmental and health consequences. Farmers perceive burning as a quick and inexpensive way to get rid of unwanted crop residue. Among other factors, shortage in the agricultural workforce exacerbates the problem. This review highlights the negative impact of environmentally unfriendly agricultural practices on regional air quality, soil and public health. Notably, reducing pollution from agriculture in general and specifically eliminating crop residue burning remains challenging due to the number of actors involved and the spatially variable and temporally dynamic nature of the pollution load from different pollutant sources. However, proper management of crop residue to reduce the environmental footprint from agriculture in South Asia is one step in the right direction. There is a need for a holistic understanding of the factors that motivate farmers to adopt alternative sustainable practices to ensure that the efforts to eliminate crop residue burning are more cost-effective and adaptable.

Notes

1. Crop residue, which mainly refers to straw, stubble, leaves, and seed pods, is often treated as harvest waste. They are the residue left in farmers' fields after harvesting valuable economic components and processing crops into useable resources.
2. Numerous studies (e.g., Atapattu and Kodituwakku, 2009; Takeshima, 2020) discussed the agricultural sector in each country in South Asia. Thus, we did not repeat the discussion in this paper.
3. Neighbourhood effect, as implied in this context, refers to 'herd' behaviour dependent on neighbouring farmers crop residue management practice.

Funding

The time author TB spent contributing to this paper results from funding by UKRI under the South Asian Nitrogen Hub (SANH). The project team includes partners from across South Asia and the UK. Neither UKRI nor any of the partner institutions are responsible for the views advanced here.

Credit author statement

Muyang Lin: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization. **Toritseju Begho**: Conceptualization, Writing – review & editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abdurrahman, M.I., Chaki, S., Saini, G., 2020. Stubble burning: effects on health & environment, regulations and management practices. Environ. Adv. 2, 100011.
Adhikari, N.P., Denich, M., 2019. Potential of crop residues for energy production in Nepal. J. Inst. Eng. 15 (3), 9–15.
Adhya, T.K., Pathak, H., Raghuram, N., AbrolY, P., 2016. Reactive nitrogen assessment in South Asia. Curr. Sci. 111 (5), 10. https://initrogen.org/sites/default/files/Adhya%20et%20al_Reactive%20nitrogen%20assessment%20in%20South%20Asia%20%282016%29%20Current%20Science_0.pdf.
Ahmad, K., 2002. Pollution cloud over south Asia is increasing ill health. Lancet 360 (9332), 549.
Ahmed, T., Ahmad, B., 2013. Burning crop waste in Punjab, Pakistan—can farmers do better for themselves and the environment? SANDEE Policy Brief, 71-13.
Ahmed, T., Ahmad, W., 2019. Burning crop residue: farmers' choice among various practices. Pakis. J. Appl. Econ. 29 (2), 265–290.
Ahmed, T., Ahmad, B., Ahmad, W., 2015. Why do farmers burn rice residue? Examining farmers' choices in Punjab, Pakistan. Land Use Pol. 47, 448–458.
Andreu, V., Imeson, A.C., Rubio, J.L., 2001. Temporal changes in soil aggregates and water erosion after a wildfire in a Mediterranean pine forest. Catena 44 (1), 69–84.
Anjum, M.S., Ali, S.M., Subhani, M.A., Anwar, M.N., Nizami, A.S., Ashraf, U., Khokhar, M.F., 2021. An emerged challenge of air pollution and ever-increasing particulate matter in Pakistan; a critical review. J. Hazard Mater. 402, 123943.
ASB, 2008. Banglapedia 2008. Asiatic Society of Bangladesh (ASB). Edited Version'.
Atapattu, S.S., Kodituwakku, D.C., 2009. Agriculture in South Asia and its implications on downstream health and sustainability: a review. Agric. Water Manag. 96 (3), 361–373.
Awasthi, A., Singh, N., Mittal, S., Gupta, P.K., Agarwal, R., 2010. Effects of agriculture crop residue burning on children and young on PFTs in North West India. Sci. Total Environ. 408 (20), 4440–4445.
Azhar, R., Zeeshan, M., Fatima, K., 2019. Crop residue open field burning in Pakistan; multi-year high spatial resolution emission inventory for 2000–2014. Atmos. Environ. 208, 20–33.
Badarinath, K.V.S., Chand, T.K., Prasad, V.K., 2006. Agriculture crop residue burning in the Indo-Gangetic Plains–a study using IRS-P6 AWiFS satellite data. Curr. Sci. 1085–1089.
Bajracharya, S.B., Mishra, A., Maharjan, A., 2021. Determinants of crop residue burning practice in the Terai region of Nepal. PLoS One 16 (7), e0253939.
Bhuvaneshwari, S., Hettiarachchi, H., Meegoda, J.N., 2019. Crop residue burning in India: policy challenges and potential solutions. Int. J. Environ. Res. Publ. Health 16 (5), 832.

Bimbraw, A.S., 2019. Generation and impact of crop residue and its management. Curr. Agric. Res. J. 7 (3), 304. https://doi.org/10.12944/CARJ.7.3.05.

Bisen, N., Rahangdale, C.P., 2017. Crop residues management option for sustainable soil health in rice-wheat system: a review. Int. J. Chem. Stud. 5 (4), 1038–1042.

Businesstoday, 2019. Air Pollution from Stubble Burning Costs India $30 Billion Annually: Study (Businesstoday. Retrieved on 24 June 2021 at. https://www.businesstoday.in/current/economy-politics/air-pollution-from-stubble-burning-costs-india-30-billion-annually-study/story/324299.html.

Cassou, E., 2018. Field Burning. Agricultural Pollution. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/29504.

Chakrabarti, S., Khan, M.T., Kishore, A., Roy, D., Scott, S.P., 2019. Risk of acute respiratory infection from crop burning in India: estimating disease burden and economic welfare from satellite and national health survey data for 250 000 persons. Int. J. Epidemiol. 48 (4), 1113–1124.

Charvesting, 2016. Eliminate Rice Field Burning in Haryana and Punjab to Ultimately Reduce Air and Water Pollution in Delhi. https://www.climatefoundation.org/charvesting.html.

Chen, B., Liu, E., Tian, Q., Yan, C., Zhang, Y., 2014. Soil nitrogen dynamics and crop residues. Rev. Agron. Sustain. Develop. 34 (2), 429–442.

Chivenge, P., Rubianes, F., Van Chin, D., Van Thach, T., Khang, V.T., Romasanta, R.R., et al., 2020. Rice straw incorporation influences nutrient cycling and soil organic matter. In: Sustainable Rice Straw Management. Springer, Cham, pp. 131–144.

Cook, S., Henderson, C., Kharel, M., Begum, A., 2016. Collaborative Action on Soil Fertility in South Asia: Experiences from Bangladesh and Nepal. IIED, London. http://pubs.iied.org/17600IIED.

Das, B., Bhave, P.V., Puppala, S.P., Shakya, K., Maharjan, B., Byanju, R.M., 2020. A model-ready emission inventory for crop residue open burning in the context of Nepal. Environ. Pollut. 266, 115069.

Dey, D., Gyeltshen, T., Aich, A., Naskar, M., Roy, A., 2020. Climate adaptive crop-residue management for soil-function improvement; recommendations from field interventions at two agro-ecological zones in South Asia. Environ. Res. 183, 109164.

Dobermann, A., Fairhurst, T.H., 2002. Rice straw management. Better Crop. Int. 16 (1), 7–11.

Environmental Performance, 2020. Index (EPI). Yale University and Columbia University, New Haven, CT, USA. https://epi.yale.edu/epi-indicator-report/AIR.

Ganguly, T., Selvaraj, K.L., Guttikunda, S.K., 2020. National Clean Air Programme (NCAP) for Indian cities: review and outlook of clean air action plans. Atmos. Environ. X, 100096.

Gathala, M.K., Jat, M.L., Saharawat, Y.S., Sharma, S.K., Singh, Y., Ladha, J.K., 2017. Physical and Chemical Properties of a Sandy Loam Soil under Irrigated Rice-Wheat Sequence in the Indo-Gangetic Plains of South Asia.

Ghosh, P., Sharma, S., Khanna, I., Datta, A., Suresh, R., Kundu, S., Goel, A., Datt, D., 2019. Scoping study for South Asia air pollution. Energy Resour. Inst. 153. https://www.gov.uk/dfid-research-outputs/scoping-study-for-south-asia-air-pollution.

Goswami, S.B., Mondal, R., Mandi, S.K., 2020. Crop residue management options in rice–rice system: a review. Arch. Agron Soil Sci. 66 (9), 1218–1234.

Grover, D., Kaur, P., Sharma, H.R., 2015. Possible reasons and farmers awareness towards crop residue burning: an overview and a case study from Mirzapur village of Kurukshetra district, India. Environ We Int J Sci Technol 10, 75–85.

Gupta, R., 2010. The economic causes of crop residue burning in Western Indo-Gangetic plains. In: Conference Held at. Indian Statistical Institute, Delhi centre, pp. 1–26.

Gupta, R., 2014. Low-hanging fruit in black carbon mitigation: crop residue burning in South Asia. Clim. Chang. Econ. 5, 1450012, 04.

Gupta, S., 2019. Agriculture crop residue burning and its consequences on respiration health of school-going children. Glob. Pediatr. Health 6, 2333794X19874679.

Gupta, V.V.S.R., Grace, P.R., Roper, M.M., 1994. Carbon and nitrogen mineralization as influenced by long-term soil and crop residue management systems in Australia. Defin. Soil Q. Sustain. Environ. 35, 193–200. SSSA Special Publication.

Haider, M.Z., 2012. Options and Determinants of Rice Residue Management Practices in the South-West Region of Bangladesh. SANDEE. Working Paper No. 71-12, 27pp. http://www.sandeeonline.org/uploads/documents/publication/988_PUB_Working_Paper_71_Ziaul_Haider.pdf.

Haider, M.Z., 2013. Determinants of rice residue burning in the field. J. Environ. Manag. 128, 15–21.

Hiloidhari, M., Das, D., Baruah, D.C., 2014. Bioenergy potential from crop residue. Renew. Sustain. Energy Rev. 32, 504–512.

Irfan, M., Riaz, M., Arif, M.S., Shahzad, S.M., Saleem, F., van den Berg, L., Abbas, F., 2014. Estimation and characterization of gaseous pollutant emissions from agricultural crop residue combustion in industrial and household sectors of Pakistan. Atmos. Environ. 84, 189–197.

Irwin, A., 2015. Tackling Crop-Residue Burning in South Asia. Reflections.

Jain, N., Bhatia, A., Pathak, H., 2014. Emission of air pollutants from crop residue burning in India. Aerosol Air Qual. Res. 14 (1), 422–430.

Jalil, X., 2019. Pakistan Threatens Farmers with Jail over Stubble Burning. The third pole. https://www.thethirdpole.net/en/pollution/pakistan-threatens-farmers-with-jail-over-stubble-burning/. (Accessed 1 July 2021).

Joshi, R.S., 2020. Women and Crop Residue Burning in Nepal. https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjgvtSD4rDwAhW0QEEAHYmNBjsQFjAAegQIAxAD&url=https%3A%2F%2Flib.icimod.org%2Frecord%2F34976%2Ffiles%2FHimalDoc_FL_WomenCropResidueBurningNepal.pdf&usg=AOvVaw24yO1c6oOeCR2Vw1jlWRVm.

Kashif, M., Awan, M.B., Nawaz, S., Amjad, M., Talib, B., Farooq, M., Rehan, M., 2020. Untapped renewable energy potential of crop residues in Pakistan: challenges and future directions. J. Environ. Manag. 256, 109924.

Kaskaoutis, D.G., Kumar, S., Sharma, D., Singh, R.P., Kharol, S.K., Sharma, M., et al., 2014. Effects of crop residue burning on aerosol properties, plume characteristics, and long-range transport over northern India. J. Geophys. Res. Atmos. 119 (9), 5424–5444.

Kaur, A., 2017. Crop residue in Punjab agriculture- status and constraints. J. Krishi Vigyan 5 (2), 22–26. https://doi.org/10.5958/2349-4433.2017.00005.8.

Kaur, D., Bhardwaj, N.K., Lohchab, R.K., 2017. Prospects of rice straw as a raw material for paper making. Waste Manag. 60, 127–139.

Kaur, R., Kaur, S., Deol, J.S., Sharma, R., Kaur, T., Brar, A.S., Choudhary, O.P., 2021. Soil properties and weed dynamics in wheat as affected by rice residue management in the rice–wheat cropping system in South Asia: a review. Plants 10 (5), 953.

Kaushal, L.A., 2020. Examining the policy-practice gap-The issue of crop burning induced Particulate Matter pollution in Northwest India. Ecosys. Health Sustain. 6 (1), 1846460.

Kaushal, L.A., Prashar, A., 2021. Agricultural crop residue burning and its environmental impacts and potential causes–case of northwest India. J. Environ. Plann. Manag. 64 (3), 464–484.

Keil, A., Krishnapriya, P.P., Mitra, A., Jat, M.L., Sidhu, H.S., Krishna, V.V., Shyamsundar, P., 2020. Changing agricultural stubble burning practices in the Indo-Gangetic plains: is the Happy Seeder a profitable alternative? Int. J. Agric. Sustain. 1–24.

Khare, P., Deshmukh, Y., Yadav, V., Pandey, V., Singh, A., Verma, K., 2021. Biochar production: a sustainable solution for crop residue burning and related environmental issues. Environ. Prog. Sustain. Energy 40 (2), e13529.

Kondo, Y., Morino, Y., Takegawa, N., Koike, M., Kita, K., Miyazaki, Y., et al., 2004. Impacts of biomass burning in Southeast Asia on ozone and reactive nitrogen over the western Pacific in spring. J. Geophys. Res. Atmos. 109 (D15).

Krishna, B., Balakrishnan, K., Siddiqui, A.R., Begum, B.A., Bachani, D., Brauer, M., 2017. Tackling the health burden of air pollution in South Asia. bmj 359.

Kumar, P., Singh, R.K., 2021. Selection of sustainable solutions for crop residue burning: an environmental issue in northwestern states of India. Environ. Dev. Sustain. 23 (3), 3696–3730.

Kumar, P., Kumar, S., Joshi, L., 2015. Valuation of the health effects. In: Socioeconomic and Environmental Implications of Agricultural Residue Burning. Springer, New Delhi, pp. 35–67.

Kumari, S., Lakhani, A., Kumari, K.M., 2020. Transport of aerosols and trace gases during dust and crop-residue burning events in Indo-Gangetic Plain: influence on surface ozone levels over downwind region. Atmos. Environ. 241, 117829.

Kumari, S., Verma, N., Lakhani, A., Kumari, K.M., 2021. Severe haze events in the Indo-Gangetic Plain during post-monsoon: synergetic effect of synoptic meteorology and crop residue burning emission. Sci. Total Environ. 768, 145479.

Kumari, S., Verma, N., Lakhani, A., Tiwari, S., Kandikonda, M.K., 2018. Tropospheric ozone enhancement during post-harvest crop-residue fires at two downwind sites of the Indo-Gangetic Plain. Environ. Sci. Pollut. Control Ser. 25 (19), 18879–18893.

Kurmi, O., Regmi, P.R., Pant, P.R., 2016. Implication of air pollution on health effects in Nepal: lessons from global research. Nepal J. Epidemiol. 6 (1), 525.

Lal, R., 2010. Soil degradation and food security in South Asia. In: Climate Change and Food Security in South Asia. Springer, Dordrecht, pp. 137–152.

Lohan, S.K., Jat, H.S., Yadav, A.K., Sidhu, H.S., Jat, M.L., Choudhary, M., et al., 2018. Burning issues of paddy residue management in north-west states of India. Renew. Sustain. Energy Rev. 81, 693–706.

Lopes, A.A., Viriyavipart, A., Tasneem, D., 2020. The role of social influence in crop residue management: evidence from Northern India. Ecol. Econ. 169, 106563.

Mandal, K.G., Misra, A.K., Hati, K.M., Bandyopadhyay, K.K., Ghosh, P.K., Mohanty, M., 2004. Rice residue-management options and effects on soil properties and crop productivity. J. Food Agric. Environ. 2, 224–231.

Maraseni, T.N., Deo, R.C., Qu, J., Gentle, P., Neupane, P.R., 2018. An international comparison of rice consumption behaviours and greenhouse gas emissions from rice production. J. Clean. Prod. 172, 2288–2300.

Mathur, R., Srivastava, V.K., 2019. Crop residue burning: effects on environment. In: Greenhouse Gas Emissions. Springer, Singapore, pp. 127–140.

Ministry of Health and Population, 2014a. Department of Health Services, Kathmandu. Department of Health Services Annual Report 2070/71 (2013/2014).

Ministry of Health and Population, 2014b. National Health Policy 2014. Ministry of Health and Population, Kathmandu.

Mohan, D., Abhishek, K., Sarswat, A., Patel, M., Singh, P., Pittman, C.U., 2018. Biochar production and applications in soil fertility and carbon sequestration–a sustainable solution to crop-residue burning in India. RSC Adv. 8 (1), 508–520.

Mohanty, P., 2020. Rebooting Economy 40: why Punjab farmers burn stubble? https://www.businesstoday.in/opinion/columns/indian-economy-agriculture-why-punjab-farmers-burn-stubble-crop-residue-paddy-burning/story/419879.html.

National Policy for Management of Crop Residues (NPMCR), 2014. Government of India Government of India Ministry of Agriculture Department of Agriculture & Cooperation (Natural Resource Management Division) Krishi Bhawan, New Delhi November. Available online: http://agricoop.nic.in/sites/default/files/NPMCR_1.pdf.

Nawaz, A., Farooq, M., Ul-Allah, S., Gogoi, N., Lal, R., Siddique, K.H., 2021. Sustainable soil management for food security in South Asia. J. Soil Sci. Plant Nutr. 21 (1), 258–275.

Pathak, H., Saharawat, Y.S., Gathala, M., Ladha, J.K., 2011. Impact of resource-conserving technologies on productivity and greenhouse gas emissions in the rice-wheat system. Greenh. Gas.: Sci. Technol. 1 (3), 261–277.

Rafiq, M., Ahmad, F., Atiq, M., 2019. The determinants of the crop residue management in Pakistan: an environmental appraisal. Bus. Econ. Rev. 11 (4), 179–200.

Rasul, G., 2016. Managing the food, water, and energy nexus for achieving the sustainable development goals in South Asia. Environ. Develop. 18, 14–25.

Ravindra, K., Singh, T., Mor, S., 2019. Emissions of air pollutants from primary crop residue burning in India and their mitigation strategies for cleaner emissions. J. Clean. Prod. 208, 261–273.
Ravindra, K., Singh, T., Sinha, V., Sinha, B., Paul, S., Attri, S.D., Mor, S., 2021. Appraisal of regional haze event and its relationship with PM2. 5 concentration, crop residue burning and meteorology in Chandigarh, India. Chemosphere 273, 128562.
Raza, M.H., Abid, M., Yan, T., Naqvi, S.A.A., Akhtar, S., Faisal, M., 2019. Understanding farmers' intentions to adopt sustainable crop residue management practices: a structural equation modeling approach. J. Clean. Prod. 227, 613–623.
Rodríguez, A., Sánchez, R., Requejo, A., Ferrer, A., 2010. Feasibility of rice straw as a raw material for the production of soda cellulose pulp. J. Clean. Prod. 18 (10–11), 1084–1091.
Rondon, M.A., Lehmann, J., Ramírez, J., Hurtado, M., 2007. Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with bio-char additions. Biol. Fertil. Soils 43 (6), 699–708.
SAARC, 2019. Possible uses of crop residue for energy generation instead of open burning. SAARC Energy Centre. https://www.saarcenergy.org/wp-content/uploads/2020/03/Final-Draft-SEC-report-on-crop-residue_14022020-1540-IM-1.pdf.
Saggu, G.S., Mittal, S.K., Agarwal, R., Beig, G., 2018. Epidemiological study on respiratory health of school children of rural sites of Malwa region (India) during post-harvest stubble burning events. MAPAN 33 (3), 281–295.
Sain, M., 2020. Production of bioplastics and sustainable packaging materials from rice straw to eradicate stubble burning: a Mini-Review. Environ. Conserv. J. 21 (3), 1–5.
Santín, C., Doerr, S.H., 2016. Fire effects on soils: the human dimension. Phil. Trans. Biol. Sci. 371 (1696), 20150171.
Sarkar, S., Singh, R.P., Chauhan, A., 2018. Crop residue burning in northern India: increasing threat to Greater India. J. Geophys. Res. Atmos. 123 (13), 6920–6934.
Sarkar, S., Skalicky, M., Hossain, A., Brestic, M., Saha, S., Garai, S., Brahmachari, K., 2020. Management of crop residues for improving input use efficiency and agricultural sustainability. Sustainability 12 (23), 9808.
Satyendra, T., Singh, R.N., Shaishav, S., 2013. Emissions from crop/biomass residue burning risk to atmospheric quality. Int. Res. J. Earth Sci. 1 (1), 1–5.
Shyamsundar, P., Springer, N.P., Tallis, H., Polasky, S., Jat, M.L., Sidhu, H.S., et al., 2019. Fields on fire: alternatives to crop residue burning in India. Science 365 (6453), 536–538.
Singh, P., Singh, G., Sodhi, G.P.S., 2020. Energy and carbon footprints of wheat establishment following different rice residue management strategies vis-à-vis conventional tillage coupled with rice residue burning in north-western India. Energy 200, 117554.
Singh, R.P., Kaskaoutis, D.G., 2014. Crop residue burning: a threat to South Asian air quality. Transact. Am. Geophys. Union 95 (37), 333–334.
Singh, R.P., Dhaliwal, H.S., Humphreys, E., Sidhu, H.S., Singh, M., Singh, Y., Blackwell, J., 2008. Economic assessment of the Happy Seeder for rice-wheat systems in Punjab, India. In: 52nd Annual Conference of the Australian Agricultural and Resource Economics Society. AARES 2008.
Srinivasan, G., Abirami, A., 2020. Mitigation of crop residue burning induced air pollution in New Delhi–a review. Int. J. Eng. Appl. Sci. Technol. 5 (8), 282–291. ISSN No. 2455-2143.
Takeshima, H., 2020. Agriculture in South Asia: trends and prospects. In: Transforming Agriculture in South Asia. Routledge, pp. 13–29.
The Energy and Resources Institute (TERI), 2019. Scoping Study for South Asia Air Pollution. Retrieved from. https://assets.publishing.service.gov.uk/media/5cf0f3b0e5274a5eb03386da/TERI_Scoping_Study_final_report_May27_2019.pdf.
Wangchuk, N.N., 2019. How Do You Tackle Crop Burning? Here Are 5 Solutions that Can Work!. https://www.thebetterindia.com/202399/how-do-you-tackle-crop-burning-here-are-5-solutions-that-can-work/.
Xu, R.T., Pan, S.F., Chen, J., Chen, G.S., Yang, J., Dangal, S.R.S., et al., 2018. Half-century ammonia emissions from agricultural systems in Southern Asia: magnitude, spatiotemporal patterns, and implications for human health. GeoHealth 2 (1), 40–53.
Yousaf, H.S., Abbas, M., Ghani, N., Chaudhary, H., Fatima, A., Ahmad, Z., Yasin, S.A., 2021. A comparative assessment of air pollutants of smog in wagah border and other sites in Lahore, Pakistan. Braz. J. Biol. 84.