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Economics of Crop Residue Management

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Abstract

More than five billion metric tons of agricultural residues are produced annually worldwide. Despite having multiple uses and significant potential to augment crop and livestock production, a large share of crop residues is burned, especially in Asian countries. This unsustainable practice causes tremendous air pollution and health hazards while restricting soil nutrient recycling. In this review, we examine the economic rationale for unsustainable residue management. The sustainability of residue utilization is determined by several economic factors, such as local demand for and quantity of residue production, development and dissemination of technologies to absorb excess residue, and market and policy instruments to internalize the social costs of residue burning. The intervention strategy to ensure sustainable residue management depends on public awareness of the private and societal costs of open residue burning.

1. INTRODUCTION

This review examines the economics of residue management in agriculture. The fibrous crop biomass (e.g., leaves, stem cuts, seed pods) left after harvesting more valuable parts, such as grain, is considered crop residue (Schiere 2010) and often treated as the noneconomic part of crop production. Using a grain-residue conversion factor, Shinde et al. (2022) calculated that the global production of crop residues was five billion metric tons in 2020–2021, which is more than three times higher than the 1960–1961 production levels. The multiple uses and economic values of crop residue are not accurately accounted for in the cost-benefit analyses and technology evaluations in agriculture. There is also a dearth of estimates on the quantity of crop residues produced and used across cropping systems and countries. Universal conversion factors are used, and the crop yield and harvested area figures are loosely translated to the quantity of residue production (e.g., FAOSTAT 2021). According to Solazzo et al. (2021), estimates on the role of crop residue burning on greenhouse gas (GHG) emission have the highest uncertainty among all the emission categories of the Intergovernmental Panel on Climate Change (IPCC) because of the unavailability of data and uncertain emission conversion factors.

The lack of academic focus on the economics of sustainable crop residue management is quite surprising, given that it could play a key role in the farming system by generating subsidiary income (e.g., using as livestock feed), increasing crop productivity and profitability (e.g., using as soil mulch) and, to a limited extent, being used for industrial purposes (e.g., biochar and bioethanol production). Furthermore, in connection with climate change mitigation, crop residue retention has a public good dimension to gradually building soil organic carbon pool (Lal 2004, Xia et al. 2014). Despite its multiple values, government incentives, and public campaigns for sustainable use, a large share of crop residue is burned annually, with serious consequences for food production, the environment, and human health (Chen et al. 2019, Shinde et al. 2022, Shyamsundar et al. 2019).[1] The economic rationale behind the paradox of residue wastage motivates this review.

The most conventional and widespread use of crop residues is feed for ruminant livestock. With the increase in global demand for animal-derived foods, which may continue in the near future, one may expect an increase in demand for crop residues as feed. True, farmers in many countries value crop residues the same or more than grain (Magnan et al. 2012). However, there exists a wide variation in the nutritional quality of residues of different crops concerning intake and organic matter digestibility (López et al. 2005) and a marked preference heterogeneity owing to the differences in the perceived quality among farmers with respect to the use of a given crop residue as feed (Erenstein & Thorpe 2011). These factors, alongside farm mechanization and adoption of modern varieties in agriculture and the local density of ruminant livestock, determine the market value of crop residue as feed. The relative scarcity and hence the perceived value of crop residues could vary significantly even within a region across seasons (Magnan et al. 2012).

Another use of crop residue is mulch or soil cover, the effects of which are widely documented in the literature, especially in connection with conservation agriculture (Erenstein 2002, Krishna & Veettil 2014). The application of crop residue as mulch halts soil erosion by acting as a protective layer to the soil surface; improves physical, chemical, and biological soil properties; stabilizes (and

[1]The IPCC reports that biomass burning contributes to approximately 0.1% of global GHG emissions (Pathak et al. 2022). In comparison, rice cultivation contributes 1.7%. Considering that the overall contribution of the Agriculture, Forestry and Other Land Uses (AFOLU) sector is 21% of GHG emissions, the effect of residue burning on climate change can be considered marginal. However, the burning incidents are highly localized and often occur within a short window, causing significant negative health externalities (Raza et al. 2022).

occasionally increases) crop yield; and enhances input use efficiency (Page et al. 2019, Turmel et al. 2015). In addition, with the recent realization that soil carbon sequestration could form a viable climate mitigation approach, there has been an unprecedented interest in the sustainable use of crop residues in regenerative agriculture. Here, crop residue retention is considered a low-cost option to mitigate GHG emissions from agriculture (Venkatramanan et al. 2021, Witzgall et al. 2021). The other uses of crop residues, such as thatching for houses, bedding for livestock, substrate for mushroom production, input for paper manufacture, fuel for cooking and in brick and tile kilns, and biochar production, gain importance in different contexts and cannot be ignored while developing policies toward more efficient and sustainable use of crop residues.

As mentioned above, many farmers overlook the potential uses of crop residues, and a large amount is burned annually, with varying intensities across countries.[2] For instance, in Brazil, sugarcane preharvest burning is widespread, raising serious environmental and health concerns (Nicolella & Belluzzo 2015). Residue burning is not widely practiced in Sub-Saharan Africa, except for cotton and sugarcane (Scholes et al. 2011). Relatively low cropping intensity and high demand from the ruminant livestock sector curtail the occurrence of residue burning on the continent (Archibald 2016). Although the number of studies that address the issue of unsustainable use of crop residues in Africa is relatively scant, the few existing ones point toward problematic residue burning in some countries [e.g., Ghana (Seglah et al. 2020)]. However, it is in Asian countries that the residue burning practice poses the highest threat to the environment and human health. The unsustainable management of crop residues is particularly problematic in India (Sarkar et al. 2018a) and China (Li et al. 2022). For instance, Ravindra et al. (2019) estimated that approximately 24% of 488 million metric tons of total crop residue was burned in India in 2017, resulting in an emission of 824 Gg of particulate matter ($PM_{2.5}$) and 211 Tg of CO_2-equivalent GHGs to the atmosphere. Rice, wheat, and sugarcane are the major crops contributing to residue burning in the country (NPMCR 2014).

Government policies prohibiting residue burning are often less effective in meeting the target (Hou et al. 2019). However, one may argue that the residue burning problem can be addressed within the private value regime itself, as the burning can have unignorable private costs. After all, burning causes soil degradation, increases soil erosion risk, negatively affects soil microorganisms, and ultimately reduces crop productivity (Lin & Begho 2022). However, it may be noted that the sustainable disposal of crop residues also involves additional investments in terms of energy and money, and open burning could be the lowest-cost option for farmers (Ahmed et al. 2015). For instance, Lopes et al. (2020) indicated the high cost of environmentally friendly rice straw management (instead of open burning) in northwestern India was US$125 per hectare. The authors reviewed the literature to compare the cost estimates and found that the farming practices to avoid residue burning cost farmers US$111 in Bangladesh and US$78 in Nepal.

In this review, we argue that the development and adoption of technological options to sustainably manage crop residues are dynamic, endogenous, and dependent on the relative scarcity of human labor versus land in the region. In some countries, the scenario of limited acceptance of technological innovations to sustainably assimilate crop residues in the soil was altered by information and service provision (Krishna et al. 2022). The documented and potential implications of technology, policy, and market interventions to regulate unsustainable crop residue management and associated negative environmental and health externalities are discussed in the forthcoming sections.

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[2] Globally, the crops contributing to residue burning are largely maize, rice, wheat, and sugarcane, according to Cassou (2018). This information is derived by analyzing the FAOSTAT data through an indirect calculation using the crop acreages and conversion factors.

2. A THEORETICAL FRAMEWORK FOR RESIDUE MANAGEMENT

Several studies have attempted to explain the apparently irrational behavior of farmers concerning residue burning. Ahmed et al. (2015) highlighted the relevance of economic drivers in the Pakistani context. The mismatch between local demand and supply of crop biomass and labor scarcity led to a situation in which residue removal became costlier than full burning. Shyamsundar et al. (2019) noted several capital cost and information barriers to adopting no-burn agricultural machinery, resulting in widespread residue burning in India. Chen et al. (2019) attributed residue burning in China to insufficient external financial incentives (e.g., carbon pricing) to modify farmer behavior. While all of these studies emphasize the importance of economic factors, they address the road-blocks at different stages of an evolving residue management regime. In the early stage (Stage 1), technologies that allow for more sustainable, alternative use of residues are absent, and the amount of residue economically used is determined solely by market demand and supply factors and marginal private costs and returns for farmers (e.g., Ahmed et al. 2015). Stage 2 is marked by the presence of technologies that provide alternative private use of residues, while there is an absence of markets to incorporate the social costs of burning in the individual decision-making sphere (e.g., Shyamsundar et al. 2019). In Stage 3, the role of market institutions and policies in internalizing the social costs of individual decision making gains prominence (e.g., Chen et al. 2019). We postulate that the optimal solutions to avoid unsustainable residue management vary across these stages, primarily depending on the public awareness of the associated private and societal costs. The enhanced public awareness results in novel technologies, effective public policies, and innovative market institutions. The awareness generation, however, demands an active role played by central and local governments, agricultural research and development (R&D) systems, rural institutions, and farmers.

2.1. Stage 1

When public awareness is low and institutions internalizing public preferences are missing or ineffective, the demand-supply intersection for crop residues in the private good regime alone determines the share of residue economically used. The market demand in this phase could arise from a single sector, primarily ruminant livestock. In **Figure 1*a***, the marginal private benefit (MPB) curve represents the demand from this sector. Sustainable residue management is often labor intensive and costly for farmers (Shinde et al. 2022). When social costs are not internalized, farmers act based on MPB and their marginal private cost (MPC) of residue collection. The private optimum production is achieved at the interception of the MPB_0 and MPC_0 curves, which is at E_0. Farmers who face $MPC_0 > MPB_0$ (the region RR_0) burn the residue. With the introduction of technologies such as combine harvesters, more residue is left scattered in the field, which is difficult to retrieve and impedes the sowing of the next crop (Bajracharya et al. 2021). Due to the bulkiness and perishability of the good, the MPC of gathering, transporting, and marketing increases with the farmer adoption of such technologies, and it can be presented with an upward shift in the MPC_0 curve (MPC_1). The oversupply could result in a reduction of the market price of crop residues and, thus, marginal benefits for farmers, shown by a downward shift in the MPB_0 curve to MPB_1. In the new equilibrium (E_1), a smaller share of residue is marketed, and more (R_0R_1) is burned. After a threshold amount of residues burned (tipping point), residue burning generates a negative externality to society and a non-negative marginal social cost.

2.2. Stage 2

With the increased recognition that the unsustainable use of crop residues affects yield and farmer income, governments and R&D institutions have started investing in technologies to

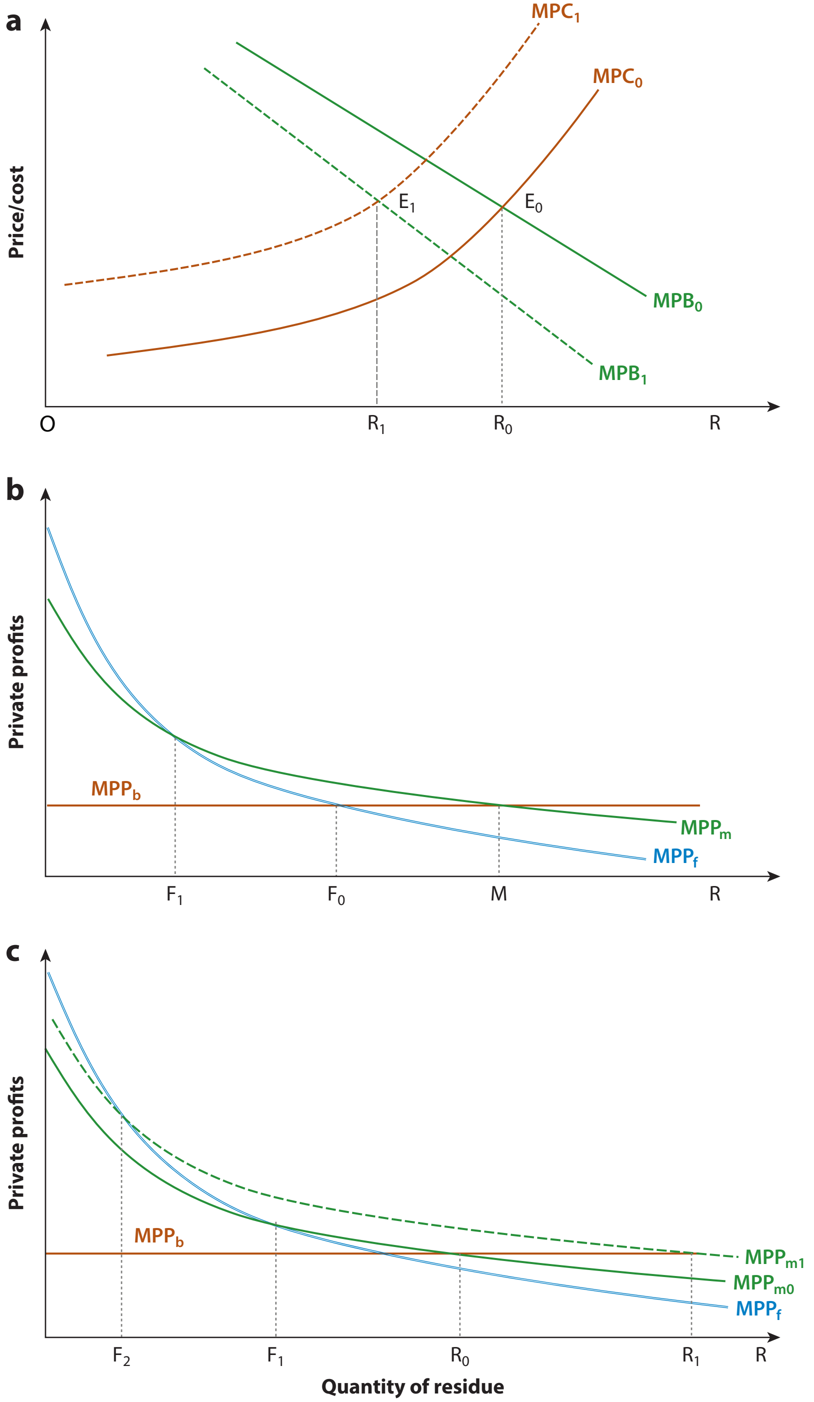

Figure 1

Conceptual framework: private benefits and costs determine farmer adoption of sustainable residue management practices. Abbreviations: MPB, marginal private benefit; MPC, marginal private cost; MPP, marginal private profit.

manage residues sustainably. This development is the primary characteristic of Stage 2. Technological interventions, such as conservation agriculture, could provide a new use for crop residues (mulch). The implications can be studied with the help of marginal private profit (MPP) curves (**Figure 1*b***). The MPP is calculated as the difference between MPB and MPC. Only three use options of crop residues—cattle feed (f), mulch (m), and burning (b)—are depicted in the figure for simplicity. Managing crop residues becomes difficult due to the increased volume of harvest and, thus, a labor-saving practice will most likely become popular. Albeit polluting, burning is one of the most labor-saving and least-expensive management practices (Shinde et al. 2022). Hence, we assume that the MPP of using residue as cattle feed (MPP_f) option is a negative function of residue available for farmers, whereas the MPP of burning (MPP_b) is not.

The quantity of crop residues used as feed is determined by the intersection of the MPP_f and MPP_b curves. The quantity OF_0 is used as feed, and RF_0 is burned. When a new technology is introduced that allows an alternative use for crop residues as mulch, the residue allocation is also determined by the MPP of that option (MPP_m). Less residue is now burned ($RM < RF_0$), and possibly, less residue is available for cattle feed ($-F_1F_0$). The relative positions of the MPP_f and MPP_m curves are determined by several agroecological, technological, institutional, and socioeconomic factors, and these positions further dictate the effectiveness of the technological intervention to curb residue burning. Alongside wage rate and availability of service provision in the village, farmer adoption of machinery for labor-saving residue management technologies is determined by their farm-household characteristics, the level of awareness, and the perceived impacts of these technologies. Several studies, including those by Brown et al. (2017) in Africa and Krishna et al. (2022) in Asia, have empirically assessed the role of these factors.

One may note that technology interventions operate solely in the private value regime in Stage 2. Externalities and public good attributes are not included in the decision making. Given that the technology is effective at incorporating excessive crop residues ($MPP_m > MPP_f$ for the entirety of OR on the horizontal axis of **Figure 1**) and is popular among farmers, its dissemination would curtail the negative externalities of unsustainable residue management just by raising the private value of residues for farmers.

2.3. Stage 3

With a further increase in public awareness and media attention concerning negative externalities from unsustainable residue management, and when the technological alternatives cannot effectively handle the crisis, the government intervenes directly through a command-and-control model or through enabling a market development to encapsulate the negative externalities. When governments introduce penalties for crop residue burning to internalize the social cost, the MPP_b curve shifts downward, making burning a less profitable alternative. On the other hand, when financial incentives are introduced, the concerned MPP curve of the sustainable option covered in the program shifts upward. Examples of such interventions include payments to increase soil organic carbon through mulching (e.g., as part of carbon farming) and subsidies on zero tillage machinery. Here, the curve MPP_m can be expected to shift upward, as shown in **Figure 1*c***. If effective, these interventions could reduce the quantity of residue burning (by R_0R_1) as farmers change their crop residue management practices from burning to retention in the field. However, this shift in the MPP of one alternative may have negative implications for other alternatives not covered in the payment scheme (e.g., livestock feed). Moreover, the financial incentives (subsidies or carbon prices) alone might not suffice to nudge farmers toward more sustainable crop residue management practices. Chen et al. (2019) address institutional challenges for sustainable residue management in this regime.

The three stages of residue management that we postulate in this section bear parallels to the three stages of technological development in agriculture in response to environmental quality proposed by Runge (1987). When the discrepancy between private and social costs of residue management widens, technological innovations are induced in the regimes of crop production and residue management in response. A three-stage induced technological and institutional innovation framework (Newell et al. 1999, Runge 1987, Ruttan & Hayami 1984) is useful to explain the evolution of crop residue management choices. First, the choice of technology, either in crop production or residue management tasks, depends on the relative factor scarcity. For example, labor-saving technologies such as machinery and herbicides are more likely to be adopted in labor-scarce societies. In the second stage, the technology choice depends on the quality of factors of production over time and on the environment. For example, the newly introduced machinery can be energy consuming and polluting. It could reduce the turnaround time between crops and for managing crop residues before sowing the next crop, with crucial implications for intensive cropping systems. These aspects are taken care of while making the adoption decisions. In the third stage, institutional changes in response to environmental challenges emerge, affecting the choices of agricultural technology. This step adds the dimension of induced institutional innovation to the conventional induced technological innovation. This theoretical framework captures all the system issues identified by the recent literature with respect to sustainable crop residue management (cf. Downing et al. 2022).[3]

3. TECHNOLOGIES AND SUSTAINABLE CROP RESIDUE MANAGEMENT

The sustainable use of crop residues is determined by a multitude of supply-side and demand-side factors (Valbuena et al. 2015). Conventionally, the factors affecting the supply of residues include the system's potential to generate residue, storability over time, and nutritional value of crop residues as livestock feed. The major demand-side factors include the extent of ruminant livestock population in the region, the availability of biomass substitutes for livestock, and alternative uses of crop residues. In this section, we focus on the technological innovations that have the potential to alter the abovementioned factors. While some technologies alter farmer demand (e.g., biological or chemical straw treatment to improve quality and digestibility), others alter the quantity of residue generated (e.g., mechanized harvesting). Some agronomic technologies introduced to increase grain yield and farm profitability may inadvertently enhance the quantity of residue produced, affecting the sustainability status of the system. A third set of technologies avoids the open burning of abundant residues by allowing for alternative uses (e.g., biochar production).

The first set of technologies affects crop residue supply, which includes cropping system intensification, mechanization, and varietal characteristics. Among them, the predominant ones are cropping system characteristics: both crop components and production intensity (Fang et al. 2020). Straw biomass not only varies significantly across crops, but the suitability of the residue as animal feed also varies from crop to crop. Including legume and fodder crops in the feed increases ruminant livestock nutrition and farm income, strengthening the complementarity between crop–livestock interaction. On the one hand, Hassen et al. (2017) indicate that forage from the mixed farming system with legumes enhances the digestibility of feed and thereby reduces methane

[3] Crop residues are considered as by-products in a multiproduct production system. Building on the work of Ayres & Kneese (1969), Khanna & Zilberman (1997) posit that externalities from by-products of crop production are largely due to inefficient use of inputs (e.g., excess fertilizers or pesticides) and that the use of precision technologies could help resolve the pollution challenges. Ang et al. (2023) and Murty et al. (2012) suggest treating by-products as a separate production process from the intended production, thereby requiring a multiequation system.

emissions from livestock production. On the other hand, increased cropping intensity could also result in excessive residue production. When coupled with the short turnaround time between crops, increased cropping intensity could lead to unsustainable management of residues, including burning. Some of the harvesting technologies generate a similar effect. Scattering of crop stalk residues from mechanized harvesting, which increases the labor cost to gather them, is the main reason for widespread residue burning in South Asia, as farmers found burning to be the most economical way of disposing of the surplus residues (Bajracharya et al. 2021, Sarkar et al. 2018b). Furthermore, certain varietal attributes, such as the length of the plant and duration of the crop, and agronomic practices (e.g., spacing, intercropping), also determine the amount of residues generated (White et al. 2020). For example, the scented basmati rice varieties of Northwest India are harvested manually, and their residue is not burned, unlike other rice varieties, because of the high palatability of basmati straw for cattle (Gupta 2014, Lohan et al. 2018).

There is another set of supply-side technologies that ensure the continuous availability of nutrients from crop biomass for livestock production. For instance, there are several technologies for long-term wet and dry residue storage (Cui et al. 2012). However, residues from many crops, such as rice straw, form inferior animal feed, being rich in polysaccharides, lignin, and silica, with low protein content; these residues undergo widespread burning. Technologies such as chemical treatments of straw (e.g., with urea) and the use of ligninolytic microorganisms are considered as viable options to enhance voluntary uptake by animals, digestibility by rumen microbes, and animal nutrition (Sarnklong et al. 2010). They also reduce GHG emissions from livestock production (Hassen et al. 2017).

The need for crop residues to feed livestock and the availability of alternative feed options are the two demand-side factors determining sustainable residue management. Adopting technologies that make livestock production more profitable and reduce risks, such as assisted reproductive technologies, improved livestock breeds, and health care (Marshall et al. 2019), could result in herd expansion and increase the local demand for crop residues as feed. Furthermore, when livestock production becomes capital intensive, farmers rely more on alternative feed supplements, especially because many crop residues have inferior nutritional quality (Khandaker et al. 2012, Komarek et al. 2015).

Based on the supply and demand from livestock and other sectors, crop residues become scarce or abundant in the system. Abundance occurs especially when the feed quality—nutrient quality, digestibility, and voluntary intake by the animals—is questionable. Farmers often find the collection and transportation of residue from the field expensive, and burning becomes the most cost-effective approach to disposing of the excessive residues (Raza et al. 2022). Against this background, a third set of technologies that avoid residue burning by absorbing the surplus residue production gains prominence; examples include biomass use in industries and sustainable intensification of cropping systems. Although one could consider them demand-side technologies, they are developed and popularized with the primary intention of avoiding residue burning. The industrial uses of crop residues such as biochar and biofuel production have the potential to augment farm income and cement intersectoral complementarities (Satpathy & Pradhan 2023, Seo et al. 2022), but an economically more relevant option is the use of residue as soil mulch.

Several studies show that when crop residue is used as mulch, the crop profitability and energy use efficiency of crop production are increased (Krishna & Veettil 2014, Yadav et al. 2020). Although a trade-off could exist in some regions between crop and livestock production sectors with respect to the use of crop residues (Jaleta et al. 2013), mulching is considered as an efficient option to utilize available crop residues in an eco-friendly manner to increase system productivity (Erenstein 2002). In fact, many studies have indicated retention as the most efficient way of utilizing crop residue. Technologies that use microbes to facilitate faster degradation of the residues

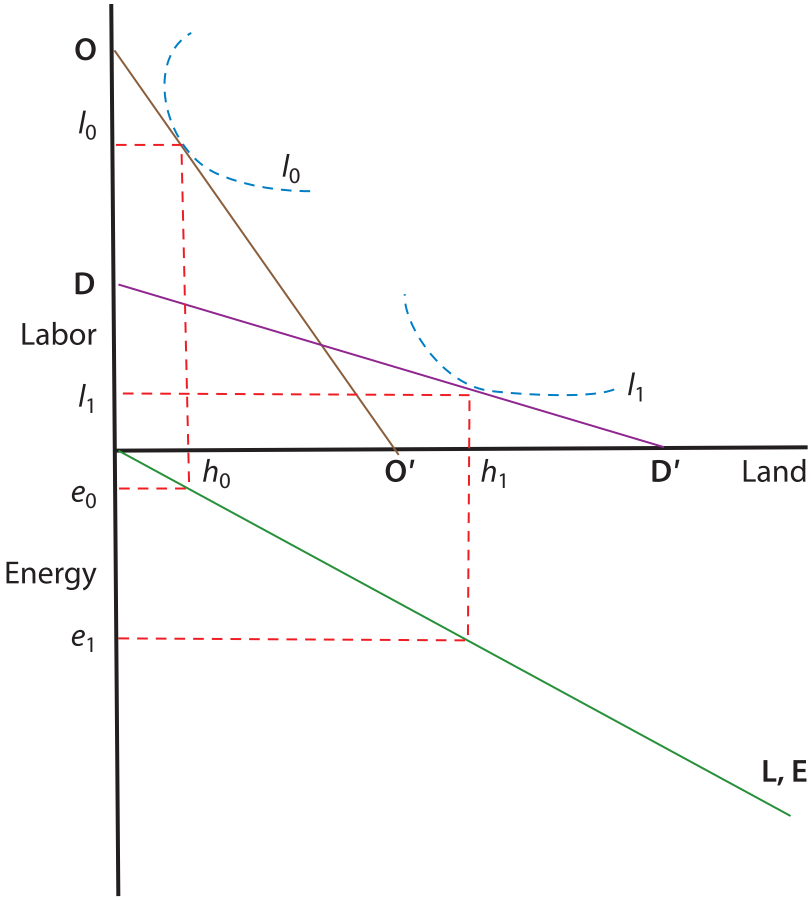

Figure 2

Farming technologies and residue management.

on-farm increase the feasibility of this option (Phukongchai et al. 2022). However, residue burning often occurs not owing to the lack of a viable technology but despite it (Shyamsundar et al. 2019).

The low adoption of technologies that could avoid residue burning can be understood by examining the agrarian change from a land-scarce/labor-abundant scenario to a labor-scarce scenario. The Green Revolution technologies (e.g., improved seeds, fertilizers, and irrigation), rapidly adopted by South Asian farmers, were designed for the land-scarce scenario. Over time, labor became scarce due to infrastructural developments (e.g., roads) and the structural transformation of economies that led to massive outmigration and reduced labor availability for agriculture. Herbicides and machinery were adopted in response, which could further speed up the structural transformation. However, mechanization for different farm tasks occurs sequentially rather than simultaneously. According to Pingali (2007), power-intensive operations (e.g., tillage) are the ones that are mechanized first, and control-intensive operations are adopted later, mostly when the wage rate increases. This transition is shown in **Figure 2** by the move from OO′ (labor abundant, land scarce, and less energy consumptive) to DD′ (labor scarce, land using, and more energy consumptive) with innovation possibility curves l_0 and l_1. At the new price line DD′, researchers are encouraged to innovate on labor-saving, land-use, and energy-consuming technologies to move from point $l_0e_0b_0$ to $l_1e_1b_1$. These are mostly adopted for the production stages (tillage and harvesting) as compared to the crop residue management stage. A simple and cheaper (albeit polluting) labor-saving technology that is adopted to deal with unwanted crop residues is fire. Burning becomes the norm for farmers adopting technologies as differentiated inputs with their attributes, including cost, factor savings, and environmental quality. Some of the environmental quality attributes include negative externalities.

4. POLICIES AND STANDARDS

Sustainable residue management has a significant public good component. On the one hand, studies have noted a gradual increase in soil organic carbon content in the topsoil under longer-term residue retention practices, making the production system a potential carbon sink, which could reduce GHG emissions (Dutta et al. 2022, Jat et al. 2019). On the other hand, residue burning increases air pollution (Bikkina et al. 2019, Yu et al. 2019), which is associated with a significant reduction in average life expectancy (Chen et al. 2013). Residue burning also emits short-lived climate pollutants (Perillo et al. 2022, Smith et al. 2008). Due to the unignorable public good component, several governments impose regulations to curtail the residue-burning practice by farming communities. According to Runge (1987), high-income and highly educated societies are more inclined to enact institutional changes to curtail pollution. However, the effectiveness of these strategies varies widely across countries. Here, we review government regulatory actions, farmer compliance, and their repercussions on residue management from four Asian countries—China, India, Thailand, and Vietnam—where a large share of crop residues are burned annually.

4.1. China

The State Environmental Protection Administration has been developing policies to ensure the sustainable use of crop residues since 1999 (Wang et al. 2022). Initially, the interventions were mainly through increased R&D investment and training, although the government also prohibited residue burning in areas with dense populations. Later, when these measures were found inadequate to meet the goal (i.e., 80% sustainable use of crop residues by 2015), more specific measures were proposed, and local governments were asked to budget more to prohibit residue burning and to find new technology options for sustainable use of crop residues. Although alternative uses of residue, such as soil mulch, input for biogas production, animal feed, organic fertilizers, and growth medium for edible fungi, were promoted, the government's current efforts have been heavily dependent on prohibition and penalties (Ren et al. 2019). Local township officials are asked to monitor farmers' fields, and remote sensing technologies are used to ensure the effectiveness of the ban (Hou et al. 2019). The 2015 Air Pollution Prevention and Control Law lent much-needed legal support for the local governments to impose nonburning in selected zones. At the same time, the central government undertook campaign-style enforcement to increase the sustainable use of crop residues (Shen & Ahlers 2019). Wang et al. (2022) indicated that these campaigns generated a long-lasting impact on farmer behavior of straw management. Another study by Hou et al. (2019) documented the trends of corn stover usage in Northeast China and found that mandatory regulations prohibiting crop residue burning were largely ineffective. Instead, providing technical support, such as availing stover choppers at a subsidized rate and setting up demonstration plots, was found to effectively promote the sustainable use of crop residue in the study areas. However, the adoption rate of these technologies and their impact on residue use in the country are not well documented.

4.2. India

The highest incidence of residue burning takes place in the northwestern Indo-Gangetic Plains, where 68.4–75.9 million metric tons of rice straw are burned annually (Singh et al. 2021). In

Indian cities, which already experience the worst air quality in the world, air pollution drastically increases during the time of residue burning in the surrounding villages. Some studies indicate that the government regulations to save groundwater form the root cause of this unsustainable use of residues. In 2009, the state governments of Punjab and Haryana prohibited rice transplanting until the onset of monsoon in northwestern India to avoid overexploitation of groundwater, which not only delayed the rice harvest but also narrowed the turnaround time between rice and wheat, prompting farmers to burn the residues to quickly remove them from the fields (Kant et al. 2022). In response to farmers burning rice residue, the government developed a National Policy for Management of Crop Residue (NPMCR) to control residue burning and promote in situ crop residue management in 2014. This policy promoted the use of residues in power generation, production of bioethanol, composting, mushroom cultivation, as packing material and input in the paper industry, and charcoal gasification (NPMCR 2014). It also encouraged the dissemination of conservation agriculture practices and incentivized the purchase of agricultural machinery that facilitates in situ crop residue management. In 2015, the National Green Tribunal banned crop residue burning in Rajasthan, Uttar Pradesh, Haryana, and Punjab. The Central Pollution Control Board and the National Remote Sensing Agency (NRSA) were authorized to detect and penalize farmers for crop burning. The penalty amount was based on the landholding size. Residue burning is also a punishable offense under the Air (Prevention and Control of Pollution) Act of 1981 (Kaushal 2020). Despite these regulations, farmers continue burning rice residues, and pollution levels have not subsided in Northwest India (Keil et al. 2021). Learning from the ineffective regulations, both the state and central governments started to focus on technology-based solutions, including the promotion of agricultural mechanization for in situ crop residue management (Gov. India 2020) and the production of fuel and energy using excess crop residues (Kaur et al. 2022).

4.3. Thailand

Open burning of rice and sugarcane residues is common in Thailand, and the associated air pollution and haze events are spread across borders in Southeast Asia (Junpen et al. 2018, Kumar et al. 2020). The government signed a legally binding 2002 Agreement on Transboundary Haze Pollution and the 2016 Roadmap on Cooperation Towards Transboundary Haze Pollution Control with Means of Implementation, both by the Association of Southeast Asian Nations (ASEAN), the regional organization consisting of ten member states (Varkkey 2022). Thailand's Eight Point Plan (2013) on open burning represents a coordinated approach to combatting open burning by prohibiting crop residue from January to April and raising public awareness (Lualon et al. 2013). However, the Plan was not conferred with any capacity for regulatory implementation and, as a result, only a few of the policies were implemented effectively (Moran et al. 2019). The government also provided subsidies to popularize farming technologies that reduce crop residue burning. The renewable energy plan of the Department of Alternative Energy Development and Efficiency was aimed at popularizing the use of agricultural residues as raw material for heat and electricity production (Junpen et al. 2018). Although these policies and programs control residue burning and promote sustainable residue management practices, implementing them in the field has been met with various challenges (Kumar et al. 2020).

4.4. Vietnam

Not all countries that experience negative externalities from the unsustainable use of crop residues conceive and implement comprehensive strategies. In Vietnam, rice straw burning has long remained the most common way of crop residue disposal, especially in the Mekong River and Red River deltas (Lasko et al. 2017). Every October, coinciding with the rice harvest, the air quality worsens due to residue burning. The government has made some efforts to encourage the use of rice straw in the most effective means, such as livestock feed, composting, mushroom cultivation, and fuel and biomass production. For example, a subsidy is provided for rice straw balers that facilitate the collection of straw for alternative uses.[4] However, these methods have proved unattractive to farmers because of several local obstacles (Pham et al. 2021). More importantly, there is a policy vacuum; the legislation on environmental protection does not directly address the issue of unsustainable crop residue management. There are also no other national policies regulating the farmers' practice of residue burning. The regional air quality strategies are ineffective in curbing the residue burning problem, although the local authorities sometimes encourage farmers to delay burning during high pollution events. While assessing this policy lacuna on regulating residue burning in Vietnam, McLaughlin et al. (2016) found the public indifference toward the practice responsible, especially in the sparsely populated Mekong Delta.[5]

In summary, the analysis of government policies across the four countries indicates that the interventions to curtail unsustainable use and waste of crop residue fall into three broad categories: (*a*) banning the practice, (*b*) encouraging alternative uses and availing technologies to farmers, and (*c*) public awareness campaigns. A comparative analysis of these different interventions could have important policy implications. For instance, can the government achieve the goal of curtailing residue burning by spending less if they invest in public campaigns rather than provide subsidies on conservation agriculture machinery? Answering such questions can help make residue management more effective and sustainable. Unfortunately, few studies have empirically assessed the impact of different government interventions on crop residue management and examined the reasons behind the differential effect of measures undertaken.

5. EVOLVING MARKET-BASED MECHANISMS

As discussed in Section 2, unsustainable crop residue management is often a result of oversupply and missing markets. Different governments have made initiatives to increase crop residue sales to avoid open burning and associated air pollution. For example, the Indian government asked the National Thermal Power Corporation to use crop residue pellets mixed with coal for electricity generation, which is expected to help farmers with a monetary return of US$77 per ton of crop residue (Bhuvaneshwari et al. 2019). Similar moves were also prescribed by the state governments and courts of India (Jack et al. 2022, Sethi 2021). However, farmers have been considered passive entities in the price fixation, and their preferences were not accounted for while estimating the supply price. Against this background, the emerging voluntary carbon markets and regenerative agricultural practices with residue retention gain special relevance. Retention of crop residues, often combined with no tillage or minimum tillage, increases soil organic carbon and reduces GHG emissions significantly (Nyawira et al. 2021). Farmers participating in the voluntary carbon

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[4] Straw collection from the fields is expensive for the procurers. Van Nguyen et al. (2016) estimated that the cost of mechanical straw collection in Vietnam (US$12–18 per ton of straw) was 10–20% of the total investment in biomass production or mushroom production.

[5] The other two Southeast Asian countries with high rates of residue burning are Indonesia and the Philippines (Kim Oanh et al. 2018). The policy situation in these countries is similar to that of Vietnam, lacking well-developed governmental policies concerning residue management. The national government entrusts the implementation of existing policies fully to local government but without transferring sufficient authority and accountability (McLaughlin et al. 2016). The geographical diversity within the borders of these two countries also reduces the government's ability to influence the nature of land uses.

markets could trade the reduced carbon emissions. Because few carbon farming agreements are present, our discussion centers around the expected effects of such interventions for sustainable residue management by smallholder farm households in developing countries.

Crop residue management plays a vital role in the new developments of regenerative agriculture and carbon farming. There is growing international interest in using soil as a carbon sink by increasing organic matter to contribute to climate change mitigation (FAO 2017). The global organic carbon stocks in the top 1 m of soil are estimated at an average of 1,500–2,400 Gt of carbon, with a spatially and temporally variable distribution (Smith et al. 2020). As shown in Section 3, several technologies exist to increase soil organic carbon and hence have great potential for climate change mitigation and adaptation. However, global adoption rates of many of these sustainable soil management practices are low because of the prevailing economic, informational, institutional, technical, and sociocultural barriers (Jones-Garcia & Krishna 2021). Combined with the abiotic factors that restrict soil organic carbon buildup (e.g., annual precipitation, temperature), these factors reduce the scope of using agricultural soil as a carbon sink (FAO 2017). There has been an emerging understanding in the policy arena that this situation can be changed by providing farmers with financial incentives to adopt regenerative agriculture. The incentives can be generated in the carbon markets; the participating proprietary firms can offset their emissions by retiring carbon credits generated by projects reducing carbon emissions in agriculture. Farmers' additional cash income through carbon credits is expected to motivate them to adopt resilient, regenerative residue management practices.

The working of carbon markets can be understood within the framework of payment for ecosystem services (PES) mechanisms. The four main sources for forest and land-use carbon offsets include afforestation (and reforestation), improved forest management (IFM), sustainable agricultural land management, and Reducing Emissions from Deforestation and Forest Degradation (REDD). Salzman et al. (2018) indicated that the 48 forest and land-use carbon PES schemes that emerged globally to combat climate change had spent US$2.8 billion since 2009. These markets range from purely voluntary exchanges to international funding mechanisms, state mandates, and treaty flexibility mechanisms. The authors indicated fungible metrics of transactions and the presence of trading protocols as advantages of the carbon compliance market over many other PES schemes. However, the demand from the private sector and philanthropy programs could satisfy only a small fraction of the potential supply for carbon offsets. One of the major challenges in building an effective carbon market is designing monitoring platforms that fulfill the criteria of completeness, transparency, consistency, accuracy, and thus comparability to support growing global initiatives to increase soil organic carbon (Smith et al. 2020). The regulatory institutions to govern carbon markets, which are necessary for aligning with global initiatives (e.g., 4p1000 Initiative) and regional public-private partnership initiatives on carbon credits for regenerative agriculture (Jat et al. 2022), are still not matured and yet to receive necessary policy backup in several developing countries.

An integral part of establishing carbon markets is setting up a measurement, reporting, and verification (MRV) platform. This multistep process measures the quantity of reduction of GHG emissions due to a specific intervention over time, reports these findings to accredited third-party verifiers, and obtains emission reduction certificates. The MRV process is highly technical, time consuming, and expensive, and many nations lack the institutional capacity to undertake it (Mitchell et al. 2017). Some researchers have indicated the potential of remote sensing data to capture unsustainable residue management practices. For example, we provide a Sentinel-2 image of on-farm residue burning in the central Indian state of Madhya Pradesh in **Figure 3**. The associated data are summarized in **Table 1**, which shows that residue from approximately 56% of sample plots in Madhya Pradesh was burned during March–May 2021. In the face-to-face interviews,

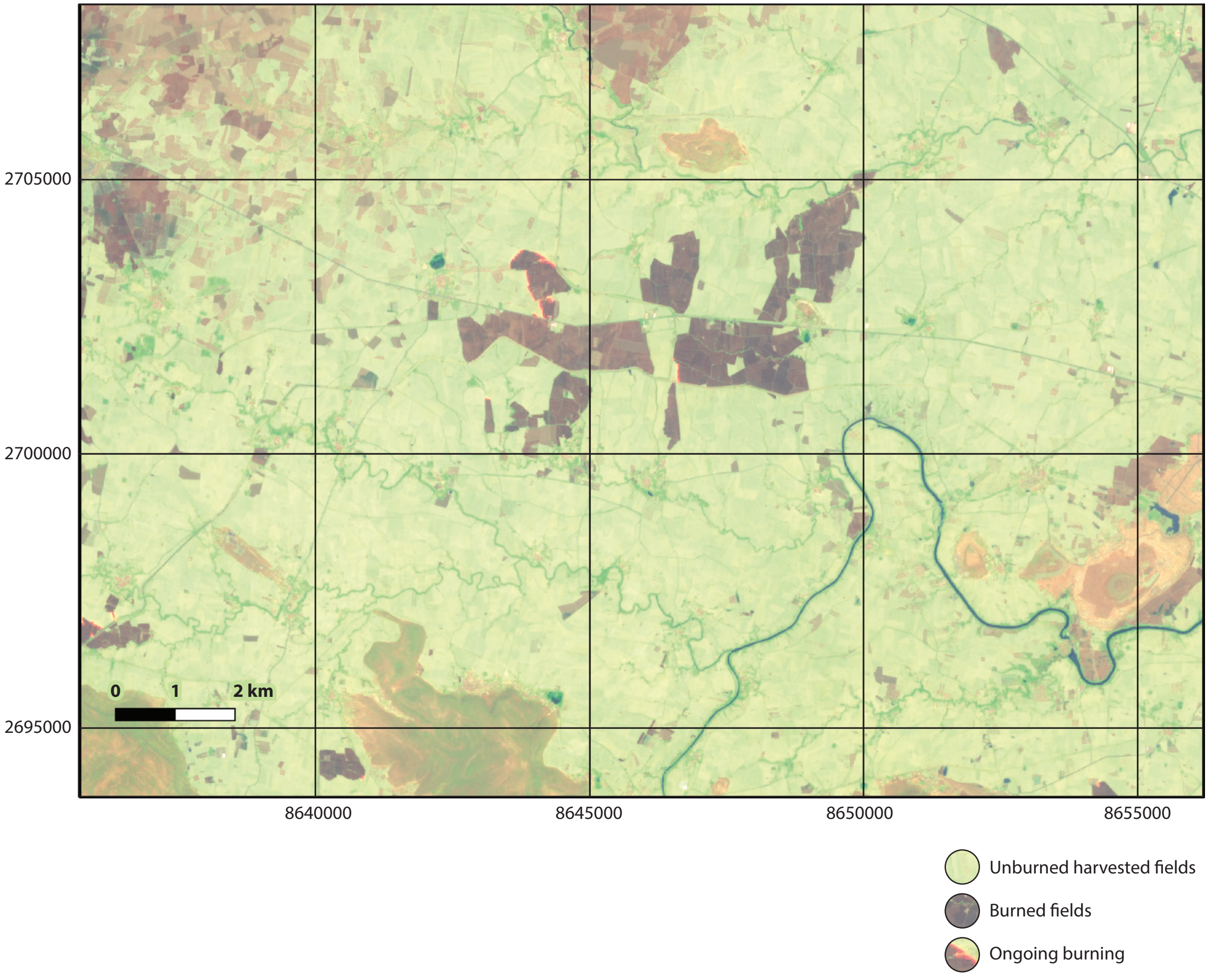

Figure 3

Sentinel-2 image for mid-April 2021 over the Madhya Pradesh state of India, showing residue burning. The false color composite (FCC) image shows burned fields in dark brown to blackish shades and unburned harvested fields in yellow-greenish shades. The orange borders of some burned fields (top left fields of the central burned patch) represent burning that was captured by the sensor. A short-wave infrared long reflectance band (band B12) and a near-infrared band (band B8) in FCC were selected for enhancing burned signatures from the fields. For the detailed methodology of residue burning detection through satellite imagery, please refer to Deshpande et al. (2022).

however, only 15% of farmers admitted it. In Punjab, approximately 46% of sample farmers revealed in the survey that they followed residue burning during October–December 2021, whereas the prevalence was much higher (84%) according to satellite data.

Although satellite imagery has a crucial role in MRV, the accuracy of satellite data to correctly identify plots with respect to residue burning depends on several atmospheric factors (e.g., the presence of clouds). Also, such data sets cannot trace out the out-of-plot burning events. Furthermore, the capacity of local and regional research institutes and universities is often insufficient to use new and more accurate monitoring technologies to track residue burning in real time (Ravindra et al. 2019).

Table 1 Incidents of residue burning: farmer reporting versus satellite detection in India

		Based on satellite data, the number of observations (% of total)		
		Residue burned	Not burned	Overall
Sample 1: Madhya Pradesh (March–May 2021)				
Based on the farmer interviews, the number of observations	Residue burned	33	18	51
		(9.48)	(5.17)	(14.66)
	Not burned	163	134	297
		(46.84)	(38.51)	(85.34)
	Overall	196	152	348
		(56.32)	(43.68)	(100.00)
	Pearson's chi-squared (DF: 1) = 1.71 ($p = 0.19$)			
Sample 2: Punjab (October–December 2021)				
Based on the farmer interviews, the number of observations	Residue burned	114	2	116
		(43.51)	(0.76)	(44.27)
	Not burned	107	39	146
		(40.84)	(14.89)	(55.73)
	Overall	221	41	262
		(84.35)	(15.65)	(100.00)
	Pearson's chi-squared (DF: 1) = 30.58 ($p < 0.001$)			

Farm surveys were conducted in both states in January 2022, during which the residue management practices were elicited. Satellite imageries from Sentinel-2 were used to detect the residue burning. Abbreviation: DF, degrees of freedom.

6. CONCLUSION

This review covered the theoretical, empirical, and policy aspects of crop residue management across the developing world. Despite high use-value and evolving alternative usages, a large share of residues is wasted or burned yearly. We have examined the economic rationale behind this paradox. Three stages of residue management governance, determined by the level of public awareness, are noted, and the reasons for residue burning vary across these stages. In the earliest stages, the sustainable use of crop residue is determined solely by marginal private costs and returns for farmers facing demand from a single sector. Then, with the increased awareness of the implicit private costs of residue burning on crop production and farm income, technologies that provide alternative use of residues are developed and disseminated. Finally, in a more advanced stage, policy instruments and market institutions evolve to incorporate the social costs of unsustainable residue management practices in farmers' decision making. We presented the three stages within the conceptual framework of environmental and resource economics, reviewed the studies relevant to each stage, and identified the key factors contributing to unsustainable residue management. More empirical research is required to distinguish these stages and to understand the relative importance of different approaches to residue management on surplus residue generation, farmer income, and the environment.

We found a severe dearth of data on residue production across crops and countries. In most cases, the quantity of biomass production is estimated from crop yield or area under cultivation, ignoring the differences in cultivation practices and agroecological conditions. The literature linking empirical aspects of crop residue management to the economics of agricultural production is equally scant, which can be attributed to the lack of data and measurement tools. Bridging this data gap is crucial for designing interventions toward healthier agroecosystems. For instance, given the emerging prominence of climate financing and carbon credits, precise crop biomass data are required to support payments and conduct welfare impact analyses. Such data sets are also crucial in the socioeconomic experiments on the efficacy of PES schemes to provide evidence on the efficacy of behavioral economics solutions (see Jack et al. 2022). In this regard, the recent advances in remote sensing to detect crop residue burning (Deshpande et al. 2022, Walker et al. 2022) have special importance.

We anticipate that, alongside financial incentivization, increasing public awareness and influencing farmer and consumer preferences toward more sustainable cropping systems could help disseminate superior residue management practices and technology choices among farmers. However, for these changes to occur, there is a need for improved integration of input and output value chain actors. More research is required in this direction to further our understanding of the sustainable use of crop residue in developing country agriculture.

The relative efficacy of different technological and policy interventions to curtail negative externalities from unsustainable crop residue use is not well established. We also identified the need for a clearer theoretical understanding of the production process of crop residues in multi-input and multi-output production systems to design environmental policies that efficiently address the trade-offs. Crop residue management is one of the tasks within a complex and interdependent farming system in which production and consumption choices are related to the quantity of residue generated and the associated risks of air pollution. Therefore, a system-level approach and methodological overview of the production networks are essential to design effective policies. Finally, while several studies showed that residue retention could be profitable for farmers and environmentally friendly, it is less evident why its uptake by farmers is marginal in many developing countries. Analysis of the role of public information campaigns in making a long-lasting impact on farmer behavior of residue management is especially necessary.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the funding agencies or institutions.

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