



International Journal of Research in Agronomy

E-ISSN: 2618-0618

P-ISSN: 2618-060X

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www.agronomyjournals.com

2024; SP-7(12): 490-496

Received: 13-09-2024

Accepted: 14-10-2024

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Agricultural residue management in India: Unlocking economic potential

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DOI: <https://doi.org/10.33545/2618060X.2024.v7.i12Sh.2231>

Abstract

In India, agriculture is the main source of income for many people, where a variety of crops such as cereals, oilseeds, sugarcane and fibers are grown for consumption and other purposes. This results in the production of a significant amount of agro-waste, also known as agricultural residues. In India, stubble burning is a serious issue. Lack of better alternative methods leads to the open-field burning of crop waste by farmers. Previous studies have shown that setting crop residues on fire will destroy the soil, increase air pollution and also harm the land heating. Soil temperature is lethal to soil microbes. In addition to the potential for further pollution caused by the increased use of chemical fertilizers, the temperature of the soil necessitates higher economic costs for restoring its fertility. In this review paper, we examined the economic potential of agricultural waste management options available to India by reviewing the literature for crop establishment practices in which planting crops in standing stubble, implementing in-situ approaches along with composting methods, biofuel generation and use of waste as feedstock for value-added products. Educational and awareness campaigns are very essential for changing perceptions and attitudes of farmers toward crop residue burning. This paper also discusses government policies, technology and private sector participation for developing a circular economy in the agriculture sector.

Keywords: Agricultural waste management, awareness, environment pollution, stubble burning, sustainability

Introduction

India is seventh largest country with 3.287 million square kilometers of land area over the world. With 139.35 million hectares (Mha) of land used for agriculture, or roughly 42.4% of our nation's total land area, India is one of the world's most significant producers of agricultural goods. Agriculture plays a vital role in the Indian economy, contributing over 25% of the gross domestic product and providing livelihood to about 70% of the country's population (Raihan *et al.*, 2024 and Nagar *et al.*, 2024) ^[29, 22]. Since independence, the nation has seen a 25% increase in cropping intensity. As per Meena *et al.*, (2020) ^[12] Indian agriculture sector produces wide range of crops, including rice, wheat, oilseeds, sugarcane, fiber and cotton, generating a large volume of agricultural waste as illustrated in fig. 1. Agricultural waste called as residues and by-products from farming activities. These include crop residues (straw, husks, stalks), animal waste, agro-industrial waste, and unutilized portions of plants (Hoang *et al.*, 2024a) ^[13]. According to estimates, India produces 500–550 million tons of crop remnants annually (Abdullah *et al.*, 2021 and Katak *et al.*, 2023a) ^[16]. This is a huge amount of agricultural waste. Sixty-six percent of total production has been used for a range of purposes, including as household firewood, industrial fuel, livestock feed, and roofing for rural homes. A total of 89 Mt of wheat, 56 Mt of sugarcane, 47 Mt of cotton, 43 Mt of rice, and 23 Mt of vegetables and fruits are wasted, making up 34% of the entire output (Athwal *et al.*, 2023) ^[3]. Most of this waste (about 65-75%) is burned in open fields as illustrated in fig. 2. Farmers frequently burn agricultural waste as it is an easiest way of disposal, effective form of weed and pest management, as well as low-cost method for field preparation for next crop (Porichha *et al.*, 2021) ^[28] and there is a dramatic fall in the incidence, after menopause due to cessation of clinical ovarian.

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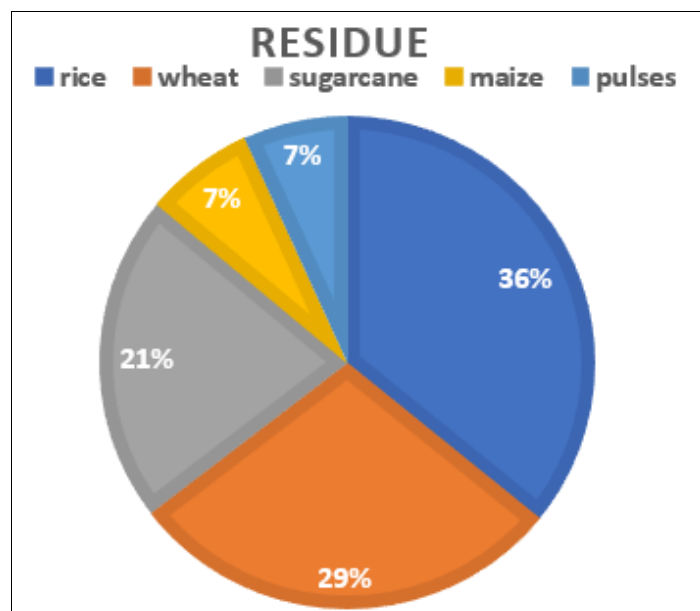


Fig 1: The proportion of unused leftovers produced by various crops in India (source- Ministry of New and Renewable Energy 2022)

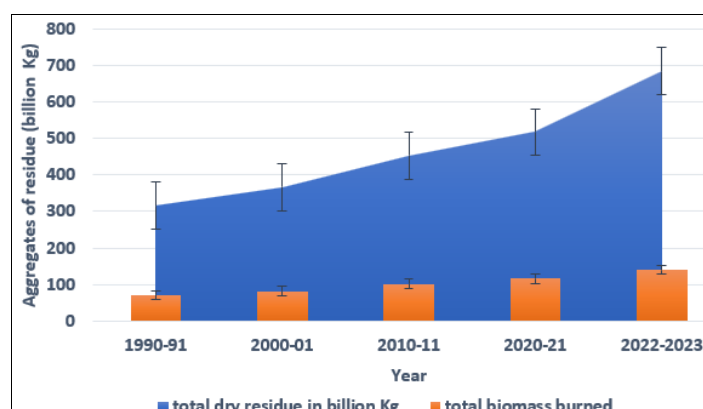


Fig 2: Crop residue generation and burning in India between 1990 to 2023 (Source-Economic survey 2023)

Burning crop residues contributes significantly to global warming through the emission of greenhouse gases (GHGs) and increases health hazards by releasing particulate matter (PM) and smog. It results in a lack of essential elements such as organic carbon, nitrogen, phosphorus, potassium, and sulfur as well as loss of biodiversity and soil fertility. Air pollutants such as CO₂, CO, NH₃, NO_x, SO_x, non-methane hydrocarbons (NMHCs), volatile organic compounds (VOCs), and semi-volatile organic compounds (SVOCs) are also released throughout the process (Parmod *et al.*, 2015) [26]. One tonne of stubble, for instance, loses more than 1 kilogram of sulfur, 25 kg of potassium, 2.3 kg of phosphorus and 5.5 kg of nitrogen, all of which are essential for healthy soil. Additionally, it drastically reduces soil nutrient levels, which has a detrimental effect on agricultural productivity. Make it shorter. Burning paddy straw destroys vital bacterial and fungal populations and raises soil temperatures to 33.8–42.2 °C (Gupta *et al.*, 2004). Crops become more susceptible to harm as a result of this approach, which damages the organic matter and microorganisms in the soil, decreasing beneficial pests and boosting harmful ones. There is also a reduction in the topsoil's capacity to dissolve minerals (Kumar *et al.*, 2015) [22]. Burning agricultural residue is a common practice in many locations, particularly in India's Indo-Gangetic plains. Burning one ton of chaff produces 199 kg of ash, more than 1 kg

of sulfur dioxide, 60 kg of carbon monoxide, and 1460 kg of carbon dioxide and 3 kg of particulate matter in air and reduction in the soil's 5.5 kg of nitrogen (N), 2.3 kg of phosphorous (P), 25 kg of potassium (K), 1.2 kg of sulfur (S), and all organic carbon (ministry of agriculture and NPMCR). Additionally, this could be a source of dangerous greenhouse gases (GHGs), as well as other significant invisible gases and aerosols that are chemically and radiatively significant. Burning agricultural leftovers produces heat that raises the soil's temperature, killing off helpful soil microbes and lowering the amount of N and C in the topmost layer of soil (Kadian *et al.*, 2024) [15]. Agro-industries have gradually come to realize that valorization of biomass leftovers is not only helpful from an environmental standpoint but can also help to prevent economic losses or even improve the net value of firms. (Singh *et al.*, 2022). Crop residue, which makes up the majority of agricultural harvests, contains a significant quantity of carbon and other nutrients like nitrogen (N), phosphorous (P), potassium (K), sulfur (S), etc., are a great supplier of soil nutrients (Kumar *et al.*, 2023) [19]. As per estimates, India generates more than 500 million tons of agricultural waste each year, of which only about half is used successfully (Singh & Prabha, 2018) [31]. A significant amount of the residual garbage is either burned in the open, producing air pollution, or wasted, resulting in environmental damage and the loss of potentially valuable resources. Proper management and disposal of crop waste remain significant concerns. This review paper addresses numerous technical breakthroughs and crop residue management tactics, including mechanised management systems, in-situ incorporation, nanotechnology, biogas production, biochar preparation, bioethanol production, and the use of decomposers. These technologies provide promising alternatives for reducing the environmental impact of residue burning while also improving soil health and encouraging renewable energy. The paper also explores policy frameworks, community engagement, and collaboration as essential components for the successful implementation of sustainable practices.

Economic Advantages of Sustainable Agricultural Waste Practices in India

The economic worth of agricultural residues is projected to be more than \$32 billion every year. However, about 60% of this wastes is in use at the moment, and the rest is either incinerated or thrown away, which causes serious ecological and health related issues (Baruah *et al.*, 2024) [5]. There are, however, great possibilities for businesses in making value added products such as biogas, organic fertilizers, bio-degradable plastics, and biofuels out of agricultural waste (A. Kumar *et al.*, 2021) [18]. It also minimizes the expensive use of chemical fertilizers when farmers create fertilizer or feedstock out of waste. Also, bioconversion of agrowastes provides bioenergy which increases alternative energy sources and minimizes fossil fuel utilization in remote areas feeding their energy upsurge. In the countryside, the growth of industries that manage waste—a full process starting from collection, treatment, and recycling—may provide employment opportunities whilst enhancing environmental conservation and economic development.

Approaches to mitigate the issue

In order to handle residues effectively, a bioeconomy strategy must modify traditional methods (Fig 3). During this shift, approaches that improve agricultural ecosystem sustainability must be implemented (Jordan *et al.*, 2007) [14]. Crop leftovers have traditionally been employed for a variety of purposes,

including roof thatching, bedding, animal feed, cooking fuel, and packing (Lohan *et al.*, 2018). Considering the current situation and the abundance of crop wastes, it is necessary to find alternate applications for them.

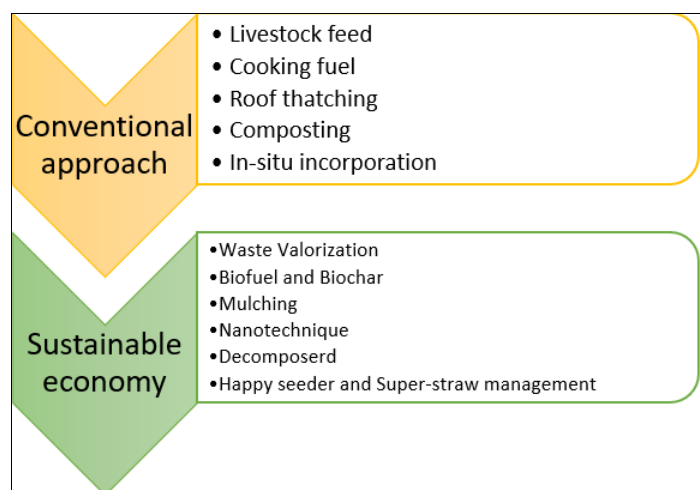


Fig 3: Crop Residue Management in India, a significant shift from traditional farming approach toward sustainable economy. (source- OPERATIONAL GUIDELINES FOR CROP RESIDUE MANAGEMENT -2023-24)

In-situ management

Using in-site approaches such as crop residues or Zero-till conservation agriculture is very eco-friendly and sustainable (Marjanovic, 2018 and Badarinath *et al.*, 2006)^[23]. Leaving crop residues on the land after harvest nourishes the soil, allows top soils to develop and provides organic nutrients due to decay. Decomposition of raw materials such as residues enriches the soil with organic material, aids in the development of top soil and provides essential nutrients such as nitrogen, phosphorus and sulphur. This allows reducing the risk of nitrogen outflow and the need for artificial fertilizers by controlling runoff and soil loss (Liu *et al.* 2023)^[20]. Additionally, it is sustainable to produce biochar from crop wastes. When applied with legumes, biochar increases biological nitrogen fixation (BNF), improves soil fertility, sequesters carbon, and increases the efficiency of fertilizer use (Rondon *et al.*, 2007; Mohan *et al.*, 2018). It is projected that turning paddy residue into biochar might save up to US\$ 10 million in fertilizer value yearly in India alone (Charvesting, 2016). Additionally, biochar made from agricultural leftover nutrients can yield 0.3–3.2 g/kg of nitrogen (Khare *et al.* 2021)^[17].

Composting

In India, composting is not a novel idea. Misra *et al.* (2003) define composting as the systematic breakdown of organic waste by microorganisms. Composting technologies, ranging from large-scale facilities to small-scale bio-compost units, enhance the efficiency and quality of organic fertilizers. In 2017, Pratap Singh and Prabha carried out an experimental trials and observational study on bio-composting. They use Vegetables, rice straw, wheat straw, and leaves as a part of the overall biomass used during this research. The ultimate bio-compost was a rich mixture of nutrients with total solids-45%, organic matter-26.7%, Carbon-15.3%, and total N-1.36%. They observed a considerable rise in the agronomic qualities of the rice and wheat crops they examined. As stated by Brady and Weil (1996), bio-compost nutrients, such as N and P, play a key role in agricultural cultivation techniques. Another form of in

situ composting is used in China, where leftover wheat or barley is buried in ditches that run alongside to the rice transplant (Peng *et al.*, 2006)^[27].

Machinery

Mechanized solutions can play an important role in reducing field burning and promoting efficient waste utilization. In standing stubble, crops can be sown using agricultural equipment like the Happy Seeder and Zero Till Seed Drill. Rotavators can also be used to incorporate agricultural leftovers into the soil (Mooventhan *et al.*, 2018) Likewise to this, the Paddy Straw Chopper minimizes the stalk and chaff so they can be composted more quickly. According to a study that was published in Science Magazine, the top scientific journal in the whole world, the Happy Seeder can, on typical, boost profit by US\$85–160 per hectare while lowering greenhouse gas emissions from crop combustion by more than 78% (Shyamsundar *et al.*, 2019; Keil *et al.*, 2020). Yet, many South Asian landowners find the expenses of owning and running these devices to be exorbitant. Consequently, to promote its use, it is essential to lower rental rates, subsidize fuels, and increase the number of machines available.

Bioenergy

The potential for producing clean energy from agricultural waste in the area was emphasized by Kashif *et al.* (2020). This covers the manufacturing of alternative fuels, biogas, and bioethanol (Kumar and Singh, 2021)^[18]. Furthermore, rice straw granules and charcoal briquettes have the potential to replace coal in power stations. Crop biomass has the potential to be used more widely because it makes about 10% of the nation's overall generation of energy (Ravindra *et al.*, 2019). According to Kashif *et al.* (2020), biomass extracted from crop residues could produce roughly 11,000 MW of electricity in Pakistan.

Bio-decomposers

It is necessary to provide bio-decomposer solutions with microbes that promote and improve in-situ composting of crop remains accessible and reasonably priced (Srinivasan and Abirami, 2020). For instance, farmers in India can purchase a crop-waste decomposer for around ₹20 per solution, which has the capacity to break down over ten thousand tons of crop residue within a month after spraying (Wangchuk, 2019).

Biochar

One of the environmentally beneficial ways of dealing with crop residue is to prepare biochar, which improves crop productivity and boosts soil fertility and retains carbon. Biochar was made by slowly pyrolyzing rice husk at 650 °C and maize stover at 550 °C. A decline in CO₂ emissions was observed along with a boost in many soil parameters when compared to biochar and unpyrolyzed rice husks in various soil types used for agriculture (Khare *et al.*, 2020)^[17]. Various methods were used to produce biochar, including pyrolysis, carbonization, hydrothermal, gasification and torrefaction. The kind of waste leftover and its chemical makeup dictate the properties of the synthesized biochar, and the time frame and temperature of the pyrolysis setup affect the biochar's excellence (Vijayaraghavan *et al.*, 2019)^[34]. Allesina *et al.*, estimated 130 kilogram of biochar can be produced annually from a one-hectare cotton crop. Instead of residue burning, using raw mulch and processed biochar in the field increased soil yield capacity (36%-64%) in the tested areas of South Asia (Dey *et al.*, 2020)^[8].

Nanotechnology

Nanotechnology presents enhanced opportunities for value addition to agricultural waste in a short span of time and, therefore, excludes the use of toxic chemicals which would otherwise cause various environmental and health problems. A greener nanomaterials (NM) synthesis using plant extracts from agricultural wastes has been gaining interests lately. These nanoparticles (NPs) have specific applications researched in detail for use as antibacterial agents, in water purification, decolouration of industrial dyes, and many others (Nath *et al.*, 2023)^[23]. In order to synthesize nanomaterials from agricultural waste, both top-down and bottom-up methods are essential. The top-down approach reduces bulk material to nanoscale particles through chemical or mechanical energy. Conversely, the bottom-up approach forms nanoparticles from individual atoms or molecules by adjusting factors like pressure, temperature, or using chemical substances (González-González *et al.*, 2022b)^[10]. Using palm pods, Dawwam *et al.*, (2022)^[7] produced bio-nanocomposites that prevent the spread of *Salmonella*, *E. Coli*, *Listeria monocytogenes*, and *Staphylococcus aureus*. The bio-nanocomposite was made by extracting cellulose nanocrystals, which were then utilized to synthesize zinc oxide. Because these nanoparticles prevented the production of exotoxins and growth of microbes, they also had an impact on the expression of genes linked to pathogenicity. Utilising rice husk waste, Unglaube *et al.* (2021)^[33] synthesized carbon-based and silver-containing silica composites. The nanomaterial had exceptional efficacy in combating virulent yeast *C. albicans*, *A. baumannii*, *E. fecium*, *S. aureus*, *K. pneumoniae*, *E. coli* and *P. aeruginosa*.

Government Policies and Initiatives

One major issue that the government is still battling with is minimizing or controlling the agricultural waste, crop post-harvest management particularly. The efforts and actions of the state and central government in this respect has been challenged in the courts several times. In this respect, both the state and central government have actively taken steps to control crop residues. Several approaches for efficient management of crop residue have been advocated and are elucidated.

National Bioenergy Programme

National Bioenergy Programme, launched by Minister of New and Renewable Energy(MNRE), seeks to utilize agricultural waste for energy. The period of the project is from FY 2021-22 till 2025-26 and various sub-schemes are included such as Waste to Energy Programme, Biomass Programme, Biogas Programme, etc (Vikaspedia 2024). These make possible putting up biogas, BioCNG, and power plants along with production of briquettes and pellets for power generation. The basic aim is reducing waste, producing clean energy and enhancement of natural ecology. The Indian government recently ordered the National Thermal Power Generation (NTPC) to produce 10% of the country's electricity using coal and agricultural residue briquettes. The farmers benefited from this, as it cost only Rs. 5500 per metric tons of agricultural leftover (Singh & Prabha, 2018)^[31]. These appealing methods are currently inactive but can be successfully applied by farmers. Only a few projects pertaining to bio-composting are supervised by the Indian government.

Subsidies and Financial Support

The government consider a multitude of subsidies and incentives in order to persuade the farmers in fully adopting the effectively useful measures of waste management, such as funding of the

expensive Happy Seeder and Straw Management System machines, assistance in the construction of biogas facilities and financial compensations aimed at composting technologies. Schemes such as Agro Machinery Service Center (AMSC), Submission on Agricultural Mechanization 9SMAM and Crop Diversification Program (CDP) are implemented (*Government Crop Residue Management Guidelines*). The financial burden to small scale farmers is further eased through the provision of these subsidies to encourage the use of eco-friendly practices. Moreover, 'Central Sector Scheme for Promotion of Agricultural Mechanisation for In-situ Management of Crop Residue' was also in force from 2018 to 2021 where subsidies were given for 50% for individual farmers and 80% for groups and cooperative societies to procure machinery for managing paddy straw (Ministry of Agriculture & Farmers Welfare 2021). Through these schemes, 76,626 CRM machines were distributed, and 19,836 custom hiring centers were established or strengthened.

Awareness Campaigns

National and regional campaigns are conducted to educate farmers about the negative impacts of burning crop residues on air quality and health. 65 Krishi Vigyan Kendras (KVKs) in Punjab, Haryana, and Uttar Pradesh are actively engaged in campaigns against residue burning (Ministry of Agriculture & Farmers Welfare 2022). These campaigns highlight the benefits of alternative waste management practices, such as using crop residues for bioenergy production, composting to improve soil health, and providing fodder for livestock. Over 357 KVKs in India are actively conducting training programs to instruct farmers on vermicomposting techniques. Through workshops, training sessions, and media outreach, these campaigns aim to change traditional practices and promote sustainable agriculture (Ministry of Agriculture & Farmers Welfare 2023).

Environment laws

Strict regulations have been implemented in India in recent years to minimize pollution and protect biodiversity. Some common laws are-The Environment Protection Act (EPA) 1986, the National Environmental Tribunal Act of 1995 (as amended in 2010), the National Environment Appellate Authority Act of 1997 (Gathala *et al.*, 2011)^[9]. The National Policy for Management of Crop Residue (NPMCR) 2014 by the Ministry of Agriculture and Farmers' Welfare (Govt. of India) with the primary objectives of tackling agricultural residue management. This promotes the use of advanced machinery; is supportive of industrial solutions, training of farmers, providing of funds and even promulgating relevant laws. This in turn makes it possible to achieve an effective and sustainable crop residue management that is advantageous to both the farmers and the ecosystem (NPMCR).

Case Studies and Success Stories

- Regions such as Punjab, Haryana, and Uttar Pradesh have made a lot of progress in the management of crop residues by Technologies like Happy Seeder machines and Super Straw Management System are already in place (Sen *et al.*, 2024)^[30]. Such measures in addition to encouraging the use of crop residues in other forms like bioenergy, composting or as fodder for livestock assist the farmers in minimizing the burning of residues while enhancing soil health (Porichha *et al.*, 2021)^[28].
- In the state of Tamil Nadu, the implementing composting practices has seen farmers with the intent of organic

fertilizers into agricultural fields and that of to marketing. The campaign implemented by the government on the community organic waste management has enlightened many on the need to reduce landfill usage and improve soils (Balasubramanian *et al.*, 2021)^[4].

- The initial project on generate bioenergy from crop and forest waste in India is initiated by Punjab government with Bharat Heavy Electricals Limited (BHEL) in 1992 by establishing Jalkheri, thermal power plant with capacity of 10 MW. Rice husk, wood chips, and stalks from various crops were used. Punjab State Electricity Board (PSEB) took the cost of the project, which was around Rs. 47.2 crores (Pramod *et al.*, 2015).
- Also, in Karnataka several biogas plants have been set up for the use of cow dung and agricultural waste to provide clean energy and reduce fertilizer application as in chemical-based fertilizers. Various schemes in the state including financial subsidies and incentives have been introduced to promote biogas plant installation among urban and rural households, industries and agriculture (MGRED Karnataka 2024). These measures introduced in different states depict a growing concern towards environmentally sustainable agriculture and waste management which are both advantageous to the farmers and the environment.
- In the year 2020-21, the Delhi Government applied Pusa Decomposer on 1920.20 acres of land, which effectively decomposed the corpses of the crops in 15-20 days and increased the wheat production by 8-10%. In this case also, in the year 2021, ICAR-IARI collaborated with a private agency to scale it up to more than 6,000 acres in Punjab covering 25,000 farmers, whereas Uttar Pradesh aims to cover 5,000 hectares. Pusa decomposer is now still under patent rights of 10 firms and is being manufactured on a large scale and sold in the markets (Biswas *et al.*, 2023). It enhances the soil by adding organic carbon and nutrients that are beneficial to the soil and provides an environmentally friendly option other than burning which destroys useful micro-organisms and contributes to air pollution.

Future Directions and Recommendations

- **Enhance Public-Private Partnerships (PPP):** Such infrastructure and technology can be developed for waste management by both the government and the private-sector actors, and even NGOs. These initiatives can also be made sustainable through farmer's involvement in decision-making processes and community-centered mechanisms.
- **Research Expansion for Waste to Value Technologies:** Emphasis on research and development to explore other alternatives of agricultural wastes especially those that can be turned into usable biodegradable raw materials, drugs, and biofuels of high orders. Farm equipment such as Happy Seeder, Rotavator, Zero Till Seed Drill, Baler and Paddy Straw Chopper are some the machines used by farmers to effectively deal with the crop waste. Developments in these areas can enhance these technologies' economic feasibility and ability for farmers to utilize them.
- **Encourage Circular Economy Models:** Encouraging the farmers and agribusiness to practice reduce-reuse-recycle principle where waste is treated as a resource encouraging them with such incentives. This results to minimizes waste, optimizes resource use, and promotes sustainable agricultural systems.

- **Strengthen Policy Implementation:** Due to the fact that accomplishing policy objectives without effective policy enforcement cannot be considered a success, other educational campaigns are necessary to educate the farmers on sustainable waste management. Provisions from the state like subsidies, training, awareness campaigns may assist the farmers in abandoning the traditional practice of burning and embracing cleaner options
- **Sustainable agriculture practices:** It is important to encourage the use of agriculture which produces less waste and utilizes more of the nutrients. Practices such as zero tillage, crop rotation and organic agriculture will help to limit residue burning and enhance soil health as well.

Conclusions

The research underscores the substantial effects of agricultural residue combustion on air quality, soil integrity, and human well-being in India. The ongoing directly combustion of agricultural leftovers, mainly wheat and rice, results in elevated concentrations of particulate matter, CO, NO₂, SO₂, CO₂ and O₃ in the environment. In addition to significantly affecting human health by degrading air quality, this practice causes considerable soil nutrient loss, therefore reduces yields from agriculture. Approaches like in situ incorporation, biofuel, nanotechnology, composting, bio-decomposers and biochar are some management techniques and Happy Seeder and Zero Till Seed Drill mechanised advancements have been put forward and brought into practice to tackle these issues. Furthermore, there are more proactive measures that can be taken by government agencies, such as encouragement for need-based assistance, and other options aimed at preventing residue burning, than resorting to strict enforcement of the law. Lastly, the article addresses the ecological and geographical consequences of burning agro-residues in the open air and, more optimistically, offers alternative management practices. Should these techniques be widely implemented, they would assist in alleviating many environmental concerns currently discussed, and would be beneficial to the global agricultural market.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests:

No competing interest

Author Contributions: Dr Rajeev Kumar has the idea for the review article, Jyoti Nagar performed literature search, data analysis and drafted the article and Dr Rajeev Kumar critically revised the work.

Data availability: No datasets were generated or analysed during the current study.

Conflict of Interest: The authors do not have any conflict of interest.

Ethics Approval Statement: This review paper does not involve any experimentation of ethical concern.

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