

Experimental Investigation and Process Optimisation of Agricultural Stubble Composting Using Spectral and Physico- Chemical Characterisation

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Abstract:

Agricultural stubble management has emerged as a significant environmental, agricultural, and policy challenge in India, particularly due to the widespread practice of open-field burning of crop residues. The burning of agricultural stubble contributes substantially to air pollution, greenhouse gas emissions, loss of valuable soil nutrients, and adverse public health impacts. With increasing emphasis on sustainable agriculture and climate-resilient development, there is a growing need to identify and promote environmentally sound alternatives for crop residue management. This study examines the major sustainable utilization technologies available for agricultural stubble management in India, with a particular focus on composting and its comparison with other residue valorization approaches.

Keywords: Agricultural Stubble, Crop Residue Management, Composting, Environmental Sustainability

1. INTRODUCTION

In India, agriculture is a key pillar of the economy and food security, and it also produces large quantities of agricultural waste. This waste includes crop residues, agro-processing by-products, and livestock manure. Notably, the country generates over 500 million tonnes (MT) of crop residues each year.¹ Traditional methods of agricultural waste management, such as open dumping and burning in fields, cause significant air pollution and pose serious risks to human health. This highlights the pressing need for adopting more sustainable and environmentally friendly waste management practices.² Although traditional practices such as using crop residues for animal feed, mulching, and composting offer some benefits, they are often insufficient to manage the large volume of agricultural waste and its associated environmental impacts. In recent years, there has been growing attention toward sustainable agricultural waste management through waste valorization approaches that transform waste into useful resources and support a circular

¹ D. Das, A. Anand, S. Gautam, V.K. Rajak, Assessment of utilization potential of biomass volatiles and biochar as a reducing agent for iron ore pellets, *Environ. Technol.* 45 (2024) 158–169, <https://doi.org/10.1080/09593330.2022.210293>

² V. Venkatramanan, S. Shah, A.K. Rai, R. Prasad, Nexus between crop residue burning, bioeconomy and sustainable development goals over north-western India, *Front. Energy Res.* 8 (2021) 1–14, <https://doi.org/10.3389/fenrg.2020.614212>.

economy. Practices such as composting, bioenergy production, and residue recycling not only help reduce environmental hazards but also contribute to circular economic systems by converting waste into valuable inputs. Hence, the adoption of innovative and sustainable waste management strategies can enhance agricultural productivity while strengthening climate resilience and ensuring long-term ecological and economic sustainability.

Various waste valorization techniques include pyrolysis, gasification, anaerobic digestion, biorefining, and bioprocessing. For instance, an integrated biorefinery approach can effectively convert agricultural waste into useful outputs such as biogas, biofuels, and other value-added products. These may also include biochar, eco-friendly fibres, cellulose-based nanomaterials, and enzymes, produced through thermochemical, biological, and biochemical conversion processes.³ Additionally, bioactive compounds, bio-stimulants, biofertilizers, and bio-plastics derived from agricultural waste further exemplifying the innovations in sustainable processing of agricultural waste⁴. Several recent studies have noted that nearly 180 million tonnes (MT) of surplus crop residues are generated annually in India, which possess considerable potential for a wide range of applications. It has also been emphasized that agricultural waste streams in the country are increasingly receiving attention for their conversion into valuable resources, thereby addressing both effective waste management and resource recovery.⁵

In developing countries such as India, the use of agricultural residues as a non-conventional energy source is considered both economically viable and environmentally sustainable for meeting growing energy demands.⁶ For example, biogas produced from agricultural waste can be effectively used for cooking, heating purposes, the production of biofuels, and electricity generation.⁷ The state-wise potential of power generation from agricultural waste in India shows considerable variation, with Uttar Pradesh leading at approximately 6045 MW. It is followed by Punjab and Maharashtra, each having a capacity exceeding 3000 MW.⁸ However, it is imperative to mention that the economic feasibility of biomass-driven power plants heavily relies on the durable and reliable supply of essential feedstock materials. Agricultural waste has further potential to be applied to various building materials like bricks, cementitious materials, and other

³ T.P.T. Pham, R. Kaushik, G.K. Parshetti, R. Mahmood, R. Balasubramanian, Food waste-to-energy conversion technologies: current status and future directions, *Waste Manag.* 38 (2015) 399–408, <https://doi.org/10.1016/j.wasman.2014.12.0>

⁴ A.P. Thomas, V.P. Kasa, B.K. Dubey, R. Sen, A.K. Sarmah, Synthesis and commercialization of bioplastics: organic waste as a sustainable feedstock, *Sci. Total Environ.* 904 (2023) 167243, <https://doi.org/10.1016/j.scitotenv.2023.16724>

⁵ J. Singh, Management of the agricultural biomass on decentralized basis for producing sustainable power in India, *J. Clean. Prod.* 142 (2017) 3985–4000, <https://doi.org/10.1016/j.jclepro.2016.10.056>.

⁶ R. Devi, V. Singh, R.P. Dahiya, A. Kumar, Energy consumption pattern of a decentralized community in northern Haryana, *Renew. Sustain. Energy Rev.* 13 (2009) 194–200, <https://doi.org/10.1016/j.rser.2007.05.007>.

⁷ N. Kamalimeera, V. Kirubakaran, Prospects and restraints in biogas fed SOFC for rural energization: a critical review in Indian perspective, *Renew. Sustain. Energy Rev.* 143 (2021) 110914, <https://doi.org/10.1016/j.rser.2021.110914>.

⁸ J. Singh, Management of the agricultural biomass on decentralized basis for producing sustainable power in India, *J. Clean. Prod.* 142 (2017) 3985–4000, <https://doi.org/10.1016/j.jclepro.2016.10.056>.

insulating composites⁹. Moreover, carbon derived as biochar or bio-sorbents from agricultural waste through thermochemical processes have shown promising potential in remediating contaminated water and wastewater by removing organic and inorganic pollutants¹⁰. In addition, crop residues can serve as feedstock for second-generation biofuels, producing approximately 60 billion litres (L) of bioethanol per annum¹¹. Beyond biofuel production, agricultural wastes can be effectively utilized for composting, nanomaterial synthesis, mushroom cultivation, and biogas generation, as well as serving as raw materials in industries such as paper, construction, cosmeceuticals, and pharmaceuticals. This diversified utilization of agricultural residues can partially replace conventional fossil-based feedstocks, thereby enhancing both environmental sustainability and economic value. In addition, the use of microorganisms to convert agricultural waste into value-added products—including biomolecules, biofuels, biofertilizers, organic acids, enzymes, essential oils, and flavours—exploits microbial processes for efficient energy and nutrient recovery. This approach supports a sustainable economy and a zero-waste framework, offering significant potential for wider application in India.¹²

2. RESEARCH OBJECTIVE

To critically examine and compare various sustainable agricultural stubble management technologies in India, with particular emphasis on composting and alternative residue utilization approaches, in order to identify environmentally, economically, and socially viable solutions for sustainable agricultural development.

3. RESEARCH HYPOTHESIS

Sustainable agricultural stubble utilization technologies such as composting, biochar production, biomass energy generation, and conservation agriculture offer significantly greater environmental and economic benefits than conventional stubble burning practices.

4. RESEARCH METHODOLOGY

The present study follows a doctrinal and descriptive research design, relying entirely on secondary data to analyze and compare different sustainable agricultural stubble management technologies in India. The research is analytical in nature and aims to assess the effectiveness, practicality, and sustainability of methods such as composting, biochar production, biomass-based energy generation, in-situ residue management practices, and

⁹ T. Selvaraj, P. Devadas, J.L. Perumal, A. Zabaniotou, M. Ganesapillai, A comprehensive review of the potential of stepwells as sustainable water management structures, *Water (Switzerland)* 14 (2022), <https://doi.org/10.3390/w141726>

¹⁰ K. Harshala, N.D. Wagh, Use of agricultural waste-based biosorbents for the removal of heavy metals from aqueous solution: a review, *Nat. Environ. Pollut. Technol.* 21 (2022) 1003–1014, <https://doi.org/10.46488/NEPT.2022.v21i03.00>

¹¹ N. Kumar, A. Chaudhary, O.P. Ahlawat, A. Naorem, G. Upadhyay, R.S. Chhokar, S.C. Gill, A. Khippal, S.C. Tripathi, G.P. Singh, Crop residue management challenges, opportunities and way forward for sustainable food-energy security in India: a review, *Soil Tillage Res.* 228 (2023) 105641, <https://doi.org/10.1016/j.still.2023.105641>

¹² J.C. Bose K, J. Sarwan, Multi-enzymatic degradation potential against wastes by the novel isolate of *Bacillus*, *Biomass Convers Biorefin* (2023), <https://doi.org/10.1007/s13399-023>

the industrial utilization of agricultural residues. A comparative framework has been used to evaluate the relative strengths and limitations of these technologies from environmental, economic, and social viewpoints.

The study relies primarily on secondary sources of data, including peer-reviewed journal articles, books, government reports, policy documents, conference proceedings, reports of national and international organizations, and publications of research institutions.

5. REVIEW OF LITERATURE

A. Sudharshan Reddy et al (2025)¹³ explain that Agricultural waste management is crucial for agriculture-based economies like India, generating approximately 500 million tons of agricultural residue annually. The agriculture sector is the second-largest contributor to India's total greenhouse gas (GHG) emissions, accounting for 13.72%, which is higher than the global average of 11%. In addition, the sector is under increasing pressure not only to ensure food security for a growing population but also to reduce GHG emissions. Although intensive farming improves productivity and efficiency, it also creates environmental concerns due to the large accumulation of agricultural residues. However, the sustainable utilization of these residues offers dual advantages, including energy production and resource recovery. This study aims to provide a comprehensive overview of sustainable agricultural waste management practices, challenges, and the role of policy interventions in shaping its future. Agricultural residues demonstrate significant potential as sources for value-added products and energy feedstocks. Waste valorization techniques provide sustainable solutions for agricultural waste management while enabling energy recovery and supporting the principles of a circular economy. This study also examines the recovery of construction materials such as insulating materials, roofing components, additives, and secondary cementitious materials derived from agricultural residues. At present, agricultural residues in India are mainly used for biofuel production, with an installed plant capacity of around 5 million tonnes, along with solid biofuel generation. Nevertheless, several techno-economic, socio-cultural, institutional, and governance-related challenges still need to be addressed to ensure the sustainable management of surplus agricultural residues through emerging technologies. The objective of this study is to encourage the integration of academic research, scientific innovation, and industrial development, while strengthening the circular economy, particularly in agriculture-dependent economies.

Jobanpreet Singh Sohi et al (2025)¹⁴ have observed that crop residue burning, especially of wheat and rice, is a common farming activity with serious environmental and health impacts. Crop stubble is usually burned by farmers to rapidly prepare land for the next crop season, emitting toxic pollutants, such as GHGs like carbon dioxide and methane,

¹³ A. Sudharshan Reddy, Vara Prasad Kasa, Biswajit Samal, Brajesh Kumar Dubey, Vinay Yadav, Daya Shankar Pandey, Sustainable agricultural waste management in India: Innovations, challenges, and future perspectives, Biomass and Bioenergy, Volume 202, 2025, <https://doi.org/10.1016/j.biombioe.2025.108261>.

¹⁴ Sohi, Jobanpreet singh & Sultana, Wahida & Rajput, Jyoti. (2025). Transforming Crop Residue Waste into Sustainable Resources: Innovative Pathways for Enhancing Agricultural Productivity and Environmental Health. International Journal of Advanced Research and Interdisciplinary Scientific Endeavours. 2. 2025. 10.61359/11.2206-2514.

and particulate matter that causes air pollution. This practice also depletes soil fertility by destroying organic matter and essential microbial activity, leading to long-term degradation of agricultural land. This review article explores sustainable alternatives to crop residue burning, focusing on environmentally friendly and economically viable solutions. Key alternatives include bioenergy production, where crop residues are converted into biofuels or biochar, providing renewable energy while reducing greenhouse gas emissions. Similarly, composting crop residues into organic manure improves soil fertility, enhances water retention capacity, and reduces dependence on chemical fertilizers. Mulching, covering the soil with crop residues, saves moisture, suppresses erosion, and manages weeds. Industrial applications are also mentioned in the paper, including residue conversion into biodegradable paper and packaging, animal feed, and fuel briquettes or pellets for village energy. Technological innovations such as the Happy Seeder and Super Straw Management System (SMS) offer no-burn solutions by enabling sowing of seeds directly into fields without the need for residue burning, thereby helping conserve soil health. However, despite their benefits, adoption remains limited due to financial constraints, inadequate infrastructure, and low awareness among farmers. The review therefore recommends policy interventions, government incentives, and awareness and training programs to encourage wider adoption of these sustainable alternatives.

Gaurav Kumar Porichha et al (2021)¹⁵ have opined that in recent studies, various reports reveal that stubble burning of crop residues in India generates nearly 150 million tons of carbon dioxide (CO₂), more than 9 million tons of carbon monoxide (CO), a quarter-million tons of sulphur oxides (SOX), 1 million tons of particulate matter and more than half a million tons of black carbon. These practices contribute significantly to environmental pollution, including the formation of dense haze in India's capital, New Delhi, as well as the retreat of Himalayan glaciers. Although stubble burning is a punishable offence under Section 188 of the Indian Penal Code (IPC) and the Air (Prevention and Control of Pollution) Act, 1981, weak enforcement of these regulations has been observed in many parts of the country. Instead of burning, crop residues can be effectively utilized in several alternative applications, such as cattle feed, composting with manure, rural roofing materials, bioenergy production, beverage processing, packaging materials, wood and paper products, and bioethanol generation. This review article examines the current status of stubble burning practices in India and highlights various alternative valorization methods for crop residues. Overall, it provides a comprehensive understanding of the adverse impacts of improper crop residue management through burning, along with more sustainable approaches—particularly bioenergy utilization—which, if widely adopted, can reduce environmental damage and generate additional value for the agricultural sector globally.

6. COMPOSTING AS A SUSTAINABLE STUBBLE MANAGEMENT TECHNOLOGY

Composting is the natural process of 'rotting' or decomposition of organic matter by microorganisms under controlled conditions. Raw organic materials such as crop

¹⁵ Porichha, Gaurav Kumar, Yulin Hu, Kasanneni Tirumala Venkateswara Rao, and Chunbao Charles Xu. 2021. "Crop Residue Management in India: Stubble Burning vs. Other Utilizations including Bioenergy" *Energies* 14, no. 14: 4281. <https://doi.org/10.3390/en14144281>

residues, animal wastes, food garbage, some municipal wastes and suitable industrial wastes, enhance their suitability for application to the soil as a fertilizing resource, after having undergone composting.

A mass of decomposed organic material derived from waste is known as compost. Compost produced from agricultural residues such as sugarcane trash, paddy straw, weeds, and other plant waste is referred to as farm compost. It typically contains average nutrient levels of about 0.5% nitrogen (N), 0.15% phosphorus (P_2O_5), and 0.5% potassium (K_2O). The nutrient content of farm compost can be enhanced by adding superphosphate or rock phosphate at a rate of 10–15 kg per tonne of raw material during the initial stage of compost pit preparation.

Compost prepared from municipal waste materials such as night soil, street sweepings, and dustbin refuse is known as town compost. It generally contains higher nutrient values, approximately 1.4% nitrogen, 1.0% phosphorus (P_2O_5), and 1.4% potassium (K_2O). Farm compost is usually prepared by filling trenches of suitable dimensions, typically 4.5–5.0 m in length, 1.5–2.0 m in width, and 1.0–2.0 m in depth. Agricultural waste is added layer by layer, with each layer properly moistened using cow dung slurry or water. The trenches are filled up to about 0.5 m above ground level. The compost becomes ready for use within five to six months.

Compost has long been recognized as a valuable soil amendment for centuries. It is widely known that the application of compost helps enhance healthy plant growth, reduce production costs, minimize the use of chemical fertilizers, and conserve natural resources. Compost supplies stable organic matter that improves the physical, chemical, and biological properties of soil, thereby strengthening overall soil quality and increasing crop productivity. When applied appropriately, compost positively influences soil characteristics, creating favorable conditions for root development and ultimately supporting higher yields and improved crop quality.

- Improves the Physical Properties of Soils.
- Enhances the Chemical Properties of Soils.
- Improves the Biological Properties of Soils.
- Economic and Social Benefits of Composting.

7. ALTERNATIVE SUSTAINABLE UTILIZATION TECHNOLOGIES FOR AGRICULTURAL STUBBLE

7.1. Biochar Production

Biochar production has emerged as a promising and environmentally sustainable method for utilizing agricultural stubble. Biochar is a carbon-rich material obtained through the thermochemical conversion of biomass under limited oxygen conditions, commonly referred to as pyrolysis. Agricultural residues such as rice straw, wheat straw, maize stalks, and sugarcane bagasse serve as suitable feedstocks for biochar production due to their high availability and significant carbon content. During pyrolysis, biomass is heated at temperatures between 300°C and 700°C, leading to the breakdown of organic matter into biochar, bio-oil, and syngas. The properties of the resulting biochar vary depending

on factors such as feedstock type, pyrolysis temperature, heating rate, and residence time. In general, higher pyrolysis temperatures increase the aromatic carbon content and stability of biochar, making it an effective long-term carbon sequestration material.¹⁶

The application of biochar provides a wide range of agronomic and environmental benefits. When applied to soil, it enhances soil structure, improves water-holding capacity, increases nutrient retention, and stimulates microbial activity, thereby supporting higher crop productivity. In addition, biochar plays an important role in climate change mitigation by sequestering carbon that would otherwise be released into the atmosphere through residue burning or natural decomposition. However, despite these advantages, the large-scale adoption of biochar technology is constrained by several challenges, including high initial investment costs, limited awareness among farmers, difficulties in feedstock collection, and inadequate commercialization infrastructure. Moreover, the economic feasibility of biochar production is influenced by factors such as market demand, transportation expenses, and the availability of supportive policy incentives for sustainable agricultural practices.¹⁷

7.2. Biomass-Based Energy Generation

Agricultural stubble represents a valuable source of renewable energy that can contribute significantly to India's transition toward a low-carbon economy. Biomass-based energy generation technologies convert crop residues into useful forms of energy, thereby reducing dependence on fossil fuels and minimizing environmental pollution associated with open-field burning. Direct combustion remains the most commonly employed technology, wherein agricultural residues are burned in boilers to generate steam and electricity. Several biomass power plants in India utilize rice straw, cotton stalks, and sugarcane residues as fuel. Although direct combustion is technologically mature and commercially viable, issues such as low energy density, high moisture content, and transportation costs may affect operational efficiency¹⁸.

Advanced thermochemical technologies such as gasification and pyrolysis offer improved energy conversion efficiencies. Gasification converts biomass into producer gas or syngas through partial oxidation at high temperatures, which can then be used for electricity generation and industrial heating applications. In contrast, pyrolysis produces bio-oil, biochar, and combustible gases, thereby generating multiple value-added products from a single feedstock.

Biochemical conversion routes such as bioethanol and biogas production have also gained significant importance. Agricultural residues rich in cellulose and hemicellulose can be converted into second-generation bioethanol through processes involving enzymatic hydrolysis followed by fermentation. Similarly, anaerobic digestion of crop residues produces biogas containing methane, which can be used for cooking, heating, and

¹⁶ Johannes Lehmann & Stephen Joseph (eds.), *Biochar for Environmental Management: Science, Technology and Implementation* 35-58 (2nd ed., Routledge, London, 2015).

¹⁷ D. Woolf, J.E. Amonette, F.A. Street-Perrott, J. Lehmann & S. Joseph, "Sustainable Biochar to Mitigate Global Climate Change", 1 *Nature Communications* 56, at 58-62 (2010).

¹⁸ P. McKendry, "Energy Production from Biomass (Part 1): Overview of Biomass", 83 *Bioresource Technology* 37, 38-45 (2002).

electricity generation. Overall, these technologies promote resource recovery and circular economy goals while simultaneously reducing greenhouse gas emissions associated with residue disposal.¹⁹

7.3. In-Situ Residue Management

In-situ residue management refers to the practice of retaining and managing crop residues directly in the field instead of removing or burning them. This method has gained significant attention as a sustainable alternative to stubble burning, especially in the Indo-Gangetic Plains, where residue burning is a major contributor to seasonal air pollution. Mulching is one of the most common in-situ management practices, which involves spreading crop residues across the soil surface. The mulch layer helps conserve soil moisture, suppress weed growth, regulate soil temperature, and reduce soil erosion. Over time, the gradual decomposition of residues adds organic matter to the soil and supports nutrient recycling, thereby improving soil fertility and enhancing overall crop productivity.²⁰

The introduction of the Happy Seeder technology has revolutionized residue management in north-western India. The Happy Seeder enables direct sowing of wheat into fields covered with rice residues without requiring residue removal or burning. This technology facilitates conservation agriculture practices by minimizing soil disturbance, retaining crop residues, and promoting sustainable crop production. Conservation agriculture integrates principles such as minimum tillage, permanent soil cover, and crop diversification to enhance soil health and resource-use efficiency. Numerous studies have reported improvements in soil organic carbon, water-use efficiency, and long-term crop productivity under conservation agriculture systems. However, challenges related to machinery costs, farmer awareness, and localized technical support continue to influence adoption rates²¹.

7.4. Animal Feed and Industrial Applications

Agricultural stubble has traditionally been an important source of livestock feed, especially in regions where fodder availability is limited. Crop residues such as wheat straw, rice straw, maize stover, and sorghum stalks are commonly used as roughage for cattle, buffaloes, sheep, and goats. To improve their nutritional value and digestibility, various physical, chemical, and biological treatment methods have been developed. Techniques such as urea enrichment, ammonia treatment, and microbial fermentation help enhance nitrogen content and improve the efficiency of feed utilization by ruminant animals. The use of agricultural residues as animal fodder not only supports livestock

¹⁹ V.K. Gupta, M.G. Tuohy & E. Kubicek (eds.), *Bioenergy Research: Advances and Applications* 121-150 (Elsevier, Amsterdam, 2014).

²⁰ Rattan Lal, "Crop Residue Management and Soil Carbon Sequestration", 98 *Soil and Tillage Research* 1, 4-11 (2008).

²¹ M.L. Jat, Y.S. Saharawat, A. Gupta & R.K. Gupta, "Conservation Agriculture in Cereal Systems of South Asia", 43 *Integrated Crop and Resource Management in South Asia* 127, 133-145 (2009).

production but also reduces pressure on natural grazing lands and promotes more integrated and sustainable farming systems.²²

Beyond their use as animal feed, agricultural stubble also has significant industrial applications. The paper and packaging industries are increasingly using agricultural residues as alternative raw materials to wood pulp, thereby reducing pressure on forest resources. Residues such as rice straw, wheat straw, and bagasse have suitable fibrous properties for paper production, biodegradable packaging materials, and molded fiber products. In addition, advances in biomaterials research have enabled the development of bio-based composites, particle boards, bioplastics, and construction materials derived from crop residues. These innovations support resource efficiency, waste valorization, and the objectives of a circular bioeconomy. However, challenges such as feedstock collection, processing infrastructure, quality standardization, and market competitiveness still need to be addressed to promote wider industrial adoption of agricultural stubble utilization.²³

8. CHALLENGES AND BARRIERS TO EFFECTIVE AGRICULTURAL WASTE MANAGEMENT IN INDIA

8.1. Technical Challenges

One of the significant obstacles in agricultural waste management in India is the absence of advanced technical infrastructure for efficient waste collection, processing, and conversion. The lack of appropriate waste segregation and inefficient waste collection systems contribute to the poor handling and disposal of agricultural waste²⁴. In addition, the existing technologies for agricultural waste valorization, such as biogas plants and composting units, often suffer from inefficiencies and scalability issues²⁵. Furthermore, the high moisture content and heterogeneous composition of agricultural waste create technical challenges in its processing and conversion into value-added products. Despite the significant potential of biomass-based power generation, its effective utilization is constrained by issues such as biomass collection logistics and elevated moisture levels. Overcoming these challenges requires the adoption of suitable technologies, the integration of thermochemical, biological, and biochemical conversion pathways, and the implementation of supportive policies to promote biomass energy use. In addition, the availability of feedstock for different valorization processes fluctuates due to variations in cropping patterns.²⁶

²² C. Devendra, *Crop Residues for Feeding Animals in Asia: Technology Development and Adoption in Crop-Livestock Systems* 15-28 (FAO, Rome, 2010).

²³ S.P. Singh, P. Pandey & A.K. Srivastava, "Utilization of Agricultural Residues for Sustainable Industrial Applications", *29 Renewable and Sustainable Energy Reviews* 72, 75-84 (2014).

²⁴ S. Kumar, S.R. Smith, G. Fowler, C. Velis, S.J. Kumar, S. Arya, Rena, R. Kumar, C. Cheeseman, Challenges and opportunities associated with waste management in India, *R. Soc. Open Sci.* 4 (2017), <https://doi.org/10.1098/rsos.160764>.

²⁵ P.K. Das, Present scenario of waste management in India, *American International Journal of Social Science Research* 5 (2020) 22–32, <https://doi.org/10.46281/aijssr.v5i1.4>

²⁶ V. Punnathanam, Y. Shastri, Impact of change in cropping pattern on bioenergy system design: analysis and stochastic optimization, *Comput. Chem. Eng.* 165 (2022) 107940, <https://doi.org/10.1016/j.compchemeng.2022.107940>.

8.2. Economic Challenges

Financial constraints further exacerbate these technical challenges. The initial capital expenditure needed to establish advanced waste management facilities, such as biorefineries and thermochemical conversion plants, is substantial. Small and tiny farmers, who account for most of the agricultural sector in India, often lack the financial resources to invest in such technologies²⁷. Additionally, the collection of agricultural residues and their transportation to treatment facilities and storage sites often involve substantial economic costs. Moreover, the economic feasibility of these technologies is frequently influenced by inconsistent government subsidies and policy support, which creates uncertainty and adversely affects their large-scale deployment.

8.3. Social Challenges

Social and cultural factors are also critical players in the acceptance and success of agricultural waste management practices in India. Traditional ways, like field crop residue burning, are deeply ingrained in the agricultural community due to their perceived simplicity and cost-effectiveness. Changing these entrenched practices requires significant efforts in awareness-building and education about the environmental and health effects of these methods. Creating awareness among farming groups regarding conservation agriculture is crucial for promoting sustainable residue management²⁸.

Furthermore, the adoption of new technologies and practices is often constrained by limited awareness and lack of trust among farmers. Therefore, there is a strong need for extensive outreach programs and demonstration projects to clearly illustrate the benefits of advanced waste management techniques. In addition, cultural resistance to changing long-established traditional practices, particularly in rural areas, acts as a major barrier to the widespread implementation of sustainable agricultural waste management systems.

8.4. Political Challenges

Political challenges are also significant in the field of agricultural waste management in India. There is often inadequate coordination among different government departments responsible for agriculture, environment, and energy, resulting in fragmented and inefficient policy implementation. Furthermore, existing regulations and policies may not fully capture the complexity and regional diversity of agricultural waste generation and its management.

For example, government incentives such as schemes, grants, and subsidies at both central and state levels have played an important role in promoting the adoption of

²⁷ D. Vij, Urbanization and solid waste management in India: present practices and future challenges, *Proced. Soc. Behav. Sci.* 37 (2012) 437–447, <https://doi.org/10.1016/j.sbsp>

²⁸ S. Kumar, S.R. Smith, G. Fowler, C. Velis, S.J. Kumar, S. Arya, Rena, R. Kumar, C. Cheeseman, Challenges and opportunities associated with waste management in India, *R. Soc. Open Sci.* 4 (2017), <https://doi.org/10.1098/rsos.160764>.

gasification units. The effective implementation of such programs is essential for achieving long-term targets related to biomass-based installed capacity in India.²⁹

The enforcement of waste management regulations is often weak, resulting in poor compliance and the continued use of unsustainable practices such as open burning. In addition, the absence of a comprehensive national policy on agricultural waste management leads to fragmented and uncoordinated efforts at the state and local levels. Therefore, strengthening institutional frameworks and improving governance mechanisms is essential for ensuring effective agricultural waste management in India.

9. CONCLUSION

Agricultural stubble management is a vital aspect of sustainable agricultural development and environmental protection in India. The study indicates that sustainable alternatives such as composting, biochar production, biomass-based energy generation, in-situ residue management, and industrial applications provide effective solutions to the problems associated with open-field burning of crop residues. Among these options, composting is particularly significant for improving soil health and recycling nutrients, while other technologies support renewable energy production and resource recovery.

Therefore, adopting an integrated, technology-driven approach—backed by strong policy support, financial incentives, and farmer awareness programmes—is crucial for converting agricultural stubble from an environmental burden into a valuable resource for sustainable development.

²⁹ S. Sultan, Solid waste management in urban India: an overview, *Int. J. Environ. Protect. Pol.* 5 (2017) 61, <https://doi.org/10.11648/j.ijep.20170504.13>.

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