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AGRICULTURAL CROP-RESIDUE WASTE CONVERTED INTO ELECTRICITY IN INDIA

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ABSTRACT

The importance of adopting a "waste-to-wealth" approach lies in reusing waste as a valuable resource rather than an economic burden and environmental issue. India's agricultural residues have the potential to generate over 18,000 MW of power annually. Biogas plants are a progressive step taken by the Government of India to curb crop burning to prevent pollution. In India, as agriculture plays a pivotal role in ensuring food and nutritional security, it also generates significant waste during cultivation, harvesting, and processing. Agricultural waste is generated throughout the journey from farm to food plate. Inadequate management of agricultural waste has become a substantial source of environmental contamination affecting air, soil, and water. Agricultural waste management in India presents both significant challenges and opportunities. Traditional practices, particularly crop residue burning, although ingrained, are often unsustainable and environmentally damaging. Residue burning leads to the depletion of soil nutrients, degradation of soil health, and the emission of greenhouse gases. The implementation of advanced waste valorization methods, like thermochemical and biochemical processes, can transform agricultural waste into valuable products, contributing to the circular economy and sustainable development. Various agricultural wastes are generated in large amounts with different compositions, which plays an important role in selecting suitable velarization methods. Addressing the technical, financial, social, cultural, and institutional barriers is crucial for the successful implementation of sustainable waste management. Effective policy implementation is crucial for promoting sustainable agricultural waste management practices in India.

Keywords: Agricultural waste, Biogas, Electricity, Environmental issues, India, Velarization.

1 INTRODUCTION

Agricultural waste management is crucial for agriculture-based economies like India, generating approximately 500 million tons of agricultural residue annually [1-44-50]. The agriculture sector is the second largest contributor to India's total greenhouse gas (GHG) emissions, with a share of 13.72 % compared to global average of 11 % [1-23-34-44]. Furthermore, the agriculture sector is not only strained to secure food production for growing population but also

expected to minimize GHG emissions [1-48]. Intensive farming, while more productive and efficient, poses a threat to the environment due to accumulation of large quantities of agricultural residue [1-48-55]. Nevertheless, the sustainable conversion of agricultural residue could offer twin benefits: energy generation and resource recovery. The growing scale of waste generation has emerged as a critical environmental challenge with substantial economic implications [1-48-56]. Currently, agricultural residue in India is primarily utilized to produce biofuels with installed plant capacity of 5 million tons, and solid biofuel [1-48-59-218-221]. In India, as agriculture plays a pivotal role in ensuring food and nutritional security, it also generates significant waste during cultivation, harvesting, and processing [1-38-56-218]. Inadequate management of agricultural waste has become a substantial source of environmental contamination affecting air, soil, and water [1-48-61]. The country generates an estimated 500 million tons of agricultural waste annually, comprising crop residues, husk, straw, and by-products from food processing activities [1-28-62]. The agricultural waste cycle begins at the post-harvest stage, when crops leave behind residues such as stalks, straw, and stubble. Agricultural waste is generated throughout the journey from farm to food plate [1-48-68]. It includes crop residues, animal manure, processing by-products, and effluents produced during crop cultivation, livestock rearing, post-harvest handling, and the processing of grains, fruits, vegetables, sugarcane, oilseeds, and dairy products [1-58-70]. A substantial proportion of this biomass is productively utilized as cattle feed, compost, biogas, mulch, or fuel [1-48]. However, a significant share is still burned in situ to facilitate rapid land preparation for subsequent cropping cycles [1-48-67]. Residue burning leads to the depletion of soil nutrients, degradation of soil health, and the emission of greenhouse gases [1-68]. The importance of adopting a "waste-to-wealth" approach lies in reimagining waste as a valuable resource rather than an economic burden and environmental issue. It necessitates a rethinking of material flows within the economy, emphasizing the recovery, reuse, and reintegration of value [1-48-80]. The circular economy has emerged as the most comprehensive and scalable approach for enhancing resource efficiency across the full lifecycle of products and processes [1-68-75-218-218-221].

According to the Ministry of New and Renewable Energy, India's agricultural residues have the potential to generate over 18,000 MW of power annually [1-78]. In addition to energy generation, these residues can be used to produce nutrient-rich organic fertilizers [1-78-221]. Such fertilizers could help to enhance soil health and reduce dependence on chemical inputs in agriculture. Converting agricultural residues into electricity in India is vital for reducing reliance on fossil fuels, curbing crop burning, and boosting rural economies [1-78-218]. India generates massive amounts of surplus crop residue—such as rice straw, wheat straw, and sugarcane bagasse—which are converted into power through biomass cogeneration and anaerobic digestion [1-88-218-221]. In addition, globally, an estimated 1.3 billion tons of food produced for human consumption are wasted annually, while nearly one-third of biodegradable municipal solid waste is generated in household kitchens [1-68-80]. When organic waste, such as food waste, agricultural residues, and other biodegradable municipal waste, is inadequately managed, it decomposes in landfills, releasing methane and other greenhouse gases [1-68-80]. This contributes to air and groundwater pollution, generates noxious odors, and accelerates environmental degradation, thereby intensifying the impacts of climate change [1-68-84-218]. Therefore, land use, resource utilization, and sustainable waste management solutions have become both environmental priorities and economic necessities [1-68-80].

2 FOOD WASTE

Food waste occurs later in the value chain, including markets, retail outlets, and households, where edible food is discarded [1-48-50]. Such wastage contributes significantly to greenhouse gas emissions [1-48-50]. However, emerging technologies are increasingly converting food waste into value-added products, such as engineered biochar, which has the potential to sequester carbon, enhance soil health, and remove environmental contaminants [1-48-50]. By transforming waste into a resource, food waste management is evolving into a crucial pillar of circularity within the agriculture and food systems [1-48-50]. Biochar is a carbon-rich material made by heating biomass (such as crop residues or wood waste) in low-oxygen conditions [1-48-50, 220]. When this biochar is engineered, it is further treated or enhanced to improve specific properties, such as soil fertility and water retention, and to improve nutrient use efficiency [1-48-80, 220].

3 WASTE TO WEALTH: CIRCULAR ECONOMY

The importance of adopting a "waste-to-wealth" approach lies in reimagining waste as a valuable resource rather than an economic burden and environmental issue [1-25-60-218]. It necessitates a rethinking of material flows within the economy, emphasizing the recovery, reuse, and reintegration of value [1-90]. The circular economy has emerged as the most comprehensive and scalable approach for enhancing resource efficiency across the full lifecycle of products and processes [1-90-100]. At its core, circularity represents a systemic transformation in production and consumption patterns, aimed at minimizing the extraction of raw materials, water, and energy, while eliminating waste at every stage [1-65-74-90]. This approach is guided by the principles of the six Rules- Reduce, Reuse, Recycle, Refurbish, Recover, and Repair, ensuring that materials remain in productive use for extended periods [1-15-20-218]. A defining feature of this model is "true recycling," in which waste is converted back to its original form without compromising quality, enabling

higher-value recovery and avoiding the losses associated with downcycling [1-25-60-100]. Actualized Pathway to Circular Economy and Resource Sustainability are as follows [1-25-80-218].

- **Refuse** – Avoid products or packaging that create unnecessary waste.
- **Rethink** – Redesign and reconsider consumption habits for sustainability.
- **Reduce** – Cut down on resource use and energy demand.
- **Reuse** – Keep items in circulation by using them repeatedly.
- **Repair** – Fix broken goods instead of replacing them.
- **Restore** – Revive worn or damaged products to extend their life.
- **Remanufacture** – Rebuild items from existing parts to make them like new.
- **Repurpose** – Assign new functions to materials beyond their original use.
- **Recycle** – Convert waste into raw materials for new products.
- **Recover** – Extract energy or valuable resources from residual waste.

India's shift towards a circular economy in agriculture demonstrates that environmental sustainability and economic growth can be mutually reinforcing [1-25-96]. While the scale of agricultural and food waste poses a significant concern, targeted policies, strategic infrastructure investments, and coordinated institutional action are increasingly converting waste into energy, organic inputs, water resources, and livelihood opportunities [1-25-100]. Flagship initiatives such as GOBARdhan, crop residue management programmes, the Agriculture Infrastructure Fund (AIF), and the Animal Husbandry Infrastructure Development Fund (AHIDF) represent the potential of circular agriculture to enhance soil fertility and water security, and to strengthen farm resilience [1-25-30]. By scaling proven interventions, strengthening local institutions, and aligning economic incentives with ecological outcomes, circular agriculture can play a pivotal role in ensuring long-term food security, climate resilience, and inclusive rural development, turning agricultural waste into a cornerstone of sustainable prosperity [1-25-40].

4 INDIAN POLICIES TO PROMOTE CIRCULARITY

The government of India is implementing various policies to promote circularity in agriculture and allied sectors by converting waste into valuable resources [1-25-100]. Initiatives such as Galvanizing Organic Bio-Agro Resources Dhan (GOBARdhan) and Crop Residue Management are transforming agricultural, animal, and food waste into organic manure [1-25-60].

4.1 Galvanising Organic Bio-Agro Resources Dhan (GOBARdhan)

The scheme brings together multiple ministries to convert cattle dung, crop residues, and food waste into compressed biogas (CBG) and organic manure [1-25-60]. In 2023, the government launched the Unified GOBARdhan Portal to enhance transparency and functionality. By 14th January 2026, the scheme covered 51.4% of India's districts and had 979 operational biogas plants, indicating substantial progress in sustainable waste management. Additionally, the Indian Council of Agricultural Research (ICAR) has developed crop-specific guidelines to help farmers use biogas slurry to enhance soil health [1-25-30]. Additionally, the government has eased regulations and introduced targeted incentives to enhance the scheme's impact [1-25-40]. The inclusion of compressed biogas (CBG) in carbon credit trading, tax relief on CBG-blended fuels, and simplified norms for organic manure under the Fertiliser Control Order have accelerated biogas adoption, attracted private investment, and strengthened the national waste-to-wealth ecosystem [1-25-50].

4.2 Crop Residue Management (CRM)

The CRM initiative aims to reduce the open burning of crop residues by promoting in-situ management, where residues are directly incorporated into the soil or used as mulch, and ex-situ management, where residues are collected for composting, biogas production, or bioenergy [1-25-30]. These practices help to improve soil health, enhance farm productivity, and promote effective waste management. Under the scheme, from 2018-19 to 2025-26, Rs. 3,926.16 crore has been released to the states of Punjab, Haryana, Uttar Pradesh, NCT of Delhi, and ICAR [1-15-20]. During this period, the states have set up over 42,000 Custom Hiring Centres (CHCs) for crop residue management machines, and more than 3.24 lakh machines have been supplied to these CHCs and individual farmers [1-15-20].

4.3 Agriculture Infrastructure Fund (AIF)

The AIF plays a key role in strengthening the agricultural value chains, including those involved in organic agriculture [1-15-20]. Organic farmers, Farmer Producer Organizations (FPOs), Primary Agricultural Credit Societies (PACS), and agri-entrepreneurs have leveraged AIF support to establish warehouses, cold storage facilities, sorting and grading units, and primary processing centres [1-15-20]. Launched in 2020-21, the AIF provides medium to long-term institutional credit for the development of post-harvest infrastructure and farm-level assets [1-15-20]. As of 2025, the

AIF has supported 545 projects related to organic input production, with loan sanctions totaling ₹ 850 crore, underscoring the growing recognition of organic farming as both environmentally sustainable and economically viable [1-20]. Additionally, ₹66,310 crore has been sanctioned across 1,13,419 projects, mobilising total investments of ₹1,07,502 crore in the agriculture sector [1-15-20]. Major projects supported under AIF include:

The Government of India recently directed the National Thermal Power Corporation (NTPC) to mix crop residue pellets (nearly 10%) with coal for power generation [1-63]. This helped the farmers with a monetary return of approximately Rs. 5500 (77 USD) per ton of crop residue [1-15-20]. These lucrative measures are yet to be in action and it can be profitably exploited by the farmers. Few measures, associated with bio-composting are run by the Indian government [1-15-20]. The Rashtriya Krishi Vikas Yogna (RKVY), State Plan Scheme of Additional Central Assistance launched in August 2007 is a government initiative, as a part of the 11th Five Year Plan by the Government of India [1-64]. Under this scheme eight demonstration and training projects were established in different villages of Azamgarh and Marinath Bhanjam districts of eastern Uttar Pradesh [1-15-20]. Around 456 farmers were trained for agro-waste bio-conversion and bio-compost production [1-15-20-90]. These large-scale efforts supported farmers in gaining economic advantages [1-64]. In addition to above, the Ministry of Agriculture of India recently developed a National Policy for Management of Crop Residue (NPMCR) [1-7-100]. The following are the main objectives of the NPMCR [1-7-23].

5 AGRICULTURE CROP RESIDUE BURNING

India, the second largest agro-based economy with year-round crop cultivation, generates a large amount of agricultural waste, including crop residues [1-7-23-45-67-71-93-100-218]. Bhuvaneshwari et al., (2019) [1] reviewed that in the absence of adequate sustainable management practices, approximately 92 metric tons of crop waste is burned every year in India, causing excessive particulate matter emissions and air pollution [1-7-23-100]. Crop residue burning has become a major environmental problem causing health issues as well as contributing to global warming. Composting, biochar production and mechanization are a few effective sustainable techniques that can help to curtail the issue while retaining the nutrients present in the crop residue in the soil [1-7-23-100]. The government of India has attempted to curtail this problem, through numerous measures and campaigns designed to promote sustainable management methods such as converting crop residue into energy. However, the alarming rise of air pollution levels caused by crop residue burning in the city of Delhi and other northern areas in India observed in recent years, especially in and after the year of 2015, suggest that the issues is not yet under control [1-7-23-100]. Bhuvaneshwari et al., (2019) [1] indicated that the solution to crop residue burning lies in the effective implementation of sustainable management practices with Government interventions and policies [1-7-23-100]. The agricultural waste sector can benefit immensely from some of the examples from other waste sectors such as the municipal solid waste (MSW) and wastewater management where collection, segregation, recycling and disposal are institutionalized to secure an operational system [1-7-23-180]. The government of India as well as governments of other developing countries can benefit from the emerging concept of nexus thinking in managing environmental resources [1-7-23-100]. Nexus thinking promotes a higher-level integration and higher level of stakeholder involvement that goes beyond the disciplinary boundaries, providing a supporting platform to solve issues such as crop residue burning [1-17-43-180].

Bhuvaneshwari et al., (2019) [1] reviewed that the burning of crop residues generates numerous environmental problems [1]. The main adverse effects of crop residue burning include the emission of greenhouse gases (GHGs) that contributes to the global warming, increased levels of particulate matter (PM) and smog that cause health hazards, loss of biodiversity of agricultural lands, and the deterioration of soil fertility [1-22-45-60-71-92-190]. Crop residue burning significantly increases the quantity of air pollutants such as CO_2, CO, NH_3, NO_X, SO_X, Non-methane hydrocarbon (NMHC), volatile organic compounds (VOCs), semi volatile organic compounds (SVOCs) and PM [1-46,47-1001-]. This basically accounts for the loss of organic carbon, nitrogen, and other nutrients, which would otherwise have retained in soil [1-7-43-100]. Crop burning increases the particulate matter (PM) in the atmosphere and contributes significantly to climate change [1-7-23-100]. In addition to the emission of gases and aerosols, there is continuous deterioration of soil fertility due to burning [1-7-23-100]. Frequent burning reduces nitrogen and carbon potential of the soil and kills the microflora and fauna beneficial to the soil, and further removes the large portion of the organic matter [1-56,57-100].

6 AGRICULTURAL WASTE: ENVIRONMENTAL PROBLEM

The agricultural industry plays a major role in the overall economic growth of the world. The growing demand for food in developing countries have led to tremendous increase in food production around the world [1-56,57-180]. Reddy et al., (2025) [3] reviewed that agro-based activities represent profitable businesses, both in developing as well as developed countries. The multitude of agricultural activities increases the amount of agro-products produced and this has led to an overall increase in environmental pollution and waste generation [1-36-57-190]. Large stretches of wasteland have been converted to arable lands due to developments in water management systems, modern agro-technologies and large-scale agrochemical deployment [1-190]. These measures have resulted in global environmental pollution and increased complexity in the disposal of agricultural waste [1-56,57-190]. However, the national agencies

are continuously developing policies and possible options to manage these wastes, which includes their conversion to reusable resources. Waste materials derived from various agricultural operations are defined as agricultural wastes. As per the United Nations, agricultural waste usually includes manure and other wastes from farms, poultry houses and slaughterhouses; harvest waste; fertilizer run-off from fields; pesticides that enter water, air or soils; salt and silt drained from fields [1–3-190]. According to the world energy council, in addition to all above, agricultural waste can also comprise of spoiled food waste [1-49-190]. The harvest waste, which is more popularly termed as crop residue can contain both the field residues that are left in an agricultural field or orchard after the crop has been harvested and the process residues that are left after the crop is processed into a usable resource [1-56,57-180]. Reddy et al., (2025) [3] reported that stalks and stubble (stems), leaves, and seed pods are some common examples for field residues. Sugarcane bagasse and molasses are some good examples for process residue [1-2,4–6-190]. According to the Indian Ministry of New and Renewable Energy (MNRE), India generates on an average 500 Million tons (Mt here after) of crop residue per year [1-7-179]. The same report shows that a majority of this crop residue is in fact used as fodder, fuel for other domestic and industrial purposes [1-56,57-180]. However, there is still a surplus of 140 Mt out of which 92 Mt is burned each year [1-79-184]. It is also interesting to note that the portion burnt as agricultural waste in India, in volume is much larger than the entire production of agricultural waste in other countries in the region [1-56,57-180]. Waste from the agricultural industry can be beneficially utilized in various agro-based applications and other industrial processing. However, the cost of collection, processing and transportation can be much higher than the revenue from the beneficial use of such waste [1-56,57-180]. The other important reason is that the volume of crop residue, with unsustainable management practices create high adverse environmental impacts, that go far beyond India [1-90-167-190]. Specifically, India is the second largest producer of rice and wheat in the world, two crops that usually produce large volume of residue [1-56,57-180].

7 AGRICULTURE WASTE: COMPOSITION

Reddy et al., (2025) [3] reviewed that plant biomass is mainly comprised of cellulose, hemicellulose and lignin with smaller amounts of pectin, protein extractives, sugars, and nitrogenous material, chlorophyll and inorganic waste [1-14–16-178]. Lignin resist fermentation as it is very resistant to chemical and biological degradation [1-17–19-160]. The non-food-based portion of crops such as the stalks, straw and husk are categorized under lignocellulosic biomass [1-14–16-178-200]. The major agricultural crops grown in the world—maize, wheat, rice and sugarcane, respectively, account for most of the lignocellulosic biomass [1-14–16-178]. Because of its resistance to chemical and biological degradation by fungi, bacteria and enzymes, the lignin layer is usually pretreated or acted upon by the lignin degrading microorganisms to break down the lignin layer and degrade cellulose and hemicellulose matter to the corresponding monomers and sugars for effective biomass to fuel conversion [1-116-160-200]. The pretreatment could be mechanical, chemical, physico-chemical and biological. The management of agricultural waste using microbes could also be an excellent option for the detoxification of the soil and mitigation of environmental pollution [1-126-150]. Microbial population degrade the complex substances present in the biomass to simpler ones that can be reused or recycled through environmental processes. The techniques adopted can either be aerobic or anaerobic, depending on the nature of bacteria, fungi or algae involved in the degradation [1-127-150]. Thus, the bioremediation of the agricultural waste could be effectively carried out by anaerobic and aerobic processes, through some of the associated techniques like composting, vermicomposting, biogas production, bio-methanation and bio pile farming [1-126-149]. Anaerobic digesters can turn biomass into biogas, a renewable energy source, containing approximately 50% methane, and a final solid residue usable as a fertilizer rich in nutrients [1-14–16-178]. Anaerobic digestion involves microbial conversion in aqueous environment and could be processed without any pretreatment [1-30,31-150]. The anaerobic digestion proceeds through three phases, with the hydrolytic bacteria degrading polymeric organic matter into monomers (sugars, amino acids) in the first phase. Followed by monomer degradation to fatty acids, (acetate, formate) as the second stage and in the third phase, the acids are reduced to carbon dioxide and methane by acetotrophs, methylotrophs and hydrogenotrophs bacteria [1-16-31-150].

8 AGRICULTURE WASTE INTO ENERGY RESOURCES

Various techniques have been available for valorizing agricultural waste through thermochemical, bio-based, and building materials recovery. Considerable research has been done to explore the possibility of agricultural waste valorization for the recovery of energy and resource materials. Thermochemical processes Thermochemical processes are pivotal in valorizing agricultural waste, converting biomass into energy and valuable chemicals through high-temperature techniques [1-81-221]. The thermochemical processes include pyrolysis, gasification, and combustion, each with distinct mechanisms and outputs.

8.1 Pyrolysis

Pyrolysis is the thermal degradation of carbonaceous feedstock in the absence of oxygen at a typical temperature range of 300–1000 ◦ C, producing bio-oil, pyrolytic gases, and biochar [1-82-190]. Reddy et al., (2025) [3] reviewed that research has demonstrated the effectiveness of pyrolysis in converting rice husk, wheat straw, and other crop residues

into valuable products [83]. Besides feedstock composition, the quality and quantity of pyrolytic products depend on operational or process conditions such as process temperature, heating rate, and residence time [1-84-190]. Depending upon these conditions, pyrolysis is classified into different types such as slow, intermediate, and fast pyrolysis [1-85-195]. In case of slow pyrolysis, the process temperatures are up to 450 ◦C with heating rate of 0.1–2 ◦C sec^{-1} and residence time is for several hours resulting in more fraction of biochar [1-80-196]. In intermediate pyrolysis, the temperature is around 500 ◦C, heating rate of 10–200 ◦C sec^{-1} and residence time of several minutes [1-87-189-196]. In fast pyrolysis, the temperatures are 600 ◦C and above with high heating rates of 1000 ◦C sec^{-1} and low residence time below 2 sec^{-1} resulting in low solid fraction [1-88-195]. Intermediate and fast pyrolysis are suitable when liquid and gases as targeted products. Biochar derived from biomass has potential applications in agriculture, construction, and water treatment [1-190]. Developing waste-to-bioenergy solutions through pyrolysis addresses significant challenges in rural Indian communities, such as insufficient electrification, indoor air pollution, and crop land deterioration [1-191]. The biochar application improves crop growth and provides long-term carbon sequestration, indicating its effectiveness for soil amendments and car bon mitigation [1-192]. Successful large-scale implementation of pyrolysis technology for agricultural residues could reduce India's carbon emissions by 10 % and increase electricity generation by 10 –12 %, potentially producing 41.9 GWe of bioelectricity [1-194]. However, the key challenges are higher initial capital costs and increased operation and maintenance expenses due to the need for more sophisticated technology and infrastructure. Further, the quality and yield of bio-oil can vary significantly depending on the type of biomass feedstock and the operating pyrolysis parameters [1-194].

8.2 Production of Biochar

As a measure for controlling GHG emissions, the agricultural research community is constantly looking for ways to effectively enhance natural rates of carbon sequestration in the soil [1-196-220]. This has made an increased interest in applying charcoal, black carbon and biochar as soil amendment to stabilize soil organic content [1-194]. These techniques are viewed as a viable option to mitigate the GHG emissions while considerably reducing the volume of agricultural waste [1-82-190]. Reddy et al., (2025) [3] reviewed that the process of carbon sequestration essentially requires increased residence time and resistance to chemical oxidation of biomass to CO_2 or reduction to methane, which leads to reduction of CO_2 or methane release to the atmosphere [1-35-195, 220]. The partially burnt products are pyrogenic carbon/carbon black and becomes a long-term carbon sink with a very slow chemical transformation, ideal for soil amendment [1-85,86-190]. Reddy et al., (2025) [3] reviewed that biochar is a fine-grained carbon rich porous product obtained from the thermo-chemical conversion called the pyrolysis at low temperatures in an oxygen free environment [1-187-196]. It is a mix of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) and ash in different proportions [1-188-193, 221]. When amended to soil, highly porous nature of the biochar helps in improved water retention and increased soil surface area. It mainly interacts with the soil matrix, soil microbes, and plant roots, helps in nutrient retention and sets off a wide range of biogeochemical processes [1-82-195, 220]. Many researchers have reported an increase in pH, increase in earthworm population and decreased fertilizer usage [1-90,91-195, 220]. Specifically, biochar is used in various application such as the water treatment, construction industry, food industry, cosmetic industry, metallurgy, treatment of waste water and many other chemical applications [1-82-195]. In India currently, the biochar application is limited and mainly seen in villages and small towns. Based on its wide applicability, it could be more valuable to promote biochar method in India [1-82-190, 221].

8.3 Gasification

Gasification involves the transformation of lignocellulosic or carbonaceous waste into syngas through partial oxidation at high temperatures (500–1400 ◦C) [1-195]. During this process the biomass undergoes four major stages: moisture removal, release of volatile compounds, partial oxidation, and reduction reactions to produce syn- gas and char [1-96,97-123-156-178-196]. Reddy et al., (2025) [3] reviewed that gasifying agents such as air, O_2, CO_2 are usually used as a medium for gasification reaction which influences the output quality and quantity [1-98-146-190]. The resulting syngas, composed of CO, hydrogen (H_2), CO_2 and methane (CH_4), can be utilized for producing chemicals or electricity [1-99-196]. Studies have highlighted the potential of gasifying crop residues like sugarcane bagasse and coconut shells for decentralized energy production in rural India [1-82-190]. A study proposed using biomass gasification to power off-grid refrigeration systems for atmospheric water harvesting, potentially producing 800–1200 L of water per 1000 kg of biomass and meeting up to 12 % of potable water needs in some Indian states [1-190].

Optimizing conditions for converting agricultural residues like bagasse, rice straw, and wheat straw into H_2-rich syngas has shown promising results, with an H_2 content up to 40 %, a gross calorific value of 6 MJ kg and cold gas efficiency of 80 % [1-102-195]. In another study, rice husk as a renewable biomass source was utilized for producing energy-rich syngas through gasification in a fixed bed reactor, using steam alone as a gasifying agent at 950 ^{0}C yielded higher hydrogen content (70 %) and heating value (11 MJ m^{-3}) compared to an air-steam mix [1-103-195]. The results suggest steam gasification is more efficient for hydrogen-rich syngas, making it suitable for industrial fuel applications [1-103-196]. Co-gasification of rice husk and groundnut shell, common in southern India, enhances conversion efficiency. Optimal conditions for a mixture of 20 % rice husk and 80 % groundnut shells at an equivalence ratio of 0.25 and a reduction area inlet temperature of nearly 880 ◦C yielded gas compositions of CO (23.53 %), H_2 (13.97 %), and CH_4

(3.56 %) in a downdraft gasifier [1-82-190]. Furthermore, the model predicted that the net calorific value and gas production could reach 6.17 MJ $N\text{-}1m^{-3}$ and 2.369 m^3 kg^{-1} [1-82-190]. Reddy et al., (2025) [3] are of the opinion that although gasification offers immense potential feedstock variability, high initial costs, and requirement of effective tar removal technologies remain barriers to widespread adoption [1-105-195].

8.4 Combustion

Reddy et al., (2025) [3] reported that combustion is the direct burning of biomass to produce heat and power and is widely used for managing wastes such as paddy straw and bagasse [1-182-196]. These residues are commonly combusted in industrial boilers to generate steam and electricity [1-82-190]. Torrefaction is an additional thermochemical treatment that enhances the feedstock quality before its utilization in combustion, pyrolysis, or gasification [1-180-196]. The torrefaction process involves the thermal treatment of biomass at temperatures ranging from 200 to 300 ◦C in the absence of oxygen, resulting in torrefied solids or bio-coal with improved energy density, hydrophobicity, and grindability of the torrefied biomass [1-106–108-190]. One of the study reported that cofiring biomass, including bagasse, wood chips, and sugarcane trash with coal can reduce NO_x, SO_x, and CO_2 emissions while maintaining production costs, making it a cost-effective alternative for power plants [1-109-195]. However, the continuous availability of agricultural residues and their transport to the power plants are essential while considering their techno-economic feasibility [1-190]. These logistical and supply chain constraints apply broadly across all biomass-based energy conversion systems including pyrolysis and gasification [1-82-190].

Reddy et al., (2025) [3] reviewed that another approach is to design and deploy an improved cookstoves and furnaces specifically tailored for the combustion of agricultural residues [1-23-46-78-82-190]. These systems are not only aimed to enhance combustion efficiency, reduce emissions, and offer substitute to the open burning of agricultural waste but can also be used in clean cooking [1-111–115-196]. These thermochemical processes, particularly pyrolysis and gasification, offer sustainable solutions for managing agricultural waste in India, contributing to energy production, carbon sequestration, and are environmentally friendly [1-82-190]. Reddy et al., (2025) [3] reported that in Indian context, pyrolysis presents a promising opportunity for creating wealth in rural areas by producing bio-oil for biofuel applications and char for soil amendment [1-82-190]. Whereas gasification offers potential for power generation and industrial applications. Reddy et al., (2025) [3] indicated that the selection of a specific technology depends on various factors such as the type of agricultural waste, desired end products, the scale of the operation, and availability of supporting infrastructure [1-82-190]. By optimizing these technologies and scaling up their implementation, India can make significant strides in agricul tural waste management and renewable bioenergy generation [1-82-190].

8.5 Biogas Production

Biogas production from agricultural waste typically employs anaerobic digestion, a microbial process that converts organic matter into biogas (primarily CH_4 and CO_2) and digestate. This process involves a series of biochemical steps including hydrolysis, acidogenesis, acetogenesis, and methanogenesis each driven by specific microbial communities [1-126,127-196]. Factors such as substrate composition, C/N ratio, temperature, and pH play critical roles in determining the efficiency and yield of biogas production [1-128,129-187-192]. Reddy et al., (2025) [3] reviewed that in India, anaerobic digestion of cattle dung, crop residues like sugarcane, rice husk, wheat and paddy straws, and food waste have shown significant potential and is widely used for managing cattle dung and other organic agricultural waste [1-48-71-130–192]. Researcher have demonstrated that the feasibility of anaerobic digestion for generating biogas from crop residues like wheat straw and paddy straw, which can then be used as a clean cooking fuel or for electricity generation [1-133-196]. Sugarcane as feed can produce relatively higher biogas than rice husk due to low lignin levels [1-194]. As the agro-based wastes contains lignin which is complex in nature needs to be pre-treated prior to anaerobic digestion whereas the other cellulose and hemicellulose components are easily biodegradable [1-133-196]. Pre-treatment methods such as chemical and thermal treatments improve the digestibility of lignocellulosic biomass, causing improved biogas yields [1-135,136-195]. For instance, pre-treated biomass increased biogas production by 62 % for rice straw and 66 % or corn stalk compared to untreated samples, highlighting the potential of banana peel ash in enhancing energy recovery from rural biomass residues [1-195]. Chemical pre-treatments use acidic, alkaline, and oxidising agents [1-127-196].

Reddy et al., (2025) [3] reviewed that co-digestion strategies, combining multiple types of agricultural and food wastes, have been explored to optimize biogas production [1-127-196]. The mixture of sugarcane bagasse and cow dung with a food-to-biomass ratio of 2.0 showed the best physical features, with a bulk density of 429 kg m^3, nearly 14 times greater than the raw materials [1-137-196]. A biochemical methane potential test indicated that pellets with 8 % total solids content produced the highest biomethane yield of 241 mL g 1VS [1-137-194]. For instance, co-digestion of cow dung and crop residues demonstrated a 60 % improvement in resource efficiency and significant reductions in climate change and health impacts [1-138-196]. Using banana stem juice with bagasse and wheat straw wash in biogas plants has also proven effective, particularly in enhancing CH_4 production in paper mills [1-139-196].

Biogas plants are a progressive step taken by the Government of India to curb crop burning and to prevent pollution [1-139-196]. The biogas technologies have been in vogue since the 1970s and several programs are run by the National Biogas and Manure Management Program-off grid biogas power generation program to provide renewable energy for electricity generation, cooking and lighting purpose [1-139-196]. These programs were implemented by the Government under the "waste to energy mission" [1-139-196]. This is also a part of India's action plan on climate change [1-33,34,36,37-196]. Large scale industrial biogas plants generate 5000 m^3 of bio gas per day. Nearly 400 off-grid biogas power plants have been set up with a power generation capacity of 5.5 MW [1-34-37-58-190]. Currently there are 56 biogas-based power plants operational in India, the majority of them are in the states of Maharashtra, Kerala and Karnataka [1-59-190]. Small family type biogas plants have also been introduced in the rural areas, which can generate 1 to 10 m^3 biogas per day [1-139-196]. Nearly five million family biogas plants have been installed by MNRE under the biogas development program. Recent developments in technology have opened the possibility of using paddy straw and other crop residue other than dung and vegetable waste for biogas generation in an integrated approach [1-139-196]. This plant generates biogas using rice straw through bio-methanation technology [1-139-196]. The biogas plant having been certified by the premier academic institutes like the Indian Institute of Technology, Delhi and Punjab Agricultural University, generates around 4000 m^3 of biogas from 10 tons of agricultural residue [1-60-190]. In another biogas enterprise, a 12 MW rice-straw power plant can consume 120,000 tons of stubble collected from nearly 15,000 farmers [1-61,62-180]. These private enterprises generated around 700,000 jobs for the farming population. Through some of these measures implemented by the Government agencies and private sectors, crop burning has been reduced but not completely stopped [1-139-196].

According to Reddy et al., (2025) [3], governmental interventions mainly focus on the use of crop residue as a source of energy: in the form of biogas as well as a supplement for thermal power plants [1-33–37-167]. Biogas generated through anaerobic biodegradation of municipal solid waste and agricultural waste, contains around 40–70% methane, this is usually augmented to natural gas quality with a methane content of 70–99% [1-38-187]. Further it can be injected into the natural gas grid or used as fuel for transportation [1-38-187]. The methane production potential of wheat straw ranges from 0.145 m3/kg to 0.390 m3/kg for dry organic mass fed to the digester [1-39–41-170]. Rice straw has a methane production potential ranging from 0.241 m3/kg to 0.367 m3/kg [1-42-176]. A biogas production potential of around 0.550 to 0.620 m^3/kg for rice straw biomass with around 50% methane content has been reported Similarly, the reported biochemical methane production from sugarcane biomass varies from 0.266–0.314 m^3/kg [1-42-170].

8.6 Compost generation

Composting is an important bioprocessing technique for converting agricultural waste into nutrient-rich compost [1-167–169-190]. The composting process involves aerobic microbial decomposition, which occurs in three main phases: the mesophilic phase, where initial decomposition takes place; the thermophilic phase, characterized by high microbial activity and pathogen reduction; and the maturation phase, where stabilized compost is formed [1-194]. The Indian Agricultural Research Institute (IARI) has developed efficient composting methods for multiple types of agricultural waste, enhancing soil fertility and reducing chemical fertilizer dependency [1-175]. The use of efficient microorganism (EM) consortia has accelerated the composting process and improved compost quality [1-167–169-190-221]. An EM consortium, including *Candida tropicalis, Phanerochaete chrysosporium, Streptomyces globispo rous, Lactobacillus* sp., and an enhanced photosynthetic bacterial culture, was created for fast composting of rice straw amended with poultry droppings [1-175]. The results demonstrated that the EM consortium significantly accelerated composting, achieving a C/N ratio of 15:1 and a humus content of 4.82 % within 60 days, with high enzymatic activities indicating enhanced microbial performance [1-167–169-190]. Key factors influencing the efficiency of composting include C/N ratio, moisture content, aeration, and temperature [1-176]. Utilizing agricultural waste for composting not only reduces environmental pollution but also supports sustainable agriculture by enriching soil fertility and reducing dependency on chemical fertilizers [1-167–169-190-221].

Composting is not a new concept to India. While small scale backyard composting and making compost from organic material in MSW is common, there is no information in the literature to prove that it is also the case for the agriculture industry in India [1-167–169-190]. Challenges are mostly not technical but economical as the end-product does not always secure a steady market [1-167–169-190]. The high organic content in crop residue makes it an ideal raw material for compost similar to animal manure and food waste [1-167–169-190-221]. Composting is the natural process of rotting or decomposition of organic matter by micro-organisms under controlled conditions [1-169]. As a rich source of organic matter, compost plays an important role in sustaining soil fertility and thereby helping to achieve sustainable agricultural productivity [1-167–169-190]. Addition of compost to the soil improves physio-chemical and biological properties of the soil and can completely replace application of agricultural chemicals such as fertilizer and pesticides [1-167–169-190-221]. These techniques also help in higher nutrient uptake, and active nutrient cycling due to enhanced microbial activity in the soil. Composting is mediated by different microorganisms actuating in aerobic environment. Bacteria, fungi, acitnomycetes, algae, and protozoa are naturally present in organic biomass or added artificially in order to facilitate decomposition [1-172]. It is the biological maturity under aerobic condition, where organic matter of animal or plant origin is decomposed to materials with shorter molecular chains. More stable, hygienic, humus rich compost,

beneficial for agricultural crops and for recycling of soil organic matter is ultimately formed [1-221]. During composting, the organic matter is acted upon in two phases (i) degradation and (ii) maturation. The first phase of degradation starts with breakdown of easily degradable organics like sugars, amino and organic acids. The aerobic microorganisms consume oxygen and release carbon dioxide and energy [1-167–169-190]. The first thermophilic phase is dominated by high temperature, high pH and humidity, essential for activating the microorganisms and proceeds for several weeks to months [1-174]. During this phase, it is also ensured that the substrate is properly cooled with sufficient supply of oxygen [1-175]. The second phase continues for few weeks, with breakdown of more complex organic molecules followed by decrease in microbial population. There is a change from thermophilic to mesophilic phase with a decrease in temperature to 40–45 ◦ C [1-73,75–177]. Further at the final stage, temperature declines to an ambient value and the system becomes biologically less active. Finally, a dark brown to black color soil-like material is produced. This soil-like material also exhibits an increased humus content and decreased carbon-nitrogen ratio with a neutralized pH [1-169]. Aerobic composting is affected by many factors, such as the amount of oxygen, moisture content, nutrient supply, temperature, pH and lignin content. Eventually the biomass is transformed to a material rich in nutrients, which can improve the structural characteristics of the soil [1-179]. They found a significant increase in the agronomic properties of the rice and wheat crops they experimented. Nutrients like nitrogen (N) and phosphorous (P) provided to the crops by the bio-compost is of significant importance to the crop production strategy [1-182]. This also increases the microbial population and native microflora and fauna necessary for the soil health [1-83,84-189].

8.7 Bioethanol Production

Fermentation is a key biochemical process for producing bioethanol from agricultural residues [1-16-31-150]. Reddy et al., (2025) [3] reviewed that the production of bioethanol from lignocellulosic biomass involves three main stages: pre- treatment, enzymatic hydrolysis, and fermentation [1-140-168, 214-216]. Enzymatic hydrolysis then converts these polymers into fermentable sugars, primarily glucose and xylose, using cellulase and hemicellulase enzymes. Finally, microorganisms such as *Saccharomyces cerevisiae* or *Zymomonas mobilis* ferment the sugars into ethanol under controlled conditions [1-172]. Agricultural wastes with high cellulose and starch, such as sugarcane bagasse, rice straw, wheat bran, sago waste, and rice bran, undergo pre-treatment and enzymatic hydrolysis to release fermentable sugars [1-28-143-160, 214-216]. Hence, retrofitting sugar mills to generate ethanol from bagasse in India can significantly fulfil the nation's liquid fuel requirements. The government of India reported that the yearly demand for ethanol is 13.5 billion litres by 2025–26 [1-16-31-150].

8.8 Bio-processing techniques

Reddy et al., (2025) [3] reviewed that the valorization of agricultural waste through biochemical, bio- refining, and bioprocessing techniques offers promising paths for sustainable development and resource efficiency [1-116-134-140-168-195]. These methods convert waste into value-added products like biofuels, bioplastics, enzymes, organic acids, and other valuable bioproducts such as bio- active/nutraceuticals, nanoparticles, antibiotics, biosurfactants, and other specific chemicals [1-117-196]. They typically involve microbial and enzymatic processes, which necessitate multiple pre-treatments to improve biodegradability and facilitate the conversion process. For example, converting lignocellulosic biomass to ethanol includes pre-treatment, saccharification, and fermentation [1-118,119-196]. Biorefining of cellulose and hemicellulose portions of lignocellulosic biomass results in the production of various high-value chemicals such as ethanol, furfural, hydroxy methyl furfural, etc. [1-69-118-129-134-160-196]. These bio-based technologies usually demand biomass pre- treatments including physical, chemical, biological, and innovative methods such as microwave-assisted and ultrasound-assisted techniques where biodegradation or biological methods are environmentally friendly, energy-saving, and more sustainable [1-121–125-196].

8.9 Enzyme Production-

Reddy et al., (2025) [3] reviewed that agricultural waste serves as a potential substrate feedstock for producing industrial enzymes due to its rich composition of lignocellulosic biomass, proteins, and other nutrients [1-176]. Enzyme production usually involves the cultivation of microorganisms like bacteria, fungi, or actinomycetes on these substrates, utilizing solid-state or submerged fermentation techniques [1-167-190]. Enzymes such as cellulases, xylanases, pectinases, and amylases are commonly produced, which find applications in biofuel production, food processing, and textile industries [1-178-189]. Various enzymes, including lipolytic and pectinolytic enzymes, can be made through microbial processing of fruit and vegetable wastes [1-189]. Enzymes like pectinase, tannase, laccase, etc., can be generated from wastes like orange peel, pomegranate rind, corn-cob, rice bran, and wheat bran [1-150–174-180]. Reddy et al., (2025) [3] reported that enzymes such as cellulases, xylanases, pectinases, and amylases are commonly produced, which find applications in biofuel production, food processing, and textile industries [1-179]. The use of agricultural residues like wheat bran, rice husk, and corn stover not only reduces production costs but also addresses waste management challenges, promoting a circular bioeconomy [1-176].

8.10 Hydrogen (H_2) Production

Reddy et al., (2025) [3] reviewed those thermochemical methods, including gasification and pyrolysis, convert biomass into H2-rich syngas under high-temperature conditions [1-98-157-190]. Alternatively, biological processes such as dark fermentation and photo-fermentation employ microorganisms like Clostridium spp. to produce H2 by metabolizing carbohydrates in the biomass [1-188]. H2 production through dark fermentation and photo-fermentation using agricultural wastes has gained attention because of clean energy sources [1-189]. Substrates, including rice straw and rice husk hydrolysates, have been efficiently converted to H2, demonstrating high yields and process feasibility [1-160, 161-189].

8.11 Organic Acids Production

Agricultural waste provides an inexpensive and viable substrate for the production of organic acids, such as lactic acid, citric acid, and succinic acid, which are widely used in food, pharmaceutical, and chemical industries [1-163-189]. The lignocellulosic components of agricultural residues, including cellulose, hemicellulose, and starch, are hydrolyzed into fermentable sugars through enzymatic or chemical pre-treatment [1-194]. These sugars are then transformed into organic acids by microbial fermentation using strains like *Lactobacillus* spp., *Aspergillus niger*, or *Actinobacillus succinogenes* [1-193]. However, the downstream recovery of organic acids from the fermentation broth remains a major challenge due to the dilute nature of the broth and the presence of impurities. Therefore, developing cost-effective and sustainable separation technologies is essential for improving the overall viability of organic acid production from agricultural residues. Reddy et al., (2025) [3] reviewed that utilizing agricultural waste not only lowers production costs but also promotes sustainable waste valorization, contributing to the circular bioeconomy [1-167–169-190].

8.12 Polyhydroxyalkanoates (PHA) Production

According to Reddy et al., (2025) [3], biopolymers such as PHAs are produced from agricultural wastes through microbial fermentation bioeconomy [1-167–169-190]. *Halomonas campisalis* has converted agricultural wastes, including bagasse, orange, and banana peels, into PHAs, effectively reducing production costs and environmental impact [1-180]. Microorganisms such as *Cupriavidus necator*, *Bacillus* spp., and *Pseudomonas* spp. are commonly used to synthesize PHAs in fermentation systems [1-172]. The use of agricultural waste for PHA production not only addresses environmental concerns associated with conventional plastics but also adds value to agricultural byproducts, supporting UN SDGs bioeconomy [1-167–169-190].

8.13 Essential Fatty Acids Production

Essential fatty acids (EFAs), such as omega-3 and omega-6, are vital for human health and have significant industrial applications in nutraceuticals and pharmaceuticals [1-177]. Agricultural waste, including oilseed cakes, fruit peels, and lignocellulosic residues, presents a cost-effective and sustainable feedstock for EFA production [3-157]. Microbial fermentation, using oleaginous microorganisms like *Mortierella alpina*, *Cryptococcus curvatus,* and *Yarrowia lipolytica*, is a promising approach for converting the complex carbohydrates and lipids into EFAs [1-178]. Essential fatty acids such as omega-3 and omega -6 could be efficiently produced from agricultural waste substrates, with high yield, enhancing the nutritional value of aquaculture feed [1-179].

8.14 Nutritional products

According to Reddy et al., (2025) [3], agricultural residues such as oil seed cakes and fruit peels can be transformed into various high-value products such as proteins, antioxidants, sugars, and furfural [1-168-175-221]. Oil seed cakes are used in multiple industries, including biofuel production, pharmaceuticals, nutraceuticals, food, and feed, because of their rich protein content [1-179]. Fruit peels have been explored for their potential to produce natural antioxidants and pigments, enhancing the worth of these by-products [1-165]. Reddy et al., (2025) [3] reported that the oil seed cakes could generate high-protein animal feed, and fruit peels could extract natural antioxidants with significant health benefits [1-181,182-195]. Furthermore, sugarcane bagasse was used to produce C5 sugars and furfural using a solid-acid catalyzed one-pot method, achieving over 90 % conversion of hemi- cellulose [1-181,182-195].

9 ELECTROCHEMICAL PROCESSES

According to Reddy et al., (2025) [3], the electrochemical processes involve the interconversion of chemical and electrical energy through electrochemical reactions [1-168-175, 221]. One prominent technology in this category is Microbial Fuel Cells (MFCs), which utilize microorganisms to catalyze the oxidation of organic matter consisting of agricultural waste to produce electricity [1-188-221].

10 CONSTRUCTION MATERIALS

According to Reddy et al., (2025) [3], valorizing agricultural waste to recover building materials provides a sustainable way to waste management, offering economic and environmental benefits [1-168-175,198]. Various agricultural residues and processing wastes such as fibres, ashes, and biochar can be utilized in building materials applications [1-168-175]. In addition, the agricultural ash particles have shown exceptional pozzolanic properties and enhance the strength of cementitious materials [1-195, 198]. The application of agricultural waste ashes from bagasse, husk, shell, straw, leaf, etc, has shown a significant influence on fresh and hardened state properties of concrete [1-196, 198].

11 AGRO-BASED PANELS

According to Reddy et al., (2025) [3], agro-based panels, such as particleboards and fiber boards, are commonly produced from agricultural residues like rice husk, wheat straw, and bagasse [1-196]. These materials are bonded using resins to form durable and eco-friendly panels [1-196]. These boards are suitable for applications in furniture and interior construction. Previous studies have indicated that rice husk, coconut husk, and wheat straw-based particleboards or panel boards exhibit comparable strength and durability to traditional wood-based panels [1-190,193]. Therefore, utilizing agro-based panels could also help in preventing deforestation [1-196].

12 BRICKS AND BLOCKS

Reddy et al., (2025**)** [3] reviewed that the incorporation of agricultural wastes into bricks and blocks is another effective valorization strategy. Rice husk and bagasse ash, rice straw, and wheat bran have been utilized as partial replacements for clay, cement, or other substances in bricks and blocks production [1-192, 198]. These materials not only improve the sustainability of the bricks but also enhance their strength, thermal insu- lation, and hydrophobic characteristics [1-187]. Furthermore, the inclusion of RHA in concrete wall panels has been found to enhance their durability, acid resistance, and reduced thermal conductivity [1-105-170. 198].

13 INSULATING MATERIALS

Reddy et al., (2025) [3] reviewed that agricultural waste can also be processed into thermal and acoustic insulating materials for buildings. Straw bales and rice husks have been used as natural insulation materials due to their low thermal conductivity and high availability [3-157] These materials not only provide effective thermal insulation but also contribute to the reduction of energy consumption in buildings [1-105-156]. Additionally, rice husk-based insulation materials have been developed, offering similar benefits while utilizing an abundant agricultural by-product [1-110-180]. Acoustic boards made up of agricultural wastes such as rice straw and water hyacinth have shown better sound-absorbing properties along with fire resistance, low moisture, and fungal attack [3-111-187]. In addition to this, Industrial *Cannabis sativa* (hemp) is also used for the preparation of hempcrete as the building construction and insulating material [197-199].

14 CEMENT AND CONCRETE

Reddy et al., (2025) [3] reviewed that the application of agricultural ash as a fractional substitute of fine aggregates and cement in concrete showed promising potential for enhancing the concrete fresh and hard state properties [3-111-187]. Hempcrete from Cannabis sativa (hemp) is one of the best examples [198]. Agricultural ash products can also be utilized as supplementary cementitious materials (SCMs) in concrete production [3-111-187, 198]. The RHA, having more silica, is particularly effective as an SCM, enhancing concrete strength and longevity [3-111-187]. In addition to RHA, other agricultural residues like sugarcane bagasse ash and groundnut shell ash have been explored as SCMs [1-199]. Incorporation of all these materials improves concrete performance and characteristics, contributing to more sustainable construction practices [1-108-199]. These improvements are due to better void filling and reduced cracking in the cement matrix [3-111-187, 198].

15 ROOFING MATERIALS

The construction of roofing components from agricultural waste is another area of interest. Coconut husk fibres, for instance, have been used to reinforce roofing sheets, enhancing their durability and resistance to environmental factors [3-111-187]. These eco-friendly roofing materials are suitable for rural and low-cost housing applications [3-111-187]. By incorporating residues like RHA, sugarcane bagasse, and wheat straw into construction products, it is possible to produce eco-friendly, cost-effective, and high- performance building materials [3-111-187]. Agricultural waste valorization in India offers diverse pathways such as composting, bioenergy, animal feed, and bioplastics etc., each with its own set of benefits and limitations [3-111-187]. Some of the residues are processed to be used in construction

applications, such as the use of rice husk ash in cement mixes. Banana peels and sugarcane waste are being utilized in the paper industry, while husk and bagasse ash are utilized for mushroom cultivation [4]. In certain cases, logistic issues in transportation of the materials to larger distances also adds to the cost [3-111-187].

16 INDIANAGRICULTURAL WASTE MANAGEMENT: CHALLENGES

According to Reddy et al., (2025) [3], 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 [3]. The lack of appropriate waste segregation and inefficient waste collection systems contribute to the poor handling and disposal of agricultural waste [1-147-160]. In addition, the existing technologies for agricultural waste valorization, such as biogas plants and composting units, often suffer from inefficiencies and scalability issues [3-45-89]. Despite the high biomass power potential, several challenges hinder its exploitation, including the logistics of biomass collection and high moisture content [3-46]. Reddy et al., (2025) [3] reviewed that addressing these challenges requires the selection of appropriate technologies, finding synergies between thermo- chemical, biological, biochemical processes and the implementation of supportive policies for biomass energy use [3-15].

Reddy et al., (2025) [3] are of the opinion that financial constraints further exacerbate these technical challenges [3]. The initial capital expenditure needed to establish advanced waste management facilities, such as biorefineries and thermochemical conversion plants, is substantial [3]. Small and tiny farmers, who account for most of the agricultural sector in India, often lack the financial resources to invest in such technologies [3]. Additionally, the collection of residues and their transportation to treatment facilities and storage sites are often associated with significant economic burdens [3-24]. Reddy et al., (2025) [3] indicated that social and cultural factors are also critical players in the acceptance and success of agricultural waste management practices in India [3]. Traditional ways, like field crop residue burning, are deeply ingrained in the agricultural community due to their perceived simplicity and cost-effectiveness [3]. Changing these entrenched practices requires significant efforts in awareness-building and education about the environmental and health effects of these methods [3]. Creating awareness among farming groups regarding conservation agriculture is crucial for promoting sustainable residue management [3-47]. Furthermore, the acceptance of new technologies and practices is often hindered by a lack of trust and awareness among farmers [3]. Cultural resistance to adopting new practices, especially in rural areas where traditional methods have been followed for generations, poses a significant barrier to the widespread application of sustainable agricultural waste management [3].

Reddy et al., (2025) [3] reviewed that political challenges are also prevalent in the realm of agricultural waste management in India [3]. There is often poor collaboration among various governmental bodies responsible for agriculture, environment, and energy, leading to fragmented and inefficient policy implementation [3]. Additionally, existing regulations and policies may not adequately address the complexities and regional variations in agricultural waste generation and management [3]. The enforcement of regulations related to waste management is often weak, leading to non-compliance and continued reliance on unsustain- able practices like open burning [3-43]. Strengthening institutional frameworks and governance mechanisms is essential for effective agricultural waste management in India [3-23].Future research should focus on optimizing existing processes, including anaerobic digestion, pyrolysis, gasification and scale-up, while exploring new methods for waste valorization, such as application in building materials [3-23-156].

17 CONCLUSION

The sustainable management of agricultural waste has become a great challenge, especially for developing countries such as India with an increasing population, production rates and economic growth. It is a common practice in many of the developing countries, especially in Asia to burn the surplus crop residue. On an average 500 Mt of crop residue is generated yearly in India. While a majority of it is used for fodder, raw material for energy production, etc., still there is a huge surplus of 140 Mt out of which 92 Mt is burnt each year, mainly in Bihar, Punjab, Haryana, Madhya Pradesh, Uttar Pradesh, Maharashtra and Karnataka. Especially, the small-scale farmers resort to burning of crop waste as it is an inexpensive alternative due to the lack of technical awareness and lack of proper disposal opportunities. Large scale burning of crops increases CO_2, CO, N_2O and NO_x in the atmosphere and has led to shocking increase in the air pollution. There was an alarming deterioration of the air quality in India to nearly twice the permissible Indian standard and ten times higher than the WHO standard. The Indian Government has attempted many interventions to curtail the amount of crop residue burning through different campaigns. The Indian Agricultural Research institute (IARI), Indian Ministry of New and Renewable Energy (MNRE) are continuously promoting research and innovative measures to handle crop waste without burning. The National policy for management of crop residue (NPMCR) recently formulated by the Central Government, has laid out policies and regulations to be undertaken by the local agencies to curb crop burning and initiatives towards sustainable management practices. As a result, the National Remote Sensing Agency (NRSA) and the Central Pollution Control board (CPCB) now monitor crop burning through aerial surveillance and penalize farmers

who burn crops. The real reasons behind the crop residue burning have more socioeconomic roots rather than agricultural or waste management ones. Relatively overlooked bio-based products such as biogas, biochar and in-situ management with mechanical intensification are recognized as viable option for crop waste utilization. Large scale harnessing of methane gas from the waste, through biogas plants should be practiced.

Another area for further investigation is the assessment of the environmental footprints through LCAs. Research should also focus on developing integrated solutions that combine emerging technologies like remote sensing (RS) and geographical information systems (GIS), artificial intelligence (AI), and machine learning (ML) for comprehensive waste management. RS and GIS can be used to map and monitor agricultural waste generation and distribution, enabling better planning and resource allocation. AI and ML can be leveraged to optimize waste collection, processing, and conversion processes, enhancing efficiency and reducing costs. Additionally, regulations should be strengthened to enforce sustainable practices and discourage environmentally harmful methods like open burning. By leveraging these opportunities, India can effectively manage its agricultural waste, reduce environmental pollution, and create wealth from waste, contributing to the nation's economic growth and environmental sustainability.

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