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# Sustainable agricultural waste management in India: Innovations, challenges, and future perspectives

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ABSTRACT

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, with a share of 13.72 % compared to global average of 11 %. Furthermore, the agriculture sector is not only strained to secure food production for growing population but also expected to minimize GHG emissions. Intensive farming, while more productive and efficient, poses a threat to the environment due to accumulation of large quantities of agricultural residue. Nevertheless, the sustainable conversion of agricultural residue could offer twin benefits: energy generation 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 have shown potential for value added products and energy feedstocks. Valorization techniques offer sustainable agricultural waste management solutions while recovering energy and promoting the circular economy. This study further explored the recovery of building materials including insulating materials, roofing components, additives, and secondary cementitious materials from agricultural residues. Currently, agricultural residue in India is primarily utilized to produce biofuels with installed plant capacity of 5 million tons, and solid biofuel. Nevertheless, techno-economic, socio-cultural, institutional, and governance challenges still need to be addressed to ensure the sustainable management of surplus agricultural residue through emerging techniques. The goal of this study is to promote integration of academic, scientific, and industrial development while strengthening the circular economy, particularly in agriculture-based economies.

## 1. Introduction

In India, agricultural activities play a critical role in the country's economy and food security and also generate substantial amounts of agricultural waste. Crop residues, by-products from agro-processing, and livestock manure constitute a significant portion of this agricultural waste, where more than 500 million tons (MT) of crop residues are produced annually in India [1]. Conventional agricultural waste handling methods, like dumping and open burning, lead to severe air pollution and health issues, stressing the urgent need for sustainable management solutions [2]. While somewhat effective, other traditional practices such as animal feeding, mulching, and composting are often fall short in addressing the scale and environmental impact of agricultural waste. Recently, there has been a rising focus on sustainable agricultural waste management practices through waste valorization techniques that can convert waste into valuable resources, and promoting a circular economy. Sustainable practices, including composting, bioenergy generation, residue recycling, etc. not only mitigate environmental risks but also promote circular economy principles by converting waste into resources. Therefore, adopting innovative sustainable waste management strategies can improve farm productivity and support climate resilience with long-term ecological and economic

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sustainability.

Different valorization techniques include pyrolysis, gasification, anaerobic digestion, biorefining, bioprocessing, etc. For example, an integrated biorefinery approach can efficiently transform agricultural wastes into biogas, biofuels, and other valuable products, including biochar, eco-fibres, cellulose-based nanomaterials, and enzymes through thermochemical, biological, and biochemical processes [3–8]. Additionally, bioactive compounds, bio-stimulants, biofertilizers, and bio-plastics derived from agricultural waste further exemplifying the innovations in sustainable processing of agricultural waste [9–11]. Several contemporary researchers have highlighted that about 180 MT of surplus crop residues generated in India annually, hold significant potential for diverse applications [12,13]. Furthermore, it was emphasized that agricultural waste streams in India had received greater attention for converting agricultural waste into valuable resources, addressing both waste management and resource recovery [5,8,14–16].

In developing countries like India, utilizing agricultural residue as a non-conventional energy source is both economically attractive and environmentally friendly to meet energy demands [17,18]. For instance, biogas generated from agricultural waste can be utilized for cooking, heating, biofuels, and electricity [19,20]. The state-wise power capacity of agricultural waste in India varies significantly, with Uttar Pradesh having the highest potential (6045 MW), followed by Punjab and Maharashtra with above 3000 MW capacity [15]. 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 insulating composites [21]. 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 pollutants [22–24]. In addition, crop residues can serve as feedstock for second-generation biofuels, producing approximately 60 billion litres (L) of bioethanol per annum [25]. Beyond biofuels, agricultural wastes can be used in making compost, nanomaterials, mushroom growing, biogas production, and as raw materials for industries such as paper, construction, cosmeceuticals, and pharmaceuticals [26]. The diversified utilization of agricultural waste can partially substitute conventional fossil derived feedstock, enhancing sustainability and economic value [25]. Utilizing microorganisms to transform agricultural waste into value-added products, including biomolecules, biofuels, biofertilizers, organic acids, enzymes, essential oils, and flavours, leverages microbial communities for energy and nutrient recovery, supporting the sustainable economy and zero-waste perspective and has a larger scope in India [27–31].

The research in this direction aligns with key global sustainability frameworks, particularly the United Nations Sustainable Development Goals (SDGs), by addressing critical environmental and socio-economic challenges. Specifically, it contributes to SDG 7 (Affordable and Clean Energy) via bioenergy generation from crop residues, and SDG 13 (Climate Action) by reducing greenhouse gas (GHG) emissions from open burning. Additionally, the circular economy approach supports SDG 12 (Responsible Consumption and Production) by minimizing waste and maximizing resource efficiency. At the national level, the Swachh Bharat Mission (Grameen) and the Waste to Wealth Mission under the Prime Minister's Science, Technology, and Innovation Advisory Council (PM-STIAC) reinforce the importance of converting agricultural waste into valuable products, fostering a circular economy. Globally, the push for a bio-based economy and net-zero emissions underscores the need for innovative waste valorization techniques, making this research highly relevant. Therefore, integrating technological innovations, sustainability studies, policy insights, existing conditions and persisting challenges towards sustainable agricultural waste management is crucial.

A review of existing literature on agricultural waste management in India reveals several critical research gaps. While previous studies have explored specific aspects such as the environmental impacts of crop residue burning [32,33], biogas potential [34], and pyrolysis techniques [35], there remains a lack of comprehensive discussion integrating traditional and advanced waste management methods within the Indian context. Previous studies were mainly focused either on technological solutions or policy challenges without adequately addressing the socio-economic dimensions of wealth creation from agricultural waste [36–38]. Additionally, although circular economy principles have been discussed, limited emphasis has been given to Life Cycle Assessment (LCA) studies and stakeholder perspectives for effective implementation [39–42]. Furthermore, while recent works [43–45] examine mechanical, biological, and thermal management of agricultural waste, a holistic analysis combining innovation, challenges, and future pathways for sustainable agricultural waste management in India is still lacking. This review purposes to bridge these gaps by systematically evaluating traditional and modern waste management strategies, economic opportunities, LCA insights, and stakeholder engagement, thereby providing a more actionable framework for policymakers and practitioners.

The aim of this study is to explore and provide comprehensive research on various aspects of agricultural waste management in India with the concept of recovery of value-added products. The paper is systematically organized and begins with an overview of the types and distribution of crop residues, followed by a discussion on traditional management practices, the composition of agricultural wastes, India's policy landscape on agricultural waste management, and its comparison with similar agricultural economics. Further, the conversion of agricultural waste into wealth through current research and emerging practices were examined, focusing on thermochemical and biobased processes and building materials recovery. A detailed section is dedicated to reviewing the sustainability of various valorization routes studied using LCA. The challenges and barriers to effective waste management were highlighted, addressing technical, financial, social, cultural, and institutional factors. Finally, the article proposed future directions and research priorities, emphasizing the role of technological innovations, policy frameworks and intervention in achieving sustainable agricultural waste management.

## 2. Overview of agricultural waste in India

### 2.1. Types, quantity, and distribution

Agricultural waste in India includes a diverse array of organic materials produced throughout the agricultural production cycle. The primary sources of agricultural waste include crop residues, animal manure, and by-products from agro-processing industries [46]. Crop residues like straw, stubble, husks, and shells are among the most abundant forms of agricultural waste, originating from cereal crops, including rice, wheat, maize, and pulses [47]. Additionally, residues from cash crops such as sugarcane bagasse and cotton stalks significantly contribute to the overall volume of agricultural waste. Fig. 1(a) shows different crop residues produced in India. Animal manure from cattle, buffalo, and poultry also plays a considerable part in the agricultural waste streams. Furthermore, various by-products from agro-industries, including press mud from sugar factories, bran from rice mills, and husk from oilseed processing units, add to the agricultural waste generated in India. As represented in Fig. 1(b), nearly 80 % of the surplus crop residue is accounted for rice straw, sugarcane bagasse, cotton stalk, and wheat straw [48].

Quantifying agricultural waste in India is challenging due to variations in crop yields, cropping patterns, and regional agricultural practices. However, estimates suggest that India produces over 500 MT of crop residue annually, making it one of the major producers of agricultural waste globally [1]. In addition, as per the National Dairy Development Board (NDDB), livestock animals produce an estimated

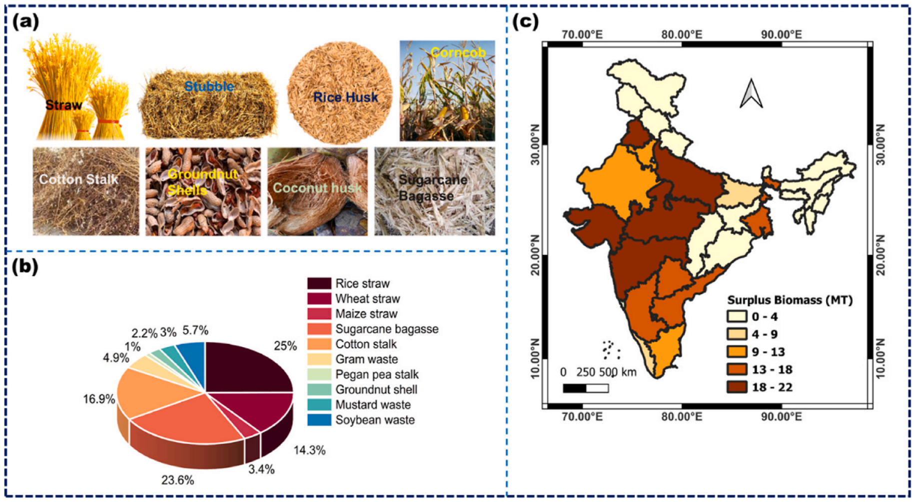


**Fig. 1.** a) Different types of crop residues in India; b) Typical proportions of various surplus crop residues in India; c) Distribution of surplus crop residue across Indian states for the year 2023.

1655 MT of manure annually released by the Press Information Bureau (PIB), Government of India in 2021. The distribution of agricultural waste across different regions in India varies significantly based on features, including agroclimatic conditions, cropping intensity, and the prevalence of certain crops. Northern states like Punjab, Haryana, and Uttar Pradesh are known for their high generation of residues, particularly rice and wheat stubble which is depicted in Fig. 1(c) [49]. Coastal states like Andhra Pradesh, Tamil Nadu, and Gujarat generate substantial crop residues from rice and sugarcane cultivation. States with significant horticultural crops, such as Maharashtra and Karnataka, produce diverse agricultural waste, including fruit and vegetable residues.

### 2.2. *Traditional agricultural waste management practices*

Traditional agricultural waste management methods in India have evolved over centuries to handle the abundance of agricultural residues and the limited resources available to rural communities. Fig. 2. (a) shows mostly practised traditional ways such as crop residue burning, animal feeding, mulching, and composting for managing agricultural wastes in India. While open-field burning served as primary means of waste disposal, it often entails environmental and socio-economic issues that need to be addressed. On the other hand, mulching, composting, and use as fodder appear to be reasonable solutions for waste utilization, especially to further advance local agricultural practices specific to local conditions and farming systems.

**Open-Field Burning:** Crop stubble burning is a usual process in many regions, especially after harvesting crops like rice and wheat, to clear fields quickly and economically for the new crop. For instance, the disposal of paddy residue has become a significant issue in many Indian states, predominantly Punjab and Haryana, where farmers often resort to burning residues in situ due to a deficiency of practical substitutions [50]. A study revealed that the trouble spot areas in Punjab and Haryana contributed 26 % of the overall fires in India, with significant activity after the paddy (77.08 %) and wheat harvesting season (16.44 %) [51]. Madhya Pradesh contributed substantially to crop-burning emissions, being the second-largest crop-burning emission state in 2020 [52]. However, the indiscriminate burning of crop residues contributes significantly to air pollution, releasing harmful pollutants like particulate matter (PM), carbon monoxide (CO), volatile organic compounds, and other gases, raising concerns about human health and climate change [2,53–56]. In 2017, India generated 488 MT of crop residue, with almost 24 % burned in fields, resulting in 824 Gigagram (Gg) of $PM_{2.5}$, 58 Gg of elemental carbon, 239 Gg of organic carbon, and 211 tera-grams (Tg) of carbon dioxide ($CO_2$) equivalent GHG emissions [57]. For instance, burning rice straw in north-western India leads to soil nutrient losses and severe air quality issues [58,59]. People in these areas face higher risks of respiratory diseases [60]. Additionally, stubble burning results in the loss of useful organic substances and nutrients from the soil, adversely affecting soil quality [50,61,62]. Despite the enforcement of regulations banning stubble burning, its prevalence persists due to factors such as limited awareness, inadequate enforcement mechanisms, and socio-economic pressures faced by farmers [49].

A multi-satellite observation study reported that the biomass burning effect on aerosol optical properties in Northern India, and the same study also observed black carbon concentrations for Patiala and

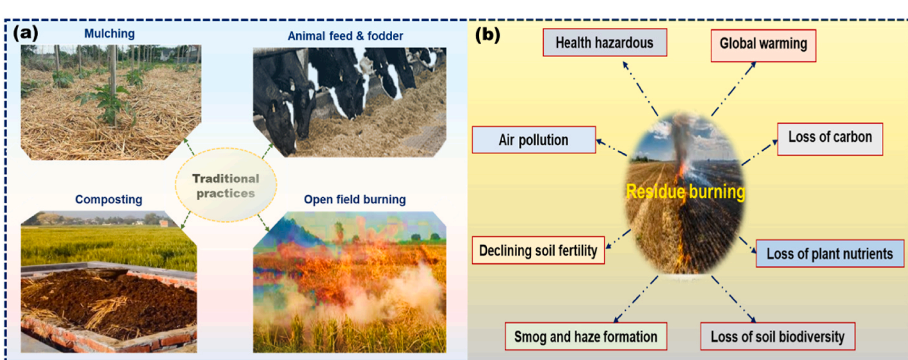


**Fig. 2.** (a) Traditional agricultural waste management practices in India; (b) Effects of crop residue burning.

Dehradun were 8.43 ± 3.14 $\mu gm^{-3}$ and 3.36 ± 1.26 $\mu gm^{-3}$, respectively between the year 2003 and 2017 [51]. The analysis further revealed that these aerosols were mostly within the planetary boundary layer, occasionally reaching altitudes of 2–3 km, and were transported to the eastern Indo-Gangetic Plain (IGP), central India, and neighbouring ocean areas after the monsoon periods, causing high air pollution episodes [51,63]. Another study in Panipat, Haryana, India that investigated the impact of rice straw burning on soil microbial dynamics, reported a significant reduction in the microbial community [64]. Fig. 2 (b) shows the disadvantages of burning the crop residues.

**Mulching:** Managing paddy residues through mulching, particularly with no-tillage systems, offers multiple benefits for the subsequent wheat crop, which is also typically practised in India. Mulching can enhance yield, improve water utilization efficiency, increase profitability, and reduce weed pressure [58]. Additionally, incorporating surplus residues from the earlier wheat cultivation into rice paddies does not negatively impact rice yield but improves soil health by enhancing soil characteristics [58].

**Composting:** Composting represents a more sustainable alternative to burning for handling crop residue in India. Composting entails the biological breakdown of organic matter under regulated conditions to create compost, a nutrient-dense soil enhancer. Farming by-products such as crop straw, vegetable waste, and animal manure can be effectively composted to generate premium-quality organic fertilizer [61]. Composting helps recycle nutrients and organic content and enhances soil properties, water holding, and microbial activity [65]. However, the widespread adoption of composting practices in India faces challenges such as lack of awareness, training, and access to appropriate composting technologies. Furthermore, composting is a slow process with low economic returns that requires larger space.

**Animal Feed and Fodder:** Agricultural waste, particularly crop residue, is a valuable feed resource for livestock in India [61]. Farmers often use crop straw, husks, and stalks as supplementary fodder for cattle, buffalo, and other livestock species. By converting agricultural residues into animal feed, farmers can reduce feed costs and improve the nutritional value of livestock diets [66]. Additionally, feeding crop residues to livestock helps in recycling nutrients and organic matter within the agricultural system. However, the nutritional quality of crop residues changes largely depending on crop type, stage of maturity, and post-harvest handling practices. Ensuring optimal utilization of crop residues as animal feed requires proper processing techniques, nutritional supplementation, and management practices to enhance digestibility and minimize wastage.

Despite their widespread use, traditional agricultural waste management practices in India face several challenges and limitations that impede their effectiveness and sustainability. In addition, the inefficient utilization of agricultural residues signifies a missed chance for resource recovery and value addition. Resource recovery strategies have recently emerged to utilize agricultural waste as primary material for various applications, promoting the circular economy and effectively handling agricultural residues to mitigate associated negative impacts.

### 2.3. Composition of agricultural waste

Agricultural residues vary in chemical components, and physical characteristics determine their suitability for different conversion processes. The constituents of agricultural waste in India differs based on crop type and agricultural practices. Table 1 represents the agricultural waste types, their composition, and their potential applications.

Understanding the composition of agricultural waste streams enables targeted valorization approaches that maximize resource recovery, energy generation, and value addition. It is worth to mention that the selection of valorization strategies should consider the inherent properties and potential applications of agricultural residues to encourage sustainable economy and waste management [67]. The comprehensive understanding is essential for developing effective utilization strategies that can transform agricultural waste into valuable resources, thereby supporting sustainable agricultural practices in India. For instance, crop residues, including straws, stalks, husks, and leaves, can be transformed into biofuels, biogas, and compost, dropping dependency on non-renewable energy and chemical fertilizers. Agro-industrial derivatives, including bagasse and husk, can be used to yield bioethanol, bioplastics, and bio-based chemicals, contributing to sustainable industrial practices [28,68,69]. However, it is important that only a portion of the total agricultural waste after accounting for local sustainable usage should be considered as viable feedstock for other valorization routes to avoid unintended competition with existing uses.

### 2.4. Policy landscape for agricultural waste management in India and comparative analysis with similar economies

The Indian government has introduced several policies and programs to address the challenges of agricultural waste management and promote sustainable practices. One of the key initiatives is the *National Policy for Management of Crop Residue (NPMCR, 2014)*, which advocates for in-situ (e.g., mulching, soil incorporation) and ex-situ (e.g., bioenergy, composting) solutions to curb on-field stubble burning, particularly in Punjab, Haryana, and Uttar Pradesh. Complementing this, the *Crop Residue Management (CRM) Scheme* provides subsidies for machinery like Happy Seeders and balers to discourage open-field burning. Regulatory measures, such as bans on open-field burning imposed by the Punjab Pollution Control Board (PPCB) under the *Air Act (1981)* and penalties enforced by the National Green Tribunal (NGT), aim to ensure compliance, though implementation challenges remain persistent. Judicial interventions, such as Supreme Court directives in *MC Mehta v. Union of India* and mandates from the *Commission for Air Quality Management (CAQM)*, require state-specific action plans supported by monitoring mechanisms.

On the energy front, the *Ministry of New and Renewable Energy (MNRE)* promotes biomass valorization by providing financial support through its *Biomass Power & Cogeneration Programme* and the *National Bioenergy Programme (2021–26)*. This includes sub-schemes for waste-to-energy projects, biogas plants, and biomass pellet production. The *Sustainable Alternative Towards Affordable Transportation (SATAT) initiative (2024)* further incentivizes compressed biogas (CBG) production from agricultural residues, offering financial support for biomass aggregation. At the state level, Punjab's *Biofuel Policy* mandates industries to use paddy straw in boilers, backed by fiscal incentives like State Goods and Services Tax (SGST) reimbursement. Despite these efforts, significant gaps remain due to weak enforcement, limited farmer

**Table 1**
Agricultural waste types, their composition, and uses.

| Category | Types | Composition | Uses | References |
|---|---|---|---|---|
| **Crop residues** | Straw, Stalks, Husks, Leaves | Cellulose, Hemicellulose, Lignin, Proteins, Lipids, Minerals | Bioenergy production, Composting, Animal bedding, Soil amendment | [49] |
| **Agro-industrial by-products** | Bagasse, Rice husk, Wheat bran, Oilseed cake | Carbohydrates, Proteins, Lipids, Phytochemicals | Bioethanol production, Biocomposite Manufacturing, Industrial applications, Livestock feed | [70] |
| **Livestock manure** | Poultry Litter, Cattle Dung, Pig Slurry | Nutrients, Carbon, Trace elements, Organic matter | Biogas production, Bioenergy, Composting, Vermicomposting, Nutrient recycling for plant growth | [71,254] |

awareness, and challenges related to supply-chain logistics. Unlike the EU's integrated *Common Agricultural Policy (CAP)*, India's agriculture framework lacks binding compliance measures, underscoring the need for stronger decentralized governance and private-sector engagement to bridge policy-practice disparities.

Globally, major agricultural economies face comparable challenges in managing crop residues and livestock waste, though their policy approaches and implementation efficacy vary significantly. China, the world's largest agricultural waste producer (980 MT of crop straw annually; [72]), mirrors India's struggles with stubble burning and air pollution [73]. However, post-2013 reforms combining strict enforcement with subsidies for alternative uses (e.g., straw-to-energy, composting) reduced open burning by practical alternatives and fostering multi-stakeholder collaboration among governments, farmers, and markets [74]. In contrast, Brazil leverages its agro-waste potential (1.77 billion tons/year where 932 MT from cattle rearing, 62 MT from maize cultivation, and 44 MT from sugarcane production) through structured bioeconomy frameworks like *RenovaBio*, which incentivizes biofuels and sugarcane bagasse-based bioelectricity [75], though decentralized residue collection remains a bottleneck [76]. Southeast Asian nations like Vietnam (100 MT of crop residues/year) and Thailand (19 MT of rice straw/year) prioritize low-cost solutions such as animal feed and mushroom cultivation along with biofuel production [77–79], yet policy gaps such as Thailand's *Alternative Energy Development Plan (2012)* failing to address collection costs and awareness that hinder progress [78]. Vietnam's systemic limitations in infrastructure and management capacity further underscore the gap between policy intent and on-ground execution [79]. In Spain, most biomass waste is sent to external recycling plants or used as animal feed and a smaller amount is reused by growers as fertilizer, while very little is turned into compost in greenhouses [80]. While India shares similarities with these economies in waste volume and burning-related pollution, its policy framework lacks the integrated enforcement seen in China or the market-driven biofuel incentives of Brazil. This comparison highlights the need for India to adopt context-specific strategies balancing regulatory rigor, farmer incentives, and infrastructure investment to bridge the implementation gap.

## 3. Agricultural waste valorization

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.

### 3.1. Thermochemical processes

Thermochemical processes are pivotal in valorizing agricultural waste, converting biomass into energy and valuable chemicals through high-temperature techniques [81]. The thermochemical processes include pyrolysis, gasification, and combustion, each with distinct mechanisms and outputs, as given in Fig. 3.

**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 [82]. 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 [84]. Depending upon these conditions, pyrolysis is classified into different types such as slow, intermediate, and fast pyrolysis [85]. 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 [86]. In intermediate pyrolysis the temperature is around 500 °C, heating rate of 10–200 °C $sec^{-1}$ and residence time of several minutes [87]. 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 resulting in low solid fraction [88]. Intermediate and fast pyrolysis are suitable when liquid and gases as targeted products. Studies have revealed that pyrolysis of rice straw can yield bio-oil with significant energy potential and biochar suitable as a soil amendment [89]. Biochar derived from biomass has potential applications in agriculture, construction, and water treatment [90]. 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 [91]. Investigations into rice husk and corn stover biochar produced via slow pyrolysis have shown positive effects on soil fertility, water retention, total organic carbon, and cation exchange capacity while reducing soil $CO_2$ emissions [92]. The biochar application improves crop growth and provides long-term carbon sequestration, indicating its effectiveness for soil amendments and carbon mitigation [92]. In terms of scale, pyrolysis can produce 212.04 ± 44.27 MT of biochar from 517.82 MT of crop wastes in India, sequestering about 376.11 ± 78.52 MT of $CO_{2eq}$ carbon and holding 1.66 ± 0.46 MT of soil nutrients [93]. Successful large-scale implementation of pyrolysis technology for agricultural residues could reduce India's

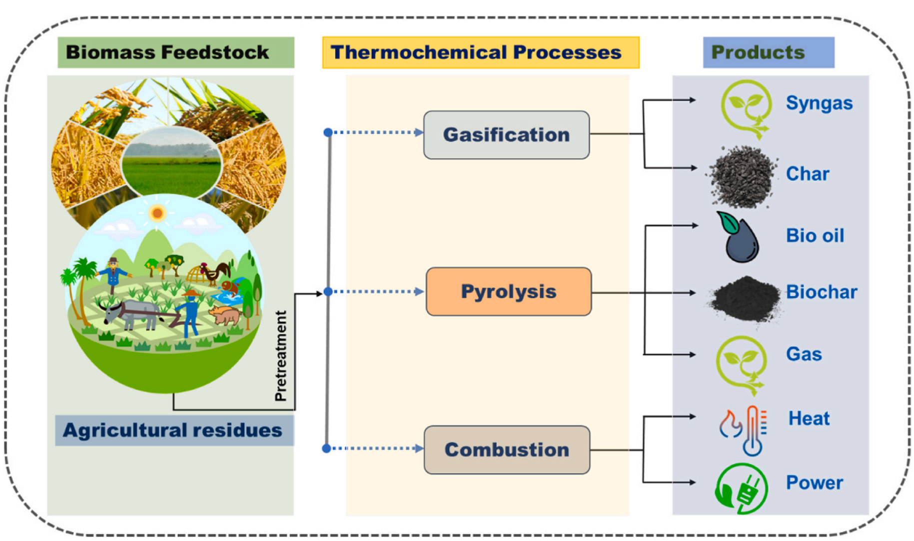


**Fig. 3.** Thermochemical processes for converting agricultural residues into valuable products.

carbon emissions by 10 % and increase electricity generation by 10 –12 %, potentially producing 41.9 GWe of bioelectricity [94]. 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.

**Gasification:** Gasification involves the transformation of lignocellulosic or carbonaceous waste into syngas through partial oxidation at high temperatures (500–1400 °C) [95]. During this process the biomass undergoes four major stages: moisture removal, release of volatile compounds, partial oxidation, and reduction reactions to produce syngas and char [96,97]. 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 [98]. The resulting syngas, composed of CO, hydrogen ($H_2$), $CO_2$ and methane ($CH_4$), can be utilized for producing chemicals or electricity [99]. Studies have highlighted the potential of gasifying crop residues like sugarcane bagasse and coconut shells for decentralized energy production in rural India. 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 [100]. A techno-economic study in rural Uttar Pradesh showed while not cost-competitive with solar PV alone, hybrid systems (solar PV and biomass gasification) present a viable solution pending operational testing [101]. Another innovative approach combines steam-air biomass gasification with solar energy to produce green $H_2$. 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 $kg^{-1}$, and cold gas efficiency of 80 % [102]. 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 °C yielded higher hydrogen content (70 %) and heating value (11 MJ $m^{-3}$) compared to an air-steam mix [103]. The results suggest steam gasification is more efficient for hydrogen-rich syngas, making it suitable for industrial fuel applications [103]. 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. Furthermore, the model predicted that the net calorific value and gas production could reach 6.17 MJ $N^{-1}m^{-3}$ and 2.369 $m^3$ $kg^{-1}$, respectively [104]. Although gasification offers immense potential feedstock variability, high initial costs, and requirement of effective tar removal technologies remain barriers to widespread adoption [105].

**Combustion:** 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. These residues are commonly combusted in industrial boilers to generate steam and electricity. Torrefaction is an additional thermochemical treatment that enhances the feedstock quality before its utilization in combustion, pyrolysis, or gasification. 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 [106–108]. Narayanan and Natarajan (2007) 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 [109]. However, the continuous availability of agricultural residues and their transport to the power plants are essential while considering their techno-economic feasibility [110]. These logistical and supply chain constraints apply broadly across all biomass-based energy conversion systems including pyrolysis and gasification. Another approach is to design and deploy an improved cookstoves and furnaces specifically tailored for the combustion of agricultural residues. 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 [111–115]. 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. 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. Whereas gasification offers potential for power generation and industrial applications. Therefore, 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. By optimizing these technologies and scaling up their implementation, India can make significant strides in agricultural waste management and renewable bioenergy generation.

### 3.2. Biochemical, biorefining, and bio-processing techniques

The valorization of agricultural waste through biochemical, biorefining, and bioprocessing techniques offers promising paths for sustainable development and resource efficiency [116]. These methods convert waste into value-added products like biofuels, bioplastics, enzymes, organic acids, and other valuable bioproducts such as bioactive/nutraceuticals, nanoparticles, antibiotics, biosurfactants, and other specific chemicals [117]. 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 [118,119]. 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. [69,118,120].

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 [121–125]. This section discusses the production of specific products from agricultural waste using bio-based techniques, as shown in Fig. 4, highlighting recent advancements and research findings.

**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 [126,127]. Factors such as substrate composition, C/N ratio, temperature, and pH play critical roles in determining the efficiency and yield of biogas production [128,129].

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 [48,71,130–132]. 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 [133]. Sugarcane as feed can produce relatively higher biogas than rice husk due to low lignin levels [134]. 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. Pre-treatment methods such as chemical and thermal treatments improve the digestibility of lignocellulosic biomass, causing improved biogas yields [135,136]. For instance, pre-treated biomass increased biogas production by 62 % for rice straw and 66 %

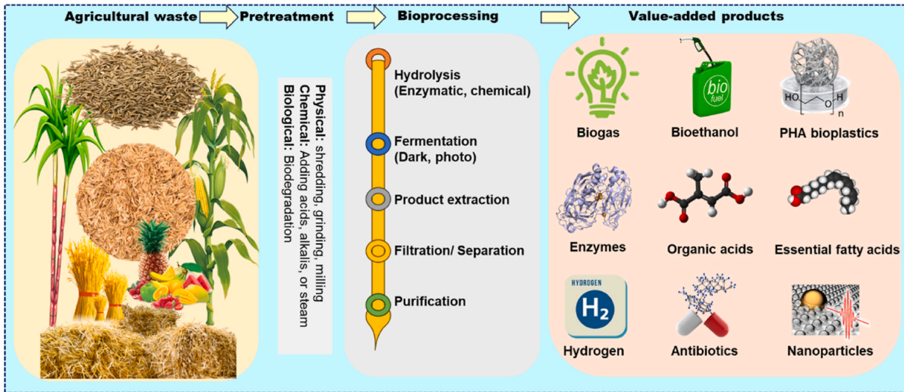


**Fig. 4.** Bio-based treatments of agricultural waste for the generation of value-added products.

for corn stalk compared to untreated samples, highlighting the potential of banana peel ash in enhancing energy recovery from rural biomass residues [135]. Chemical pre-treatments use acidic, alkaline, and oxidising agents [127].

Co-digestion strategies, combining multiple types of agricultural and food wastes, have been explored to optimize biogas production. 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 [137]. A biochemical methane potential test indicated that pellets with 8 % total solids content produced the highest biomethane yield of 241 mL $g^{-1}$VS [137]. 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 [138]. 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 [139].

**Bioethanol Production:** Fermentation is a key biochemical process for producing bioethanol from agricultural residues. The production of bioethanol from lignocellulosic biomass involves three main stages: pre-treatment, enzymatic hydrolysis, and fermentation [140]. Pre-treatment breaks down the complex lignocellulosic structure to enhance the accessibility of cellulose and hemicellulose, typically using physical, chemical, or biological methods [141]. 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 [142]. 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 [28,143]. Studies have shown efficient conversion of these substrates into ethanol and other products using specific microbial strains and biocatalysts. For example, Rajesh and Gummadi (2023) studied the transformation of lignocellulosic biomass into valuable products using *Bacillus* sp. *PM06* [144]. The fermentative process using *Bacillus* sp. *PM06* resulted in high carbohydrate utilization, particularly for wheat bran, achieving over 80 % efficiency. This conversion produced notable amounts of ethanol (1.83 g $L^{-1}$) and acetic acid (7.57 g $L^{-1}$), demonstrating a 27.67 % ethanol yield based on glucose fermentation [144]. In another study, the authors studied the hydrolysis and fermentation of four abundant residues: sugarcane bagasse, rice straw, sweet sorghum, and millet straw [142]. Using dilute-acid hydrolysis and a ligninolytic fungus, Trametes versicolor as a biocatalyst during pre-treatment, around 85–90 % of fermentable sugars were converted to ethanol at 27 °C showing significant potential for bioethanol production [142]. 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. Therefore, utilizing sugarcane waste enhances economic feasibility and hence it was recommended to have bio-ethanol plants where biomass availability per unit area is greater [143,145].

**Enzyme Production:** Agricultural waste serves as a potential substrate feedstock for producing industrial enzymes due to its rich composition of lignocellulosic biomass, proteins, and other nutrients [146]. Enzyme production usually involves the cultivation of microorganisms like bacteria, fungi, or actinomycetes on these substrates, utilizing solid-state or submerged fermentation techniques [147]. Enzymes such as cellulases, xylanases, pectinases, and amylases are commonly produced, which find applications in biofuel production, food processing, and textile industries [148]. Various enzymes, including lipolytic and pectinolytic enzymes, can be made through microbial processing of fruit and vegetable wastes [149]. Enzymes like pectinase, tannase, laccase, etc., can be generated from wastes like orange peel, pomegranate rind, corn-cob, rice bran, and wheat bran [150–154]. These enzymes derived from agricultural waste processing have applications in various industries, such as food processing, textile, and bioremediation, enhancing the value of by-products from oil seeds and other agricultural residues [149,155]. For example, the production of tannase from pomegranate rind via solid-state fermentation using *Aspergillus foetidus* has shown promising results, with a notable yield of 43.5 U $g^{-1}$ of agricultural waste substrate [150]. Similarly, orange peel waste has been utilized for pectinase production, achieving significant enzymatic activity (99.21 U $mL^{-1}$ of pectinase within 72 h under optimized conditions) when fermented with *Aspergillus niger* [151]. In another study, the maximum enzyme production (464,000 U $g^{-1}$ dry bacterial bran) was achieved utilizing wheat bran as a substrate, boosted with glycerol, soybean meal, L-proline, vitamin B-complex, and moistened with a solution containing Tween-40 and $MgSO_4{\cdot}7H_2O$ [156]. The optimal incubation parameters were 37 °C for 48 h, highlighting the importance of carefully controlled conditions in solid-state fermentation for enzyme yield. Enzymes such as cellulases, xylanases, pectinases, and amylases are commonly produced, which find applications in biofuel production, food processing, and textile industries [149]. 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. Additionally, optimizing fermentation conditions, including pH, temperature, and moisture content, enhances enzyme yield and activity, ensuring process efficiency.

**Hydrogen ($H_2$) Production:** Thermochemical methods, including gasification and pyrolysis, convert biomass into $H_2$-rich syngas under high-temperature conditions [98,157]. Alternatively, biological processes such as dark fermentation and photo-fermentation employ microorganisms like *Clostridium* spp. to produce $H_2$ by metabolizing carbohydrates in the biomass [158]. $H_2$ production through dark fermentation and photo-fermentation using agricultural wastes has gained attention because of clean energy sources [159]. Substrates, including rice straw and rice husk hydrolysates, have been efficiently converted to $H_2$, demonstrating high yields and process feasibility [160, 161]. Elsharkawy et al. (2020) reported an $H_2$ yield of 1.8 mol $H_2$ per mol glucose equivalent from rice husk hydrolysate using *Clostridium beijerinckii* [136]. Similarly, Dinesh et al. (2020) obtained $H_2$ production of 2.1 mol $H_2$ per mol glucose from rice straw hydrolysate [135]. The integration of pre-treatment techniques to enhance feedstock digestibility and optimization of pH, temperature, and substrate concentration, are crucial for improving hydrogen yields [162]. This approach aligns with renewable energy goals, providing an eco-friendly approach to reduce GHG emissions.

**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 [163]. The lignocellulosic components of agricultural residues, including cellulose, hemicellulose, and starch, are hydrolyzed into fermentable sugars through enzymatic or chemical pre-treatment [164]. These sugars are then transformed into organic acids by microbial fermentation using strains like *Lactobacillus* spp., *Aspergillus niger*, or *Actinobacillus succinogenes* [163]. Low-cost substrates such as corn starch and corncob waste have been optimized for high yields and selectivity in producing these acids, which are important for various industrial purposes [165,166]. Dasgupta et al. (2021) demonstrated the generation of xylitol from corncob waste using *Candida tropicalis*, achieving a yield of 0.71 g $g^{-1}$ of xylose [143]. Gnanasekaran et al. (2018) reported the efficient production of itaconic acid from corn starch hydrolysate using *Aspergillus terreus*, with a maximum yield of 0.60 g $g^{-1}$ of substrate [140]. 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. Techniques such as solvent extraction, membrane separation, electrodialysis, and integrated methods have been explored, but issues related to energy consumption, selectivity, and scalability persist [167–169]. Therefore, developing cost-effective and sustainable separation technologies is essential for improving the overall viability of organic acid production from agricultural residues. Factors such as substrate composition, fermentation conditions, and microbial efficiency play critical roles in determining the yield and productivity of organic acids. Utilizing agricultural waste not only lowers production costs but also promotes sustainable waste valorization, contributing to the circular bioeconomy.

**Polyhydroxyalkanoates (PHA) Production:** Biopolymers such as PHAs are produced from agricultural wastes through microbial fermentation. *Halomonas campisalis* has converted agricultural wastes, including bagasse, orange, and banana peels, into PHAs, effectively reducing production costs and environmental impact [170]. Pre-treatment processes like enzymatic hydrolysis or acid hydrolysis are employed to release fermentable sugars from agricultural residues [171]. Microorganisms such as *Cupriavidus necator*, *Bacillus* spp., and *Pseudomonas* spp. are commonly used to synthesize PHAs in fermentation systems [172]. For example, Kulkarni et al. (2015) mentioned the production of PHAs from sugarcane bagasse hydrolysate using *Halomonas campisalis*, achieving a polymer yield of 48 % of cell dry weight [170]. Optimizing carbon-to-nitrogen ratios, fermentation conditions, and recovery methods can significantly enhance PHA yields [173]. 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.

**Compost generation:** Composting is an important bioprocessing technique for converting agricultural waste into nutrient-rich compost. 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 [174]. 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 [175]. The use of efficient microorganism (EM) consortia has accelerated the composting process and improved compost quality. An EM consortium, including *Candida tropicalis, Phanerochaete chrysosporium, Streptomyces globisporous, Lactobacillus* sp., and an enhanced photosynthetic bacterial culture, was created for fast composting of rice straw amended with poultry droppings [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. Key factors influencing the efficiency of composting include C/N ratio, moisture content, aeration, and temperature [176]. Proper management of these parameters enhances the decomposition rate and quality of the compost. 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.

**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 [177]. Agricultural waste, including oilseed cakes, fruit peels, and lignocellulosic residues, presents a cost-effective and sustainable feedstock for EFA production. 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 [178]. Recent advancements have optimized solid-state fermentation composites to produce EFAs from agricultural waste for aquaculture feedstock, significantly reducing environmental and economic costs [179]. Saikia et al. (2024) reported that using agricultural waste substrates, essential fatty acids such as omega-3 and omega-6 could be efficiently produced with high yield, enhancing the nutritional value of aquaculture feed [179]. The optimized solid-state fermentation composite for maximum lipid enrichment consisted of 9.91 g per 100 mL orange peels, 5 g per 100 mL mausambi peels, 4.12 g per 100 mL pineapple peels, and 8.01 g per 100 mL banana peels, resulting in an 8.37 % lipid yield from *Aurantiochytrium* sp. ATCC276 [179]. Pre-treatment processes such as enzymatic hydrolysis or acid hydrolysis are often required to release fermentable sugars or lipids from these residues [180]. Optimizing fermentation parameters, such as pH, temperature, and substrate concentration, is critical to maximizing lipid accumulation and EFA yield [180]. Leveraging agricultural waste for EFA production not only reduces raw material costs but also contributes to sustainable waste management and bioeconomy development.

**Other value-added products:** Agricultural residues such as oil seed cakes and fruit peels can be transformed into various high-value products such as proteins, antioxidants, sugars, furfural, etc. [68]. Oil seed cakes are used in multiple industries, including biofuel production, pharmaceuticals, nutraceuticals, food, and feed, because of their rich protein content [149]. Fruit peels have been explored for their potential to produce natural antioxidants and pigments, enhancing the worth of these by-products [155]. Panda et al. (2016) confirmed that oil seed cakes could generate high-protein animal feed, while Sagar et al. (2018) reported that fruit peels could extract natural antioxidants with significant health benefits [181,182]. Sahu and Dhepe (2012) utilized sugarcane bagasse to produce C5 sugars and furfural using a solid-acid catalyzed one-pot method, achieving over 90 % conversion of hemicellulose [183]. Bhaumik and Dhepe (2014) improved the process, obtaining a 93 % yield of furfural from assorted biomass, including bagasse, rice husk, and wheat straw with no pre-treatment [183,184]. Ghosh et al. (2015) developed a biorefinery approach using sugarcane bagasse to produce ethanol, furfural, and electricity [185]. The proposed process yielded 0.366 L of ethanol, 0.149 kg of furfural, and 0.30 kW of electricity per unit of bagasse processed [185]. Madhukumar and Muralikrishna (2012) extracted water-extractable polysaccharides from wheat bran and Bengal gram husk using a commercial Drieslase enzyme

[186]. The authors reported that the prebiotic activity of Xylo-oligosaccharides (XOS) from wheat bran was more than that from Bengal gram husk due to its higher arabinose content [186]. Samanta et al. (2015) developed a process using 12 % NaOH and steam to enhance the xylan production from corn cobs, achieving a 90 % yield [187]. Overall, these biochemical, biorefining, and bioprocessing techniques highlight the significant potential of agricultural waste valorization, contributing to sustainable development and environmental conservation.

### 3.3. Electrochemical processes

Electrochemical processes involve the interconversion of chemical and electrical energy through electrochemical reactions. 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 [188]. Fig. 5 (a) and 5 (b) represent agricultural residues in MFC for electricity production and its benefits. The lignocellulosic residues from various agricultural wastes, including rice, wheat, corn, and sugarcane, undergo pre-treatments to ensure proper degradation through electrochemically active microorganisms [189]. Various pre-treatment processes can enhance bioavailability, microbial activity, and electricity generation, and reduce inhibitory compounds.

A novel three-chamber MFC was introduced for simultaneous lignocellulosic biomass degradation and bioelectricity generation. In this system, *Oscillatoria annae*, a freshwater cyanobacterium, hydrolyzed cellulose to glucose, and coculture of *Acetobacter aceti* and *Gluconobacter roseus* oxidized the glucose to produce electricity, with carbon felt serving as the anode and cathode material [190]. Using sugarcane bagasse and corn cob as substrates, the MFC's performance was evaluated through polarization studies, coulombic efficiency, chemical oxygen demand removal, and intrinsic resistance. The maximum power outputs were 8.78 W $m^{-3}$ at 20.95 A $m^{-3}$ for sugarcane bagasse and 6.73 W $m^{-3}$ at 17.28 A $m^{-3}$ for corn cob [190].

Another study by Kondaveeti et al. (2019) showed effective bioelectricity generation and organic waste treatment using citrus waste in a single-chamber mediator-less air cathode MFC [191]. Tested at four organic loading conditions (OLs: 3–12 kg $m^{-3}$), the MFC showed significant electricity production and organic lessening [191]. The highest power generation (71.1 mW $m^{-2}$) occurred at the lowest OL (3 kg $m^{-3}$). Higher OLs led to a decrease in pH and increased volatile fatty acids.

In a 30-day study, a dual-chamber MFC employed *Phlebia floridensis* and *Phlebia brevispora* fungi to degrade wheat straw while *Pichia fermentans* served as the exoelectrogenic yeast [192]. Both fungi efficiently produced lignocellulolytic enzymes, boosting reducing sugars and phenolics in the catholyte. *P. floridensis* achieved peak laccase production (9.03 CU $mL^{-1}$) on day 9, hitting an open circuit voltage of 0.504 V and a peak power density of 33.19 mW $m^{-2}$, while *P. brevispora* reached a maximum laccase production of 4.77 CU $mL^{-1}$ on day 17, with a voltage of 0.496 V and a peak power density of 12.90 mW $m^{-2}$ [192]. This degradation process enhanced catholyte efficiency, showcasing the feasibility of agricultural residue in sustainable bioelectricity production [192].

Additionally, alkaline pre-treatment of agricultural residues such as rice straw has been shown to be effective. For example, using 1.5 % NaOH for alkaline pre-treatment of rice straw resulted in the highest holocellulose generation at 80.1 % compared to 71.9 %, 73.8 %, and 78.5 % for NaOH concentrations of 0.5 %, 1.0 %, and 2 % respectively [193]. This process highlights the importance of optimizing pre-treatment conditions to improve the efficiency of electrochemical processes for agricultural waste valorization.

### 3.4. Valorization into building materials

Valorizing agricultural waste to recover building materials provides a sustainable way to waste management, offering economic and environmental benefits. Various agricultural residues and processing wastes such as fibres, ashes, and biochar can be utilized in building materials applications, as shown in Fig. 6. The excellent physical and mechanical properties of natural fibres attracted to utilize these in preparing composite materials that are suitable for use in particleboard, roofing

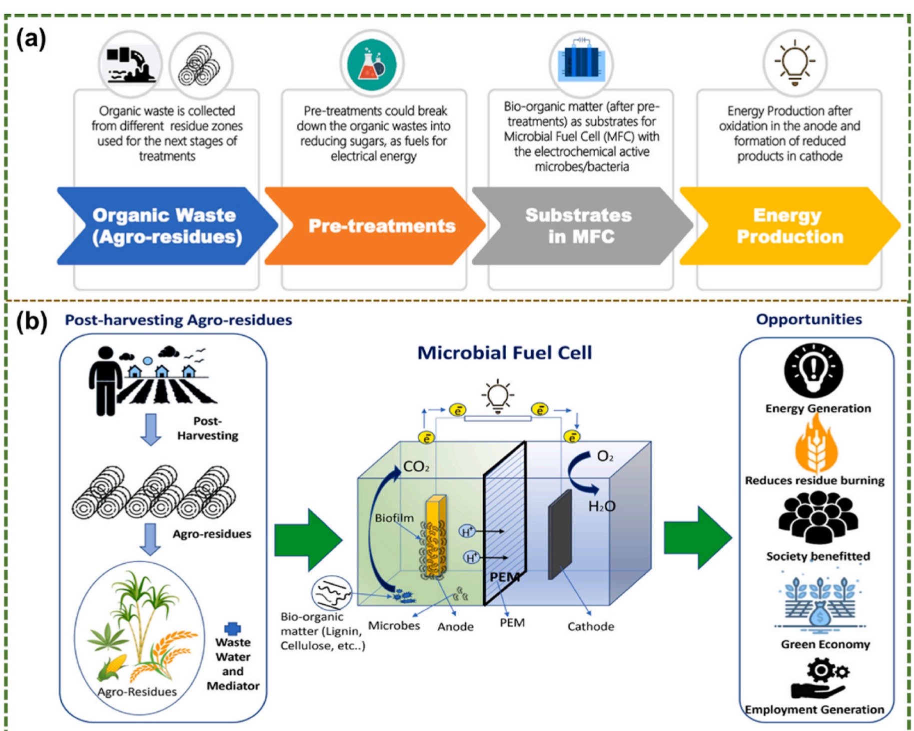


**Fig. 5.** (a) Steps in utilizing agricultural residue in MFCs for energy production; (b) Agricultural residue usage in MFC and its benefits (Reproduced from Ref. [189]).

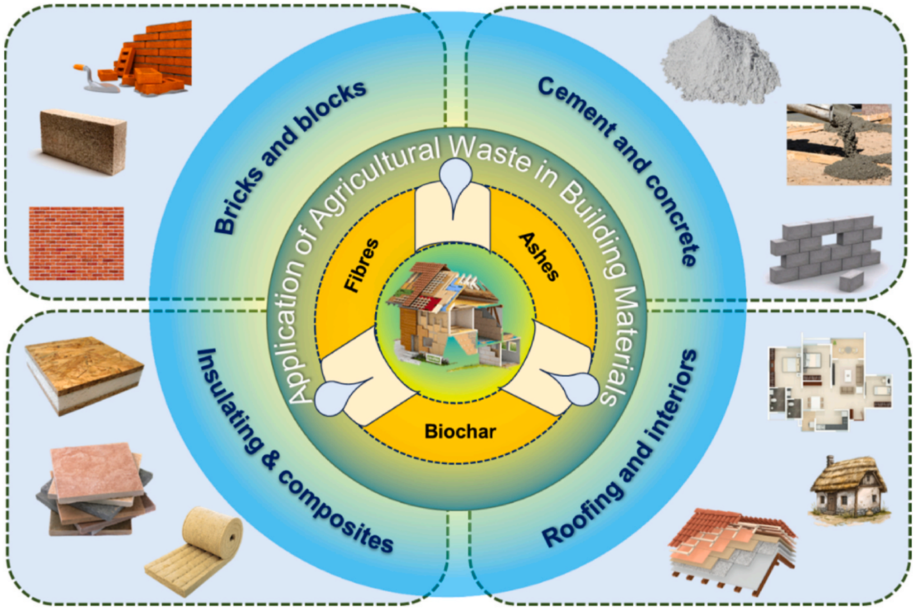


**Fig. 6.** Application of agricultural wastes in building materials.

material, and other indoor building components. Groundnut shell particles incorporated in polymeric composites have shown promising results concerning reasonable strength, and low moisture content and water absorption [194]. In addition, the agricultural ash particles have shown exceptional pozzolanic properties and enhance the strength of cementitious materials [195]. 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 [196].

**Agro-Based Panels:** Agro-based panels, such as particleboards and fiber boards, are commonly produced from agricultural residues like rice husk, wheat straw, and bagasse. These materials are bonded using resins to form durable and eco-friendly panels. Research has shown that agricultural residues can be used to produce high-quality particleboards with excellent mechanical properties. 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 [197,198]. The use of synthetic resins in the bonding process enhances the water resistance and overall performance of these panels, making them a viable alternative in the building industry. Therefore, utilizing agro-based panels could also help in preventing deforestation.

**Bricks and Blocks:** 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 [195,199–203]. These materials not only improve the sustainability of the bricks but also enhance their strength, thermal insulation, and hydrophobic characteristics [201,203]. Research conducted in India demonstrated that bricks made with partial replacement of rice husk ash (RHA) exhibit improved compressive strength, reduced permeability, and lighter weight, making them suitable for non-load-bearing walls and partitions [195,204]. Furthermore, the inclusion of RHA in concrete wall panels has been found to enhance their durability, acid resistance, and reduced thermal conductivity [205]. Singh et al. (2022) reveals that incorporating rice straw into gypsum decreases density and compressive strength, enhances thermal insulation and acoustic properties, and provides commendable fire-resistant characteristics that are suitable for non-load bearing wall applications [202].

**Cement and Concrete:** 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. Agricultural ash products can also be utilized as supplementary cementitious materials (SCMs) in concrete production. The RHA, having more silica, is particularly effective as an SCM, enhancing concrete strength and longevity [206,207]. Researchers have reported that the incorporation of RHA in concrete mixtures can minimize the total carbon footprint of the construction process [178]. In addition to RHA, other agricultural residues like sugarcane bagasse ash and groundnut shell ash have been explored as SCMs [199]. Incorporation of all these materials improves concrete performance and characteristics, contributing to more sustainable construction practices [208]. Moreover, replacing natural sand with wheat straw ash (WSA) in concrete improves mechanical properties up to a certain limit [209]. For example, concrete with up to 25 % WSA replacement shows significant increases in compressive strength (nearly 20 % higher than the target strength), tensile strength (nearly 60 %), and flexure strength (nearly 23 %). Whereas, beyond 25 % replacement by wheat straw ash, the concrete strength gain decreases [209]. The inclusion of WSA in concrete also reduces water absorption by almost 40 % at 25 % substitution, enhancing the material's durability by lowering water permeability [209]. These improvements are due to better void filling and reduced cracking in the cement matrix.

**Insulating Materials:** 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. These materials not only provide effective thermal insulation but also contribute to the reduction of energy consumption in buildings [205]. Research on the thermal performance of straw bale insulation in Indian climates has shown promising results, with significant reductions in heating and cooling loads. Additionally, rice husk-based insulation materials have been developed, offering similar benefits while utilizing an abundant agricultural by-product [210]. 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 [211].

**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. These eco-friendly roofing materials are suitable for rural and low-cost housing applications.

The recovery of building materials from agricultural wastes offers a sustainable solution to waste management challenges. 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. These innovations not only minimize the environmental damage of the construction sector, helping to decarbonize the built environment sector but also provide an effective means of managing agricultural waste in India.

In summary, 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 as given in Table 2. However, widespread adoption faces challenges related to technology access, economic viability, and awareness, particularly in rural areas (Table 3). Addressing these barriers through policy support, capacity building, and showcasing successful case studies can help scale up sustainable waste management practices effectively. Multiple case studies or the existing condition of agricultural waste valorization methods are discussed in the following section.

**Table 2**
Advantages and limitations of different valorization techniques [32–45].

| Category | Advantages | Limitations |
|---|---|---|
| **Composting** | - Easy to implement by farmers<br>- Low operational cost<br>- Reduces waste and enhances soil fertility<br>- Reduces need for chemical fertilizers | - Slow process (weeks to months)<br>- Requires more space<br>- Odor & pest issues if not managed<br>- Limited economic return |
| **Animal Feed** | - Direct use of crop residues (e.g., straw, husks)<br>- Low processing cost<br>- Reduces feed costs for livestock | - Storage & spoilage risks<br>- Needs proper safety control<br>- Not all waste types are suitable<br>- Lack of knowledge on nutritional content |
| **Bioenergy (Biogas/ Biofuels)** | - Renewable energy source<br>- Can use diverse feedstocks (manure, crop waste)<br>- Generates electricity and heat<br>- Digestate can be reused as fertilizer | - High initial investment (digesters, gas storage)<br>- Requires consistent feedstock supply<br>- Technical expertise needed for maintenance<br>- Infrastructure for energy distribution lacking in rural areas |
| **Bioethanol** | - High-value fuel additive<br>- Can use lignocellulosic waste (e.g., sugarcane bagasse, corn stover)<br>- High potential for scalability<br>- Market for transportation fuel | - Complex technology and pre-treatment required<br>- Enzymatic hydrolysis is expensive<br>- Competition with food-based ethanol<br>- Expensive for small-scale farmers |
| **Bioplastics** | - Reduces dependency on petroleum-based plastic use<br>- High market demand for eco-friendly plastics | - High production costs<br>- Requires advanced processing technology<br>- Limited availability of commercial-scale production in rural areas |
| **High-Value Chemicals (e.g., phenols, enzymes)** | - High profitability<br>- Diverse applications (pharma, cosmetics)<br>- Uses waste efficiently | - Requires specialized extraction tech<br>- Market demand fluctuations<br>- High R&D costs<br>- Needs skilled labor and knowledge<br>- Not economically feasible for small-scale operations |
| **Building Materials (e.g., fiberboard, bio-bricks)** | - Sustainable alternative to conventional materials<br>- Good insulation properties<br>- Useful for rural construction<br>- Low energy input compared to cement | - Limited durability in some cases<br>- Product standardization and quality control needed<br>- Limited awareness and technical knowledge<br>- Needs pressing, drying, and shaping equipment |

**Table 3**
Challenges faced by farmers or industries for implementing valorization techniques [32–45].

| Challenge Type | Description |
|---|---|
| **Technological Feasibility** | Advanced waste conversion methods (e.g., bioethanol, bioplastics) require sophisticated equipment, which may be expensive or unavailable for small-scale farmers and rural industries. |
| **Economic Viability** | High initial investment costs and uncertain profit margins make it difficult for farmers to adopt valorization techniques without financial support or guaranteed market demand. |
| **Infrastructure Barriers** | Inadequate rural infrastructure such as poor transportation, unreliable electricity, and lack of processing facilities limits large-scale waste utilization. |
| **Knowledge & Training Gaps** | Many farmers and local entrepreneurs lack technical expertise in waste processing, safety protocols, and commercialization strategies. |
| **Policy & Regulatory Issues** | Unclear waste management regulations, inconsistent government incentives, and bureaucratic hurdles slow down adoption and scalability. |

## 4. Agricultural waste management and wealth creation practices in India

Agricultural waste management in India increasingly incorporates mechanical methods to handle the substantial waste produced by farming activities. Tools like shredders, balers, and compost turners are pivotal in this approach. Shredders break down crop residues into smaller pieces, making them easier to manage, while balers compress them into bales for efficient transport and storage. Compost turners facilitate the aerobic decomposition of organic waste, transforming it into valuable compost. These mechanical methods improve agricultural practices efficiency and provide environmental and economic benefits to farmers [5,212].

Innovative mechanical tools such as the Happy Seeder and the tractor-operated paddy straw chopper-cum-spreader play significant roles in sustainable waste management. The Happy Seeder, developed by the Punjab Agricultural University in collaboration with the Australian Center for International Agricultural Research, allows for direct seeding of wheat into rice stubble, thereby minimizing the need for burning and reducing tillage requirements [212]. This device improves soil productivity and reduces environmental pollution by preserving organic matter and suppressing weeds [212]. Similarly, the paddy straw chopper-cum-spreader, developed through a collaboration between the Punjab Agricultural University and the Ludhiana Center of the All India Coordinated Research Project, chops and spreads the straw as mulch, enhancing soil health and reducing the labour involved in straw management [5]. Mechanical baling machines are also employed to collect and store crop residues for various applications, such as biochar production. This process offers a sustainable solution by converting waste into valuable soil enhancers and reducing GHG emissions [213]. Bagasse ash utilization in polymers as a filler component enhances the mechanical properties, showing its potential for various applications, including glass-fiber composites, particle boards, lightweight structures, and ceilings [70].

In sustainable economic aspects, the diverse composition of agricultural waste presents numerous opportunities for waste-to-wealth creation. For example, paddy straw with high silica content, is less suitable for fodder but ideal for energy generation through combustion. Wheat straw, with a higher lignin content, is more suitable for biofuel production whereas, sugarcane bagasse, with high cellulose and hemicellulose content, is an excellent raw material for paper and bioethanol production. In contrast, cotton stalks, which primarily consisting of high cellulose and lignin content, can be utilized to generate bio-composites and bioenergy. It is evident that if the surplus crop residue and animal manure in India are fully utilized solely to biogas generation, they hold the theoretical potential to generate approximately 39.07 and 29.141 billion $m^3$ of biogas annually respectively, thereby significantly contributing to the country's energy needs [214]. Similarly, if the surplus crop residues were fully directed towards gasification, it is estimated to yield approximately 327.16 MT of syngas annually [215]. Moreover, combined livestock waste and surplus crop residues could, in theory, meet 100 % of the cooking energy requirements in more than 50 % of India's districts [199]. Furthermore, residues such as cotton waste (19,652 kJ $kg^{-1}$), garden waste (20,900 kJ $kg^{-1}$), and soybean waste (18,770.52 kJ $kg^{-1}$) are considered ideal feedstocks for briquetting and can be used directly as domestic fuel, offering a sustainable alternative to traditional biomass use in cook stoves [216]. It is imperative to mention that these estimates reflect maximum theoretical potentials, assuming feedstocks are exclusively used for a single energy pathway. In practice, agricultural residues serve multiple purposes including mulching, composting, or animal feed, which significantly reduces the substantial fraction available for bioenergy or biomaterials applications. Determining the actual useable surplus after agricultural and ecological needs requires integrated regional assessments, an area currently unexplored and posing a critical gap in current estimates.

In India, several methods of recovering value-added products from agricultural waste are already in practice or have been commercialized as provided in Table 4 [217]. One prominent example is bioethanol generation from sugarcane bagasse and other lignocellulosic biomass. Theoretically, 1 ton of lignocellulosic biomass can produce 387 L of bioethanol [218]. However, practical yields are lower due to sugar degradation during pre-treatment, incomplete sugar conversion during enzymatic hydrolysis, and reduced fermentation efficiency caused by inhibitors. The National Renewable Energy Laboratory's (NREL) pilot-scale tests achieved 295 L per dry ton of corn stover, about 100 L less than the theoretical yield [218]. Based on available agricultural residues (48.4 MMT) in India, approximately 14.28 billion litres of bioethanol can be produced [218]. Companies like Praj Industries have developed advanced biorefineries that convert agricultural residues into bioethanol, which is then blended with petrol to reduce GHG emissions.

**Table 4**
Current practices on conversion of agricultural waste to value-added products in India [227,228].

| Process/ Technology | Key points |
|---|---|
| **Biomass power** | Converts agricultural residues into electricity; More than 800 plants with aggregate capacity of 10,209 MW in the states of Maharashtra, Uttar Pradesh, Karnataka, Tamil Nadu, Andhra Pradesh, Chhattisgarh, West Bengal, and Punjab. |
| **Biogas Production** | Converts agricultural waste into biogas and organic fertilizer; Actively implemented across all the states of India; Cumulative capacity of 7,71,008 $m^3$/day. |
| **Bio-CNG/CBG** | Converts agricultural waste into CNG for use as vehicle fuel; Small scale systems installed in Haryana, Gujarat, Uttar Pradesh, Madhya Pradesh, Maharashtra, Tamil Nadu, Punjab, Telangana and West Bengal; Cumulative capacity of 2,64,467 kg $day^{-1}$. |
| **Mushroom Cultivation** | Utilizes agricultural waste like paddy straw and wheat straw as substrate for growing mushrooms; Widely practised in Himachal Pradesh, Odisha, Haryana. |
| **Briquetting** | Compresses agricultural waste into briquettes used as a substitute for coal in industrial processes; Operational in various regions. |
| **Bioethanol Production** | Uses crop residues like rice straw and sugarcane bagasse to produce bioethanol for fuel; Pilot projects and scale up mainly in Uttar Pradesh, Maharashtra, and Karnataka. |
| **Biochar Production** | Pyrolysis of crop residues to produce biochar, enhancing soil fertility and soil carbon sequestration; Limited commercial scale in Madhya Pradesh, Karnataka, Maharashtra. |

The empirical model developed by the NREL biochemical conversion process was exploited to assess the bioethanol potential and was found to be 295 L per ton (dry basis) of lignocellulosic biomass [218]. Additionally, the experimental and simulation data indicate that the techno-economic viability for plants generating 5–10 tons per day (TPD) of Bio-compressed natural gas (CNG), with production costs declining significantly at larger scales [219].

Moreover, the potential for biogas production from agricultural residues is significant, with India having installed numerous biogas and bio-CNG plants. The economic analysis shows a high profitability likelihood for biogas plants [220], and properly utilized crop residue biomass could generate substantial electricity annually, minimizing GHG emissions than conventional fuels. The biogas possibility from crop residue is maximum in Uttar Pradesh, estimated at 9.31 billion $m^3$ per year [220]. Currently, India has installed more than 5 million biogas plants in all zones collectively generating 0.702 million $m^3$ of biogas per day [221]. Additionally, India has 22 bio-CNG plants producing 84,759 kg $day^{-1}$ of compressed biogas and 201 waste plants generating 330.935 MW of electricity [221]. Excess biomass can fully satisfy energy requirements in 39 % of districts if used locally [222]. Integrating animal waste with this excess can generate 3011 TJ $day^{-1}$, meeting over 100 % of energy needs in 55.6 % of rural areas [222].

The vermicomposting of agricultural waste, where earthworms are used to convert organic waste into high-quality compost, is widely practised in many parts of India. This method not only helps in managing waste but also creates nutrient-rich compost that improves soil quality. Initiatives like biogas production from cattle dung and other organic waste through anaerobic digestion are common in rural areas, supported by government schemes and subsidies such as SATAT launched in 2018, National Bioenergy Programme, and Waste to Energy scheme. These practices highlight the potential for agricultural waste to contribute to the rural economy and sustainable development.

The annual economic value of agricultural residues is estimated to exceed $32 billion [223]. The establishment of biomass-based industries, such as briquette and pellet manufacturing, biogas plants, and bioethanol production units, has driven local entrepreneurship by offering clear economic incentives. For instance, in Punjab and Haryana, farmers sell residues to bioenergy plants, earning additional income. Similarly, in states like Maharashtra and Karnataka, sugarcane bagasse is extensively used in cogeneration plants, supplying renewable power to the grid while creating skilled and unskilled jobs in supply chain management [224]. Rural development is further supported through the integration of small-scale agro-waste processing units, which empower women's self-help groups (SHGs) and cooperatives. For example, in Tamil Nadu and Odisha, paddy straw-based mushroom cultivation and coir product manufacturing have enhanced livelihood opportunities for rural women. A systematic assessment of agricultural waste valorization pathways reveals varying economic potentials based on regional availability, technological feasibility, and market demand. However, the suitability of a particular valorization method must be considered based on region or state. For example, a study observed that the crop residue availability, and consequently the bioenergy potential, in all eight North-eastern states is significantly lower compared to other regions of India [225]. Similarly, future market demand for end products must be considered while selecting appropriate technology to maximize economic benefits. For instance, the production of biofuels and high-value chemicals from sugarcane bagasse is preferred over the cogeneration of steam and power due to declining cost of electricity [226].

Overall, agricultural waste by-products are gaining increasing importance as valuable raw materials across multiple industries, fostering both economic growth and sustainability. The energy sector is a major beneficiary, utilizing crop residues such as rice straw, sugarcane bagasse, and cotton stalks for biomass power generation and CBG production, supported by government initiatives like the SATAT scheme. Additionally, the paper and pulp industry, construction industry, textile, and packaging industries rely on different kinds of agricultural waste by-products for different purposes. Established markets for these by-products exist in states with high agricultural output, such as Punjab (rice straw), Maharashtra (bagasse), and Kerala (coconut husk), driven by both domestic demand and export potential. However, challenges like fragmented supply chains, inconsistent pricing mechanisms, low farmer awareness, and inadequate storage for residues need to addressed through decentralized collection hubs and farmer education programs to unlock the sector's economic value. Furthermore, to enhance the circular economy and market growth in agricultural waste management, there is an imminent need for increased environmental

**Table 5**
LCA studies on agricultural waste valorization in India.

| Feedstock | Product | Functional unit (FU) | System boundary | Impact assessment method | Outputs | References |
|---|---|---|---|---|---|---|
| Sugarcane molasses | Ethanol | 1 kg of hydrous ethanol | Cradle-to-gate | Impact 2002+ | Requires more non-renewable energy due to irrigation needs and has greater water-related impacts from groundwater use. GHG emissions 0.09–0.64 kg $CO_2$-eq per FU. | [243] |
| Sugarcane molasses | Ethanol | 1 ton of ethanol | Cradle-to-gate | ReCiPe Midpoint and Endpoint | For each ton of ethanol produced, the GWP is 585.95 kg $CO_2$-eq. Molasses (73.01 %) and electricity (23.02 %) are the main contributors to all impact categories. | [235] |
| Rice straw | Bioethanol | 1L of ethanol | Cradle-to-gate | IMPACT World + | The main environmental impacts are from enzymatic hydrolysis and electricity consumption during ethanol production. Fossil fuel consumption of 13.62 MJ per FU. GWP is 0.966 $CO_2$-eq per FU. | [232] |
| Molasses | Bioethanol | 1 ton of ethanol | Cradle-to-gate | IMPACT 2002+ | GHG emissions ranged 820–1230 kg $CO_2$-eq per FU across different scenarios. Non-renewable energy demand is 12910–17760 MJ primary for different scenarios. | [242] |
| Rice straw | Bioethanol | 1 MJ of transportation fuel | Cradle-to-grave | | GHG emissions reduction 11,498–14,498 kt $CO_2$-eq depending upon electricity grid. Surplus rice straw and availability and pre-treatment method are key factors. | [236] |
| Rice husk, sugarcane bagasse (SB), and corn cob (CC) | Biochar | 1-ton biochar production | Cradle-to-gate | ReCiPe | CC cultivation has the highest impact across most categories. SB has the lowest impact during biomass cultivation. Diesel, electricity, and fertilizers significantly increase GWP. GWP of 5.82E3, 1.37E4, 8.84E3 kg $CO_2$-eq for biochar from rice husk, SB, and CC respectively. Also, energy demand ranged 20.2–47.3 and mineral resource scarcity 2.12–7.82 kg Cu eq. | [241] |
| Rice straw, palm shell, corn stover, and mixed crop residue | Biochar | 1 ton of biochar | Cradle-to-gate | IMPACT 2002+ | Corn stover has high impacts on carcinogens, non-carcinogens, radiation, and toxicity but the lowest GWP, while rice straw has the least impact on human health and resources. Crop residue has GWP of 282 kg $CO_2$-eq/FU, 778.325 MJ primary non-renewable energy, and resource depletion potential of 4.34E3 MJ/FU. | [244] |
| Paddy straw | Xylanase | 1 kg of dry xylanase | Cradle-to- gate | ReCiPe 2016 | Adverse impacts are from electricity and ammonium sulfate consumption. Per FU, GWP of 3018.359 kg $CO_2$-eq, mineral resource scarcity of 3.849 kg Cu-eq, and fossil resource scarcity of 840 kg oil-eq. | [239] |
| Rice straw | Fertilizer, animal fodder, electricity, biogas | Processing of 1 ton dry rice straw | Straw collection to product end use | CML2 | Straw utilization for electricity and biogas production results in the highest environmental benefits in GWP and acidification potential. GWP of 214 and 36 kg $CO_2$-eq/FU for electricity and biogas production respectively. | [238] |
| Rice and wheat straw | Bio-oil, biochar | 1-ton size-reduced dry straw to be pyrolyzed | Cradle-to-gate | IPCC 2021 | The net GWP from decentralized pyrolysis of rice straw was −124 kg $CO_2$-eq per ton straw compared to −75 kg $CO_2$-eq per ton straw for centralized biorefinery. | [237] |
| Sugarcane molasses | Fuel grade ethanol | 1 ton of ethanol | Cradle-to-grave | – | Sugarcane farming is the highest contributing process of GHG emissions. LCA of fuel ethanol is influenced by regional differences. Energy consumption of 10156 and 8405 MJ/FU for North and West regions of India from farming to ethanol transport. | [229] |
| Agro-residue | Bioethanol | 1 L of bioethanol produced | Cradle-to-gate | IMPACT 2002+ | Rice straw-based bioethanol has higher environmental impacts, especially in ecotoxicity, ionizing radiation, human toxicity, and ozone depletion. However, corn stover has the lowest GHG emissions (0.37 kg $CO_2$-eq/FU), while cassava straw has the highest (1.1 kg $CO_2$-eq/FU). Cumulative energy demand of 18.6 MJ/FU. | [245] |
| Cotton waste and RHA | Brick manufacturing | One low-cost housing unit | Cradle-to-gate | CML2001, ReCiPe | More sustainable than normal clay bricks. GWP of 1750 kg $CO_2$-eq and energy requirement of 400 MJ. | [246] |

awareness, technological advancements, accessible and cost-effective waste processing, capacity building (including infrastructure development), strong policies and regulations, robust monitoring, skill development, and cross-sector collaboration.

## 5. Sustainability of agricultural waste valorization in India: insights from Life Cycle Assessment studies

Agricultural residues in India hold significant potential for valorization into value-added products through various conversion processes. However, ensuring the sustainability of these processes is critical to minimizing environmental impacts and maximizing economic and social benefits. LCA has emerged as a robust tool to evaluate the environmental and energy-related implications of agricultural waste valorization. This section synthesizes findings from multiple LCA studies conducted in the Indian context given in Table 5, highlighting key insights, challenges, and opportunities for sustainable agricultural waste management.

### *5.1. Bioethanol production*

Bioethanol production from agricultural residues, such as rice straw, sugarcane molasses, and corn stover, has been largely explored for its potential to reduce fossil fuel dependency and GHG emissions. A study by Shveta Soam et al., 2015 shown that blending 5 % ethanol (produced from molasses) with gasoline using the mass allocation approach yields nearly 76 % GHG emissions reduction in northern and western India [229]. Another study compared two pre-treatment methods viz. steam explosion and dilute acid for ethanol production from rice straw. The study reported that steam explosion yielded 253 L per ton of ethanol with associated emissions of 288 kg $CO_2$-eq , while dilute acid yielded 239 L per ton with slightly higher emissions of 292 kg $CO_2$-eq [230]. Both methods significantly reduced GHG emissions compared to gasoline, with steam explosion achieving an 89 % reduction [230]. Further research demonstrated that modified pre-treatment methods, such as water and alkali extraction, could enhance ethanol production to 267 L per ton while reducing enzyme usage by 23–39 % [231]. Water extraction emerged as the most environmentally and economically favourable approach, lowering production costs from 0.87 to 0.70 USD $L^{-1}$ [231].

The choice of feedstock significantly influences the sustainability of bioethanol production. A study conducted a cradle-to-gate LCA of bioethanol production from various agro-residues, revealing that rice straw-based bioethanol had higher environmental impacts, particularly in ecotoxicity, ionizing radiation, and human toxicity, compared to corn stover, which exhibited the lowest GHG emissions (0.37 kg $CO_2$-eq per FU) and the highest net energy ratio (NER) of 3.28 [232]. Similarly, another study identified sorghum stalk as a promising feedstock due to its high energy return, low GHG emissions, and minimal water and land use. However, its use as animal feed limits its viability as a primary feedstock for ethanol production in India [233].

Regional variations in feedstock availability and processing methods also play a critical role. Researchers have assessed ethanol production from sugarcane in South India, finding that mulching instead of burning cane residues reduced overall emissions and enhanced soil health [234]. For each ton of sugarcane, $CO_2$ emissions were 43.86 kg during cultivation, 45.98 kg from transport, 69.05 kg from residue burning, and 6.37 kg during ethanol manufacturing [234]. These findings provide essential insights for industries and policymakers to promote sustainable ethanol production [234]. Similarly, in another study an LCA of ethanol production from sugarcane in northern India, revealing a global warming potential (GWP) of 585.95 kg $CO_2$-eq per ton of ethanol, with molasses and coal-based electricity accounting for 73.01 % and 23.02 % of the total impact, respectively [235]. Both feedstock availability and the selected pre-treatment method significantly impact energy production and emissions reduction [236].

### *5.2. Biorefineries and integrated valorization pathways*

The concept of biorefineries, which integrate multiple valorization pathways, has gained traction as a sustainable approach to agricultural waste management. In a study, authors evaluated a localized biorefinery in Punjab, India, that employed a two-stage pyrolysis process to convert rice and wheat residues into biochar and bio-oil [237]. The study found that pyrolysis of untreated rice straw resulted in the lowest global warming impact (121 kg $CO_2$-eq per ton), while washing increased emissions due to additional energy requirements [237]. On-site biomass processing was deemed more sustainable than centralized methods, with biochar production costs ranging from 172 to 623 USD per ton, indicating the environmental and economic feasibility of localized biorefineries with appropriate pre-treatment and product applications [237].

Producing electricity and biogas from 1 ton of straw reduces 1471 kg and 1023 kg $CO_2$-eq emissions, respectively, with electricity offering the most environmental benefits by replacing coal-based power [238]. Utilizing straw for bioenergy is a viable alternative to open burning, which poses significant environmental harm. Another innovative approach involves the zero-waste utilization of paddy straw for enzyme production. Garima Singh et al., 2022 proposed using *Trichoderma* spp. and nitrogen-rich neem cake for solid-state fermentation to produce cellulase-free xylanase [239]. The LCA highlighted electricity (92.84 %) and ammonium sulfate (6.17 %) as major contributors to environmental impacts, which could be mitigated by adopting renewable energy and minimizing salt usage [239]. The residual spent from this process contained bioactive compounds and minerals, making it suitable for use as a biopesticide and biofertilizer, thereby enhancing the sustainability of the valorization process [239].

### *5.3. Environmental and economic trade-offs*

While bioethanol production offers significant GHG emissions reduction benefits, it is not without trade-offs. Researchers have noted that bioethanol production increases acidification and eutrophication due to fertilizer use during crop cultivation [240]. However, utilizing lignin residues for co-generation can mitigate these impacts by lowering GHG emissions and improving the NER. Advanced technologies in pre-treatment, genetically modified microorganisms for fermentation, and integrated co-fermentation, hold promise for enhancing the sustainability of second-generation (2G) bioethanol [240]. Future LCAs should consider emissions from these technologies and include vehicle performance analysis, particularly for E20 fuel blends.

Similarly, researchers evaluated the environmental impact of biochar production from rice husk, sugarcane bagasse, and corn cob. The study found that corn cob had the highest environmental impact, while rice husk consumed the most water [241]. Sugarcane bagasse exhibited the least impact during cultivation, but the pyrolysis process required significant energy [241]. Adding biochar to soil reduced GWP, with sensitivity analysis showing a 10 %–24 % decrease in GWP and a 4–11 MWh reduction in energy use [241].

### *5.4. Policy and infrastructure considerations*

The sustainability of agricultural waste valorization is also influenced by policy and infrastructure development. Sujata et al., 2021 analysed the infrastructure requirements for processing excess molasses in India's leading sugarcane-producing states using geospatial techniques [242]. The study identified a substantial shortfall in distillation capacity and proposed optimal locations for new facilities to mitigate the environmental impact of ethanol production. LCA of three processing pathways revealed GHG emissions ranging from 820 to 1230 kg $CO_2$-eq per ton of bioethanol, providing valuable data for future bioethanol policy development [242]. Policymakers, researchers, and industry stakeholders must collaborate to develop integrated, region-specific strategies that leverage the full potential of agricultural residues while minimizing environmental impacts. Future research should focus on advancing technologies, improving infrastructure, and conducting comprehensive LCAs that account for emerging innovations and their broader implications.

## 6. Challenges and barriers to effective agricultural waste management in India

**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 waste [247]. In addition, the existing technologies for agricultural waste valorization, such as biogas plants and composting units, often suffer from inefficiencies and scalability issues [248]. Furthermore, the high moisture content and heterogeneous nature of agricultural waste pose technical challenges in its processing and conversion into value-added products. Despite the high biomass power potential, several challenges hinder its exploitation, including the logistics of biomass collection and high moisture content. Addressing these challenges requires the selection of appropriate technologies, finding synergies between thermochemical, biological, biochemical processes and the implementation of supportive policies for biomass energy use [15]. Moreover, feedstock availability for various valorization processes varies due to fluctuations in the cropping patterns [249].

**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 technologies [250]. Additionally, the collection of residues and their transportation to treatment facilities and storage sites are often associated with significant economic burdens. Since, the economic viability of these technologies is dependent on inconsistent government subsidies and support fuelling further uncertainties and impacting the deployment.

**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 [250]. Changing these entrenched practices requires significant efforts in awareness-building and education about the environmental and health effects of these methods [247]. Creating awareness among farming groups regarding conservation agriculture is crucial for promoting sustainable residue management [50].

Furthermore, the acceptance of new technologies and practices is often hindered by a lack of trust and awareness among farmers. Hence, there is a need for extensive outreach and demonstration projects to showcase the benefits of advanced waste management techniques. 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.

**Political challenges:** Political challenges are also prevalent in the realm of agricultural waste management in India. There is often poor collaboration among various governmental bodies responsible for agriculture, environment, and energy, leading to fragmented and inefficient policy implementation [251]. Additionally, existing regulations and policies may not adequately address the complexities and regional variations in agricultural waste generation and management. For instance, government incentives, including schemes, grants, and subsidies at both state and central levels, have been instrumental in encouraging the adoption of gasification units. Successful implementation of these schemes is crucial for achieving long-term objectives for biomass-based installed capacity in India [15].

The enforcement of regulations related to waste management is often weak, leading to non-compliance and continued reliance on unsustainable practices like open burning. Furthermore, the lack of a comprehensive national policy on agricultural waste handling results in ad-hoc and uncoordinated efforts at the state and local levels. Strengthening institutional frameworks and governance mechanisms is essential for effective agricultural waste management in India. Table 6 outlies the perspectives of various stakeholders on agricultural waste management.

## 7. Conclusions and recommendations

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. 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 volarization methods.

The findings of this review provide valuable insights for policymakers to design region-specific, technology-driven agricultural waste management strategies that align with both environmental and economic goals. Industries can leverage the discussed innovations to develop scalable valorization solutions, while farmers can adopt practical, low-cost techniques to convert waste into useful resources. A coordinated approach based on these insights can significantly improve the efficiency and sustainability of agricultural waste management practices in India.

Addressing the technical, financial, social, cultural, and institutional barriers is crucial for the successful implementation of sustainable waste management. One critical area is developing cost-effective and efficient technologies for the conversion of diverse agricultural wastes into valuable products. 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. Another area for further investigation is the assessment of the environmental footprints through LCAs. The techno-economic analysis of multiple technologies can provide valuable insights into their sustainability and help in making informed decisions for the technology deployment. Region-specific techno-economic analyses are needed to compare the viability of different valorization methods (e.g., biochar vs. biogas production) across India's diverse agro-climatic zones, particularly for high-residue crops like rice and wheat. Also, longitudinal studies tracking the social acceptance and long-term adoption rates of residue management technologies among smallholder farmers could inform more effective extension strategies. In addition, integrated LCAs that simultaneously evaluate environmental benefits, energy outputs, and livelihood impacts of waste-to-wealth models with standardized LCA frameworks would enable more robust and comparable assessments across technologies in India. It is worth to mention that further research should explore innovative financing mechanisms to address the current economic barriers to scale. Future research should also focus on the dynamic modelling of multi-pathway systems, incorporating stakeholder inputs and policy incentives to maximize synergies and minimize trade-offs. In other way, future research needs to evaluate the interconnections and trade-offs between competing end uses such as energy, biofuels, and soil amendments, considering region-specific feedstock dynamics.

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

**Table 6**
Stakeholder perspectives on agricultural waste management.

| Stakeholder | Primary Concerns | Key Needs | Barriers to Adoption |
|---|---|---|---|
| **Farmers** | - High labor/time costs<br>- Low market value for waste products<br>- Storage limitations | - Subsidies for waste technology<br>- Training on simple valorization techniques<br>- Stable buyer networks | - Small landholdings<br>- Upfront investment costs<br>- Lack of technical knowledge |
| **Policymakers** | - Enforcement challenges<br>- Budget constraints<br>- Inter-agency coordination issues | - Clear regulatory frameworks<br>- Public-Private Partnership funding models<br>- Farmer education programs | - Political priorities<br>- Short-term election cycles<br>- Measurement difficulties |
| **Industries** | - Feedstock inconsistency<br>- High capex requirements<br>- Uncompetitive pricing | - Tax incentives<br>- Long-term supply contracts<br>- Consumer demand creation | - Volatile policy environment<br>- Technology risks<br>- Cheap fossil fuel competition |
| **Researchers** | - Limited real-world applicability<br>- Funding biases toward high-tech solutions | - Interdisciplinary collaboration<br>- Pilot project funding<br>- Policy engagement channels | - Academic vs. industry priorities<br>- Scaling challenges<br>- Farmer adoption resistance |
| **Local Communities** | - Health impacts of burning<br>- Missed livelihood opportunities | - Community waste programs<br>- Pollution monitoring<br>- Participatory planning | - Low awareness<br>- Skill gaps<br>- Land use conflicts |

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. Effective policy implementation is crucial for promoting sustainable agricultural waste management practices in India. Policies should focus on providing monetary incentives and subsidies to assist the adoption of advanced waste management technologies. Additionally, regulations should be strengthened to enforce sustainable practices and discourage environmentally harmful methods like open burning. Collaboration among various government agencies, research institutions, farmers and the private sector is essential for developing and implementing effective policies. Public-private partnerships can play a vital role in funding and scaling up waste management projects. Capacity-building and training programs for farmers and local communities should be integral to policy initiatives to ensure widespread adoption and success.

This study recognizes certain limitations, particularly related to the availability and consistency of region-specific data on agricultural waste generation and utilization. The analysis is also constrained by the variability in methodological approaches across existing literature, which may affect the comparability of findings. Furthermore, while national-level insights are provided, localized challenges and practices may not be fully captured, indicating the need for more granular, field-based studies. Future research and technological innovations, supported by robust policies and governance frameworks, can open the way for sustainable agricultural waste management in India. 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.

## CRediT authorship contribution statement

**A. Sudharshan Reddy:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Vara Prasad Kasa:** Writing – review & editing, Writing – original draft. **Biswajit Samal:** Writing – review & editing. **Brajesh Kumar Dubey:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Vinay Yadav:** Writing – original draft, Supervision, Project administration, Conceptualization. **Daya Shankar Pandey:** Writing – review & editing, Funding acquisition, Conceptualization.

## Consent to participate

Not applicable.

## Consent to publish

Not applicable.

## Ethical approval

Not applicable.

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## Declaration of competing interests

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

## Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## References

[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/10.1080/09593330.2022.2102936.
[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.
[3] S. Achinas, G.J.W. Euverink, Theoretical analysis of biogas potential prediction from agricultural waste, Resource-Efficient Technologies 2 (2016) 143–147, https://doi.org/10.1016/j.reffit.2016.08.001.
[4] 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.2014.12.004.
[5] M. Verma, P. Singh, M. Dhanorkar, Sustainability in residue management: a review with special reference to Indian agriculture, Paddy Water Environ. 22 (2024) 1–15, https://doi.org/10.1007/s10333-023-00952-8.
[6] D.C. Pedraza-Zapata, A.M. Sánchez-Garibello, B. Quevedo-Hidalgo, N. Moreno-Sarmiento, I. Gutiérrez-Rojas, Promising cellulolytic fungi isolates for rice straw degradation, J. Microbiol. 55 (2017) 711–719, https://doi.org/10.1007/s12275-017-6282-1.
[7] A. Nayak, B. Bhushan, An overview of the recent trends on the waste valorization techniques for food wastes, J. Environ. Manag. 233 (2019) 352–370, https://doi.org/10.1016/j.jenvman.2018.12.041.

[8] P. Singh, Swetanshu, R. Yadav, H. Erfani, S. Jabin, S. Jadoun, Revisiting the modern approach to manage agricultural solid waste: an innovative solution, Environ. Dev. Sustain. (2023), https://doi.org/10.1007/s10668-023-03309-7.

[9] S.P.J. Kumar, A.D. Chintagunta, Y.M. Reddy, A. Kumar, D.K. Agarwal, G. Pal, J. Simal-Gandara, Application of phenolic extraction strategies and evaluation of the antioxidant activity of peanut skins as an agricultural By-product for food industry, Food Anal. Methods 14 (2021) 2051–2062, https://doi.org/10.1007/s12161-021-02024-1.

[10] D. Puglia, D. Pezzolla, G. Gigliotti, L. Torre, M.L. Bartucca, D. Del Buono, The opportunity of valorizing agricultural waste, through its conversion into biostimulants, biofertilizers, and biopolymers, Sustainability (Switzerland) 13 (2021) 1–26, https://doi.org/10.3390/su13052710.

[11] 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.2023.167243.

[12] F.W. MoA, Report of the Committee on Review of the Scheme "Promotion of agricultural Mechanisation for In-Situ Management of Crop Residue in States of Punjab, har-Yana, Uttar Pradesh and NCT of Delhi, Department of Agriculture, Cooperation, FarmersWelfare, Ministr, 2019, https://doi.org/10.15173/m.v1i31.1867.

[13] M. Sen, A. Roy, K. Rani, A. Nalia, T. Das, P. Tigga, D. Rakshit, K. Atta, S. Mandal, A. Das, Crop Residue: Status, Distribution, Management, and Agricultural Sustainability, Elsevier Inc., 2024, https://doi.org/10.1016/B978-0-443-18486-4.00017-8.

[14] A. Pappu, M. Saxena, S.R. Asolekar, Solid wastes generation in India and their recycling potential in building materials, Build. Environ. 42 (2007) 2311–2320, https://doi.org/10.1016/j.buildenv.2006.04.015.

[15] 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.

[16] K.L. Ong, G. Kaur, N. Pensupa, K. Uisan, C.S.K. Lin, Trends in food waste valorization for the production of chemicals, materials and fuels: case study south and southeast Asia, Bioresour. Technol. 248 (2018) 100–112, https://doi.org/10.1016/j.biortech.2017.06.076.

[17] 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.

[18] J. Singh, Identifying an economic power production system based on agricultural straw on regional basis in India, Renew. Sustain. Energy Rev. 60 (2016) 1140–1155, https://doi.org/10.1016/j.rser.2016.02.002.

[19] S. Achinas, V. Achinas, G.J.W. Euverink, A technological overview of biogas production from biowaste, Engineering 3 (2017) 299–307, https://doi.org/10.1016/J.ENG.2017.03.002.

[20] 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.

[21] 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/w14172665.

[22] D. Mohan, C.U. Pittman, Arsenic removal from water/wastewater using adsorbents-A critical review, J. Hazard Mater. 142 (2007) 1–53, https://doi.org/10.1016/j.jhazmat.2007.01.006.

[23] 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.v21i03.007.

[24] S. Mathew, J.C. Soans, R. Rachitha, M.S. Shilpalekha, S.G.S. Gowda, P. Juvvi, A. K. Chakka, Green technology approach for heavy metal adsorption by agricultural and food industry solid wastes as bio-adsorbents: a review, J. Food Sci. Technol. 60 (2023) 1923–1932, https://doi.org/10.1007/s13197-022-05486-1.

[25] 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.

[26] S. Chakroborty, K. Pal, N. Nath, V. Singh, A. Barik, S. Soren, P. Panda, N. Asthana, G.Z. Kyzas, Sustainable synthesis of multifunctional nanomaterials from rice wastes: a comprehensive review, Environ. Sci. Pollut. Control Ser. 30 (2023) 95039–95053, https://doi.org/10.1007/s11356-023-29235-9.

[27] 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/s13399-023-04620-z.

[28] A. Singh, A. Singh, Microbial degradation and value addition to food and agriculture waste, Curr. Microbiol. 79 (2022) 1–17, https://doi.org/10.1007/s00284-022-02809-5.

[29] V.M. S, P. Chiranjeevi, S. Dahiya, N.K. A, Waste derived bioeconomy in India: a perspective, Nat. Biotechnol. 40 (2018) 60–69, https://doi.org/10.1016/j.nbt.2017.06.006.

[30] 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/s13399-023-04620-z.

[31] A. Singh, A. Singh, Microbial degradation and value addition to food and agriculture waste, Curr. Microbiol. 79 (2022) 1–17, https://doi.org/10.1007/s00284-022-02809-5.

[32] S. Bhuvaneshwari, H. Hettiarachchi, J.N. Meegoda, Crop residue burning in India: policy challenges and potential solutions, Int. J. Environ. Res. Publ. Health 16 (2019), https://doi.org/10.3390/ijerph16050832.

[33] M.I. Abdurrahman, S. Chaki, G. Saini, Stubble burning: effects on health & environment, regulations and management practices, Environ. Adv. 2 (2020) 100011, https://doi.org/10.1016/j.envadv.2020.100011.

[34] R. Kapoor, P. Ghosh, M. Kumar, S. Sengupta, A. Gupta, S.S. Kumar, V. Vijay, V. Kumar, V. Kumar Vijay, D. Pant, Valorization of agricultural waste for biogas based circular economy in India: a research outlook, Bioresour. Technol. 304 (2020) 123036, https://doi.org/10.1016/j.biortech.2020.123036.

[35] A. Tagade, N. Kirti, A.N. Sawarkar, Pyrolysis of agricultural crop residues: an overview of researches by Indian scientific community, Bioresour. Technol. Rep. 15 (2021) 100761, https://doi.org/10.1016/j.biteb.2021.100761.

[36] M. Mujtaba, L. Fernandes Fraceto, M. Fazeli, S. Mukherjee, S.M. Savassa, G. Araujo de Medeiros, A. do Espírito Santo Pereira, S.D. Mancini, J. Lipponen, F. Vilaplana, Lignocellulosic biomass from agricultural waste to the circular economy: a review with focus on biofuels, biocomposites and bioplastics, J. Clean. Prod. 402 (2023), https://doi.org/10.1016/j.jclepro.2023.136815.

[37] D. Puglia, D. Pezzolla, G. Gigliotti, L. Torre, M.L. Bartucca, D. Del Buono, The opportunity of valorizing agricultural waste, through its conversion into biostimulants, biofertilizers, and biopolymers, Sustainability (Switzerland) 13 (2021) 1–26, https://doi.org/10.3390/su13052710.

[38] M.K. Awasthi, R. Sindhu, R. Sirohi, V. Kumar, V. Ahluwalia, P. Binod, A. Juneja, D. Kumar, B. Yan, S. Sarsaiya, Z. Zhang, A. Pandey, M.J. Taherzadeh, Agricultural waste biorefinery development towards circular bioeconomy, Renew. Sustain. Energy Rev. 158 (2022), https://doi.org/10.1016/j.rser.2022.112122.

[39] B. Koul, M. Yakoob, M.P. Shah, Agricultural waste management strategies for environmental sustainability, Environ. Res. 206 (2022) 112285, https://doi.org/10.1016/j.envres.2021.112285.

[40] M. Gupta, N. Savla, C. Pandit, S. Pandit, P.K. Gupta, M. Pant, S. Khilari, Y. Kumar, D. Agarwal, R.R. Nair, D. Thomas, V.K. Thakur, Use of biomass-derived biochar in wastewater treatment and power production: a promising solution for a sustainable environment, Sci. Total Environ. 825 (2022) 153892, https://doi.org/10.1016/j.scitotenv.2022.153892.

[41] P. Kumar Sarangi, S. Subudhi, L. Bhatia, K. Saha, D. Mudgil, K. Prasad Shadangi, R.K. Srivastava, B. Pattnaik, R.K. Arya, Utilization of agricultural waste biomass and recycling toward circular bioeconomy, Environ. Sci. Pollut. Control Ser. 30 (2023) 8526–8539, https://doi.org/10.1007/s11356-022-20669-1.

[42] M.M. Rao, S.M. Botsa, T.P. Rao, S.R. Goddu, C. Vijayasanthi, A comprehensive review on agricultural waste production and onsite management with circular economy opportunities, Discover Sustainability 5 (2024), https://doi.org/10.1007/s43621-024-00492-z.

[43] P.R. Rout, D.S. Pandey, M. Haynes-Parry, C. Briggs, H.L.C. Manuel, R. Umapathi, S. Mukherjee, S. Panigrahi, M. Goel, Sustainable valorisation of animal manures via thermochemical conversion technologies: an inclusive review on recent trends, Waste Biomass Valorization 14 (2023) 553–582, https://doi.org/10.1007/s12649-022-01916-5.

[44] M. Verma, P. Singh, M. Dhanorkar, Sustainability in residue management: a review with special reference to Indian agriculture, Paddy Water Environ. 22 (2024) 1–15, https://doi.org/10.1007/s10333-023-00952-8.

[45] B. Sharma, B. Vaish, Monika, U.K. Singh, P. Singh, R.P. Singh, Recycling of organic wastes in agriculture: an environmental perspective, Int. J. Environ. Res. 13 (2019) 409–429, https://doi.org/10.1007/s41742-019-00175-y.

[46] M. Naeem, A.A. Ansari, S.S. Gill, Contaminants in agriculture: sources, impacts and management. https://doi.org/10.1007/978-3-030-41552-5, 2020.

[47] R. Kapoor, P. Ghosh, M. Kumar, S. Sengupta, A. Gupta, S.S. Kumar, V. Vijay, V. Kumar, V. Kumar Vijay, D. Pant, Valorization of agricultural waste for biogas based circular economy in India: a research outlook, Bioresour. Technol. 304 (2020) 123036, https://doi.org/10.1016/j.biortech.2020.123036.

[48] P.S. Bandgar, S. Jain, N.L. Panwar, Current status, opportunities and challenges in anaerobic digestion in Indian context: an overview, Bioresour. Technol. Rep. 16 (2021) 100830, https://doi.org/10.1016/j.biteb.2021.100830.

[49] P. Bhattacharyya, J. Bisen, D. Bhaduri, S. Priyadarsini, S. Munda, M. Chakraborti, T. Adak, P. Panneerselvam, A.K. Mukherjee, S.L. Swain, P.K. Dash, S.R. Padhy, A. K. Nayak, H. Pathak, S. Arora, P. Nimbrayan, Turn the wheel from waste to wealth: economic and environmental gain of sustainable rice straw management practices over field burning in reference to India, Sci. Total Environ. 775 (2021) 145896, https://doi.org/10.1016/j.scitotenv.2021.145896.

[50] S.K. Lohan, H.S. Jat, A.K. Yadav, H.S. Sidhu, M.L. Jat, M. Choudhary, J.K. Peter, P.C. Sharma, Burning issues of paddy residue management in north-west states of India, Renew. Sustain. Energy Rev. 81 (2018) 693–706, https://doi.org/10.1016/j.rser.2017.08.057.

[51] D.S. Shaik, Y. Kant, D. Mitra, A. Singh, H.C. Chandola, M. Sateesh, S.S. Babu, P. Chauhan, Impact of biomass burning on regional aerosol optical properties: a case study over northern India, J. Environ. Manag. 244 (2019) 328–343, https://doi.org/10.1016/j.jenvman.2019.04.025.

[52] M.V. Deshpande, N. Kumar, D. Pillai, V.V. Krishna, M. Jain, Greenhouse gas emissions from agricultural residue burning have increased by 75 % since 2011 across India, Sci. Total Environ. 904 (2023) 166944, https://doi.org/10.1016/j.scitotenv.2023.166944.

[53] S. Bhuvaneshwari, H. Hettiarachchi, J.N. Meegoda, Crop residue burning in India: policy challenges and potential solutions, Int. J. Environ. Res. Publ. Health 16 (2019), https://doi.org/10.3390/ijerph16050832.

[54] H. Pathak, Greenhouse gas emission from Indian agriculture: trends, drivers and mitigation strategies, Proceedings of the Indian National Science Academy 81 (2015) 1133–1149, https://doi.org/10.16943/ptinsa/2015/v81i5/48333.

[55] P. Satpathy, C. Pradhan, Biomethanation of crop residues to combat stubble burning in India: design and simulation using ADM1 mathematical model, Methane 1 (2022) 125–138, https://doi.org/10.3390/methane1020011.
[56] B. Gadde, S. Bonnet, C. Menke, S. Garivait, Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines, Environ. Pollut. 157 (2009) 1554–1558, https://doi.org/10.1016/j.envpol.2009.01.004.
[57] K. Ravindra, T. Singh, S. Mor, Emissions of air pollutants from primary crop residue burning in India and their mitigation strategies for cleaner emissions, J. Clean. Prod. 208 (2019) 261–273, https://doi.org/10.1016/j.jclepro.2018.10.031.
[58] Y. Singh, H.S. Sidhu, Management of cereal crop residues for sustainable rice-wheat production system in the indo-gangetic plains of India, Proceedings of the Indian National Science Academy 80 (2014) 95–114, https://doi.org/10.16943/ptinsa/2014/v80i1/55089.
[59] U.S. Saharan, R. Kumar, S. Singh, T.K. Mandal, M. Sateesh, S. Verma, A. Srivastava, Hotspot driven air pollution during crop residue burning season in the indo-gangetic plain, India, Environ. Pollut. 350 (2024) 124013, https://doi.org/10.1016/j.envpol.2024.124013.
[60] S. Chakrabarti, M.T. Khan, A. Kishore, D. Roy, S.P. Scott, Risk of acute respiratory infection from crop burning in India: estimating disease burden and economic welfare from satellite and national health survey data for 250 000 persons, Int. J. Epidemiol. 48 (2019) 1113–1124, https://doi.org/10.1093/ije/dyz022.
[61] M.I. Abdurrahman, S. Chaki, G. Saini, Stubble burning: effects on health & environment, regulations and management practices, Environ. Adv. 2 (2020) 100011, https://doi.org/10.1016/j.envadv.2020.100011.
[62] A. Kumawat, D. Yadav, P. Srivastava, S. Babu, D. Kumar, D. Singh, D. K. Vishwakarma, V.K. Sharma, M. Madhu, Restoration of agroecosystems with conservation agriculture for food security to achieve sustainable development goals, Land Degrad. Dev. 34 (2023) 3079–3097, https://doi.org/10.1002/ldr.4677.
[63] T. Singh, A. Biswal, S. Mor, K. Ravindra, V. Singh, S. Mor, A high-resolution emission inventory of air pollutants from primary crop residue burning over northern India based on VIIRS thermal anomalies, Environ. Pollut. 266 (2020) 115132, https://doi.org/10.1016/j.envpol.2020.115132.
[64] A. Kumar, K.K. Kushwaha, S. Singh, Y.S. Shivay, M.C. Meena, L. Nain, Effect of paddy straw burning on soil microbial dynamics in sandy loam soil of indo-gangetic plains, Environ. Technol. Innov. 16 (2019) 100469, https://doi.org/10.1016/j.eti.2019.100469.
[65] B. Sharma, B. Vaish, Monika, U.K. Singh, P. Singh, R.P. Singh, Recycling of organic wastes in agriculture: an environmental perspective, Int. J. Environ. Res. 13 (2019) 409–429, https://doi.org/10.1007/s41742-019-00175-y.
[66] D. Cardoen, P. Joshi, L. Diels, P.M. Sarma, D. Pant, Agriculture biomass in India: part 2. Post-harvest losses, cost and environmental impacts, Resour. Conserv. Recycl. 101 (2015) 143–153, https://doi.org/10.1016/j.resconrec.2015.06.002.
[67] D. Mohan, K. Abhishek, A. Sarswat, M. Patel, P. Singh, C.U. Pittman, Biochar production and applications in soil fertility and carbon sequestration-a sustainable solution to crop-residue burning in India, RSC Adv. 8 (2018) 508–520, https://doi.org/10.1039/c7ra10353k.
[68] N. Mahato, K. Sharma, M. Sinha, A. Dhyani, B. Pathak, H. Jang, S. Park, S. Pashikanti, S. Cho, Biotransformation of citrus waste-i: production of biofuel and valuable compounds by fermentation. https://doi.org/10.3390/pr9020220, 2021.
[69] K.S. Konde, S. Nagarajan, V. Kumar, S.V. Patil, V.V. Ranade, Sugarcane bagasse based biorefineries in India: potential and challenges, Sustain. Energy Fuels 5 (2021) 52–78, https://doi.org/10.1039/d0se01332c.
[70] S. Madhu, Y. Devarajan, L. Natrayan, Effective utilization of waste sugarcane bagasse filler-reinforced glass fibre epoxy composites on its mechanical properties - waste to sustainable production, Biomass Convers Biorefin 13 (2023) 15111–15118, https://doi.org/10.1007/s13399-023-03792-y.
[71] P.M.V. Subbarao, T.C. D' Silva, K. Adlak, S. Kumar, R. Chandra, V.K. Vijay, Anaerobic digestion as a sustainable technology for efficiently utilizing biomass in the context of carbon neutrality and circular economy, Environ. Res. 234 (2023) 116286, https://doi.org/10.1016/j.envres.2023.116286.
[72] Y. Wang, X. Cui, Modeling and quantification of agricultural waste recycling for agricultural industrial structure optimization in a novelty multi-village industrial complex, Environ. Impact Assess. Rev. 106 (2024), https://doi.org/10.1016/j.eiar.2024.107484.
[73] H.N. Huang, Z. Yang, Y. Guo, J.J. Ma, B.W. Ming, J. Yang, C. Guo, L. Li, C.Q. Ou, Impact of agricultural straw open-field burning on concentrations of six criteria air pollutants in China, Environ. Pollut. 373 (2025), https://doi.org/10.1016/j.envpol.2025.126109.
[74] Z. Yu, F. Li, W. Si, W. Zhang, From agri-waste to sustainable use: a case study of straw management reform in northeast China, Sustain. Dev. (2024), https://doi.org/10.1002/sd.3315.
[75] L.M. Coelho Junior, E.P. Santos Júnior, C.F.F. da Silva, B.H.C. de Oliveira, J.B. C. Dantas, J.V. dos Reis, V.B. Schramm, F. Schramm, M. Carvalho, Supply of bioelectricity from sugarcane bagasse in Brazil: a space–time analysis, Sustain. Environ. Res. 34 (2024), https://doi.org/10.1186/s42834-024-00223-z.
[76] I.R.F.S. Alves, N. Galvão, I.D. Bassin, J.P. Bassin, Waste characterization in Brazil, in: Waste Management and Resource Recycling in the Developing World, Elsevier, 2023, pp. 85–98, https://doi.org/10.1016/B978-0-323-90463-6.00007-5.
[77] S. Fukuda, Agricultural and municipal waste management in Thailand, in: An Introduction to Circular Economy, Springer Singapore, 2020, pp. 303–324, https://doi.org/10.1007/978-981-15-8510-4_16.
[78] I. Kumar, V. Bandaru, S. Yampracha, L. Sun, B. Fungtammasan, Limiting rice and sugarcane residue burning in Thailand: current status, challenges and strategies, J. Environ. Manag. 276 (2020), https://doi.org/10.1016/j.jenvman.2020.111228.
[79] Z. Nacua, G. Lacang, Valorization of agricultural wastes to offset greenhouse gases (GHGs) emissions: an insight in southeast Asia, J. Environ. Earth Sci. 6 (2024) 87–98, https://doi.org/10.30564/jees.v6i2.6562.
[80] M. Duque-Acevedo, L.J. Belmonte-Ureña, J.A. Plaza-Úbeda, F. Camacho-Ferre, The management of agricultural waste biomass in the framework of circular economy and bioeconomy: an opportunity for greenhouse agriculture in southeast Spain, Agronomy 10 (2020), https://doi.org/10.3390/agronomy10040489.
[81] K. Krishna Koundinya, P. Dobhal, T. Ahmad, S. Mondal, A. Kumar Sharma, V. Kumar Singh, A technical review on thermochemical pathways for production of energy from corncob residue, Renew. Energy Focus 44 (2023) 174–185, https://doi.org/10.1016/j.ref.2022.12.007.
[82] M. Trninic, A. Jovovic, D. Stojiljkovic, A steady state model of agricultural waste pyrolysis: a mini review, Waste Manag. Res. 34 (2016) 851–865, https://doi.org/10.1177/0734242X16649685.
[83] A. Tagade, N. Kirti, A.N. Sawarkar, Pyrolysis of agricultural crop residues: an overview of researches by Indian scientific community, Bioresour. Technol. Rep. 15 (2021) 100761, https://doi.org/10.1016/j.biteb.2021.100761.
[84] A. Tagade, N. Kirti, A.N. Sawarkar, Pyrolysis of agricultural crop residues: an overview of researches by Indian scientific community, Bioresour. Technol. Rep. 15 (2021) 100761, https://doi.org/10.1016/j.biteb.2021.100761.
[85] V. Ferrari, M.T. Nazari, N.F. da Silva, L. Crestani, L.M. Raymundo, G.L. Dotto, J. S. Piccin, L.F.S. Oliveira, A.M. Bernardes, Pyrolysis: a promising technology for agricultural waste conversion into value-added products, Environ. Dev. Sustain. (2024), https://doi.org/10.1007/s10668-024-04760-w.
[86] B. Biswas, N. Pandey, Y. Bisht, R. Singh, J. Kumar, T. Bhaskar, Pyrolysis of agricultural biomass residues: comparative study of corn cob, wheat straw, rice straw and rice husk, Bioresour. Technol. 237 (2017) 57–63, https://doi.org/10.1016/j.biortech.2017.02.046.
[87] F. Tinwala, P. Mohanty, S. Parmar, A. Patel, K.K. Pant, Intermediate pyrolysis of agro-industrial biomasses in bench-scale pyrolyser: product yields and its characterization, Bioresour. Technol. 188 (2015) 258–264, https://doi.org/10.1016/j.biortech.2015.02.006.
[88] J. Yanik, C. Kornmayer, M. Saglam, M. Yüksel, Fast pyrolysis of agricultural wastes: characterization of pyrolysis products, Fuel Process. Technol. 88 (2007) 942–947, https://doi.org/10.1016/j.fuproc.2007.05.002.
[89] A.K. Sakhiya, P. Baghel, S. Pathak, V.K. Vijay, P. Kaushal, Effect of process parameters on slow pyrolysis of rice straw: product yield and energy analysis. Proceedings of the 2020 International Conference and Utility Exhibition on Energy, Environment and Climate Change, ICUE 2020, 2020, pp. 1–9, https://doi.org/10.1109/ICUE49301.2020.9306945.
[90] N.S. Trivedi, S.A. Mandavgane, A. Chaurasia, Characterization and valorization of biomass char: a comparison with biomass ash, Environ. Sci. Pollut. Control Ser. 25 (2018) 3458–3467, https://doi.org/10.1007/s11356-017-0689-4.
[91] S. Ascher, J. Gordon, I. Bongiovanni, I. Watson, K. Hermannsson, S. Gillespie, S. Sarangi, B. Biakhmetov, P.C. Bhargava, T. Bhaskar, B.B. Krishna, A. Pandey, S. You, Trigeneration based on the pyrolysis of rural waste in India: environmental impact, economic feasibility and business model innovation, Sci. Total Environ. 921 (2024) 170718, https://doi.org/10.1016/j.scitotenv.2024.170718.
[92] D. Mohan, K. Abhishek, A. Sarswat, M. Patel, P. Singh, C.U. Pittman, Biochar production and applications in soil fertility and carbon sequestration-a sustainable solution to crop-residue burning in India, RSC Adv. 8 (2018) 508–520, https://doi.org/10.1039/c7ra10353k.
[93] A. Anand, V. Kumar, P. Kaushal, Biochar and its twin benefits: crop residue management and climate change mitigation in India, Renew. Sustain. Energy Rev. 156 (2022) 111959, https://doi.org/10.1016/j.rser.2021.111959.
[94] K.H. Chakravarty, M. Sadi, H. Chakravarty, J. Andersen, B. Choudhury, T. J. Howard, A. Arabkoohsar, Pyrolysis kinetics and potential utilization analysis of cereal biomass by-products; an experimental analysis for cleaner energy productions in India, Chemosphere 353 (2024) 141420, https://doi.org/10.1016/j.chemosphere.2024.141420.
[95] S.M. Frolov, Organic waste gasification: a selective review, Fuels 2 (2021) 556–650, https://doi.org/10.3390/fuels2040033.
[96] E.R. Widjaya, G. Chen, L. Bowtell, C. Hills, Gasification of non-woody biomass: a literature review, Renew. Sustain. Energy Rev. 89 (2018) 184–193, https://doi.org/10.1016/j.rser.2018.03.023.
[97] A. Molino, S. Chianese, D. Musmarra, Biomass gasification technology: the state of the art overview, J. Energy Chem. 25 (2016) 10–25, https://doi.org/10.1016/j.jechem.2015.11.005.
[98] A. Khan, M.B.K. Niazi, R. Ansar, Z. Jahan, F. Javaid, R. Ahmad, H. Anjum, M. Ibrahim, A. Bokhari, Thermochemical conversion of agricultural waste to hydrogen, methane, and biofuels: a review, Fuel 351 (2023) 128947, https://doi.org/10.1016/j.fuel.2023.128947.
[99] S. You, Y.S. Ok, D.C.W. Tsang, E.E. Kwon, C.H. Wang, Towards practical application of gasification: a critical review from syngas and biochar perspectives, Crit. Rev. Environ. Sci. Technol. 48 (2018) 1165–1213, https://doi.org/10.1080/10643389.2018.1518860.
[100] B. Chaitanya, V. Bahadur, A.D. Thakur, R. Raj, Biomass-gasification-based atmospheric water harvesting in India, Energy 165 (2018) 610–621, https://doi.org/10.1016/j.energy.2018.09.183.

[101] C.L. Chambon, T. Karia, P. Sandwell, J.P. Hallett, Techno-economic assessment of biomass gasification-based mini-grids for productive energy applications: the case of rural India, Renew. Energy 154 (2020) 432–444, https://doi.org/10.1016/j.renene.2020.03.002.
[102] S. Deshmukh, R. Santhosh, Solar-assisted gasification of agriculture residues for green hydrogen production, Bioresour. Technol. Rep. 22 (2023) 101506, https://doi.org/10.1016/j.biteb.2023.101506.
[103] A. Kumar, D.S. Pandey, T. Mondal, Experimental investigation of process parameters for hydrogen-rich syngas production from rice husk gasification, Sustain. Chem. Clim. Action 6 (2025), https://doi.org/10.1016/j.scca.2025.100061.
[104] P.C. Murugan, S. Joseph Sekhar, G. Glivin, P. Saji Raveendran, T.H.T. Le, T. Mathimani, Investigation on thermochemical co-gasification of rice husk and groundnut shell in open core gasifier for the generation of producer gas: an optimization by central composite design, Environ. Res. 242 (2024) 117741, https://doi.org/10.1016/j.envres.2023.117741.
[105] S.K. Sansaniwal, M.A. Rosen, S.K. Tyagi, Global challenges in the sustainable development of biomass gasification: an overview, Renew. Sustain. Energy Rev. 80 (2017) 23–43, https://doi.org/10.1016/j.rser.2017.05.215.
[106] B. Gajera, U. Tyagi, A.K. Sarma, M.K. Jha, Impact of torrefaction on thermal behavior of wheat straw and groundnut stalk biomass: kinetic and thermodynamic study, Fuel Communications 12 (2022) 100073, https://doi.org/10.1016/j.jfueco.2022.100073.
[107] K.B. Kota, S. Shenbagaraj, P.K. Sharma, A.K. Sharma, P.K. Ghodke, W.H. Chen, Biomass torrefaction: an overview of process and technology assessment based on global readiness level, Fuel 324 (2022) 124663, https://doi.org/10.1016/j.fuel.2022.124663.
[108] S. Negi, G. Jaswal, K. Dass, K. Mazumder, S. Elumalai, J.K. Roy, Torrefaction: a sustainable method for transforming of agri-wastes to high energy density solids (biocoal), Rev. Environ. Sci. Biotechnol. 19 (2020) 463–488, https://doi.org/10.1007/s11157-020-09532-2.
[109] K.V. Narayanan, E. Natarajan, Experimental studies on cofiring of coal and biomass blends in India, Renew. Energy 32 (2007) 2548–2558, https://doi.org/10.1016/j.renene.2006.12.018.
[110] S.G. Sahu, N. Chakraborty, P. Sarkar, Coal-biomass co-combustion: an overview, Renew. Sustain. Energy Rev. 39 (2014) 575–586, https://doi.org/10.1016/j.rser.2014.07.106.
[111] M. Sharma, S. Dasappa, Emission reduction potentials of improved cookstoves and their issues in adoption: an Indian outlook, J. Environ. Manag. 204 (2017) 442–453, https://doi.org/10.1016/j.jenvman.2017.09.018.
[112] S.A. Mehetre, N.L. Panwar, D. Sharma, H. Kumar, Improved biomass cookstoves for sustainable development: a review, Renew. Sustain. Energy Rev. 73 (2017) 672–687, https://doi.org/10.1016/j.rser.2017.01.150.
[113] K.B. Sutar, S. Kohli, M.R. Ravi, A. Ray, Biomass cookstoves: a review of technical aspects, Renew. Sustain. Energy Rev. 41 (2015) 1128–1166, https://doi.org/10.1016/j.rser.2014.09.003.
[114] C. Venkataraman, A.D. Sagar, G. Habib, N. Lam, K.R. Smith, The Indian national initiative for advanced biomass cookstoves: the benefits of clean combustion, Energy Sustain. Dev. 14 (2010) 63–72, https://doi.org/10.1016/j.esd.2010.04.005.
[115] P.R. Sonarkar, A.S. Chaurasia, Thermal performance of three improved biomass-fired cookstoves using fuel wood, wood pellets and coconut shell, Environ. Dev. Sustain. 21 (2019) 1429–1449, https://doi.org/10.1007/s10668-018-0096-0.
[116] P. Kumar Sarangi, S. Subudhi, L. Bhatia, K. Saha, D. Mudgil, K. Prasad Shadangi, R.K. Srivastava, B. Pattnaik, R.K. Arya, Utilization of agricultural waste biomass and recycling toward circular bioeconomy, Environ. Sci. Pollut. Control Ser. 30 (2023) 8526–8539, https://doi.org/10.1007/s11356-022-20669-1.
[117] D. Cardoen, P. Joshi, L. Diels, P.M. Sarma, D. Pant, Agriculture biomass in India: part 2. Post-harvest losses, cost and environmental impacts, Resour. Conserv. Recycl. 101 (2015) 143–153, https://doi.org/10.1016/j.resconrec.2015.06.002.
[118] S. Takkellapati, T. Li, M.A. Gonzalez, An overview of biorefinery-derived platform chemicals from a cellulose and hemicellulose biorefinery, Clean Technol. Environ. Policy 20 (2018) 1615–1630, https://doi.org/10.1007/s10098-018-1568-5.
[119] A.M. Das, M.P. Hazarika, M. Goswami, A. Yadav, P. Khound, Extraction of cellulose from agricultural waste using montmorillonite K-10/LiOH and its conversion to renewable energy: biofuel by using Myrothecium gramineum, Carbohydr. Polym. 141 (2016) 20–27, https://doi.org/10.1016/j.carbpol.2015.12.070.
[120] M. Jindal, A. Kumar, S. Rawat, B. Thallada, Lignin-first biorefinery approach for the valorization of cotton stalks to phenolic monomers, Sustain. Energy Fuels 7 (2023) 3926–3938, https://doi.org/10.1039/d3se00178d.
[121] D. Singh, J. Zeng, D.D. Laskar, L. Deobald, W.C. Hiscox, S. Chen, Investigation of wheat straw biodegradation by phanerochaete chrysosporium, Biomass Bioenergy 35 (2011) 1030–1040, https://doi.org/10.1016/j.biombioe.2010.11.021.
[122] A.J. Chang, J. Fan, X. Wen, Screening of fungi capable of highly selective degradation of lignin in rice straw, Int. Biodeterior. Biodegrad. 72 (2012) 26–30, https://doi.org/10.1016/j.ibiod.2012.04.013.
[123] M. Hans, S. Kumar, A.K. Chandel, I. Polikarpov, A review on bioprocessing of paddy straw to ethanol using simultaneous saccharification and fermentation, Process Biochem. 85 (2019) 125–134, https://doi.org/10.1016/j.procbio.2019.06.019.
[124] G.P. Naik, A.K. Poonia, P.K. Chaudhari, Pretreatment of lignocellulosic agricultural waste for delignification, rapid hydrolysis, and enhanced biogas production: a review, J. Indian Chem. Soc. 98 (2021) 100147, https://doi.org/10.1016/j.jics.2021.100147.
[125] P.S. Bandgar, S. Jain, N.L. Panwar, A comprehensive review on optimization of anaerobic digestion technologies for lignocellulosic biomass available in India, Biomass Bioenergy 161 (2022) 106479, https://doi.org/10.1016/j.biombioe.2022.106479.
[126] A. Alengebawy, Y. Ran, A.I. Osman, K. Jin, M. Samer, P. Ai, Anaerobic digestion of agricultural waste for biogas production and sustainable bioenergy recovery: a review, Environ. Chem. Lett. 22 (2024) 2641–2668, https://doi.org/10.1007/s10311-024-01789-1.
[127] J. Kainthola, A.S. Kalamdhad, V.V. Goud, A review on enhanced biogas production from anaerobic digestion of lignocellulosic biomass by different enhancement techniques, Process Biochem. 84 (2019) 81–90, https://doi.org/10.1016/j.procbio.2019.05.023.
[128] A. Vijin Prabhu, A.R. Sivaram, N. Prabhu, A. Sundaramahalingam, A study of enhancing the biogas production in anaerobic digestion, Mater. Today Proc. 45 (2021) 7994–7999, https://doi.org/10.1016/j.matpr.2020.12.1009.
[129] M. Keerthana Devi, S. Manikandan, M. Oviyapriya, M. Selvaraj, M.A. Assiri, S. Vickram, R. Subbaiya, N. Karmegam, B. Ravindran, S.W. Chang, M.K. Awasthi, Recent advances in biogas production using agro-industrial waste: a comprehensive review outlook of techno-economic analysis, Bioresour. Technol. 363 (2022) 127871, https://doi.org/10.1016/j.biortech.2022.127871.
[130] P.V. Rao, S.S. Baral, R. Dey, S. Mutnuri, Biogas generation potential by anaerobic digestion for sustainable energy development in India, Renew. Sustain. Energy Rev. 14 (2010) 2086–2094, https://doi.org/10.1016/j.rser.2010.03.031.
[131] T. Singh, R.V.S. Uppaluri, Optimizing biogas production: a novel hybrid approach using anaerobic digestion calculator and machine learning techniques on Indian biogas plant, Clean Technol. Environ. Policy 25 (2023) 3319–3343, https://doi.org/10.1007/s10098-023-02584-2.
[132] D. Singh, M. Tembhare, S. Kumar, Compressed biogas plants in India: existing status, technological advances and challenges, Biomass Bioenergy 178 (2023) 106964, https://doi.org/10.1016/j.biombioe.2023.106964.
[133] A. Patel, B. Gami, B. Patel, V. Parmar, P. Patel, Cost benefit and environmental impact assessment of compressed biogas (CBG) production from industrial, agricultural, and community organic waste from India, Biomass Convers Biorefin 14 (2024) 4123–4137, https://doi.org/10.1007/s13399-022-02780-y.
[134] N.K. Agarwal, M. Kumar, P. Ghosh, S.S. Kumar, L. Singh, V.K. Vijay, V. Kumar, Anaerobic digestion of sugarcane bagasse for biogas production and digestate valorization, Chemosphere 295 (2022) 133893, https://doi.org/10.1016/j.chemosphere.2022.133893.
[135] D. Patowary, D.C. Baruah, Effect of combined chemical and thermal pretreatments on biogas production from lignocellulosic biomasses, Ind. Crops Prod. 124 (2018) 735–746, https://doi.org/10.1016/j.indcrop.2018.08.055.
[136] S. Kumar, K. Paritosh, N. Pareek, A. Chawade, V. Vivekanand, De-construction of major Indian cereal crop residues through chemical pretreatment for improved biogas production: an overview, Renew. Sustain. Energy Rev. 90 (2018) 160–170, https://doi.org/10.1016/j.rser.2018.03.049.
[137] P. Singh, P. Dogra, A.S. Kalamdhad, Sugarcane bagasse and cow dung pelletization in varied food-to-microorganism ratios for biogas generation, Ind. Crops Prod. 210 (2024) 118120, https://doi.org/10.1016/j.indcrop.2024.118120.
[138] S. Sfez, S. De Meester, J. Dewulf, Co-digestion of rice straw and cow dung to supply cooking fuel and fertilizers in rural India: impact on human health, resource flows and climate change, Sci. Total Environ. 609 (2017) 1600–1615, https://doi.org/10.1016/j.scitotenv.2017.07.150.
[139] S.K. Tripathi, D. Kaur, N.K. Bhardwaj, P. Pathak, S. Kumar, Improving biogas production by Co-digestion of banana stem juice with agro-based material washings and digestate along with microbial culture, Waste Biomass Valorization 12 (2021) 1385–1393, https://doi.org/10.1007/s12649-020-01101-6.
[140] N. Sarkar, S.K. Ghosh, S. Bannerjee, K. Aikat, Bioethanol production from agricultural wastes: an overview, Renew. Energy 37 (2012) 19–27, https://doi.org/10.1016/j.renene.2011.06.045.
[141] J.K. Saini, R. Saini, L. Tewari, Lignocellulosic agriculture wastes as biomass feedstocks for second-generation bioethanol production: concepts and recent developments, 3 Biotech 5 (2015) 337–353, https://doi.org/10.1007/s13205-014-0246-5.
[142] K.M. Harinikumar, R.L. Kudahettige-Nilsson, A. Devadas, M. Holmgren, A. Sellstedt, Bioethanol production from four abundant Indian agricultural wastes, Biofuels 11 (2020) 607–613, https://doi.org/10.1080/17597269.2017.1387744.
[143] R.K. Sukumaran, V.J. Surender, R. Sindhu, P. Binod, K.U. Janu, K.V. Sajna, K. P. Rajasree, A. Pandey, Lignocellulosic ethanol in India: prospects, challenges and feedstock availability, Bioresour. Technol. 101 (2010) 4826–4833, https://doi.org/10.1016/j.biortech.2009.11.049.
[144] R. Rajesh, S.N. Gummadi, Production of multienzymes, bioethanol, and acetic acid by novel bacillus sp. PM06 from various lignocellulosic biomass, Biomass Convers Biorefin 13 (2023) 13949–13961, https://doi.org/10.1007/s13399-022-02418-z.
[145] P.V. Vikash, P.V. Mandade, Y. Shastri, Assessment of bagasse and trash utilization for ethanol production: a case study in India, Environ. Prog. Sustain. Energy 37 (2018) 2165–2174, https://doi.org/10.1002/ep.12900.
[146] V. Sharma, M.L. Tsai, P. Nargotra, C.W. Chen, C.H. Kuo, P.P. Sun, C. Di Dong, Agro-industrial food waste as a low-cost substrate for sustainable production of industrial enzymes: a critical review, Catalysts 12 (2022), https://doi.org/10.3390/catal12111373.
[147] A. Mishra, Production of L-asparaginase, an anticancer agent, from Aspergillus Niger using agricultural waste in solid state fermentation, Appl. Biochem. Biotechnol. 135 (2006) 33–42, https://doi.org/10.1385/ABAB:135:1:33.

[148] A. Salihu, O. Abbas, A.B. Sallau, M.Z. Alam, Agricultural residues for cellulolytic enzyme production by aspergillus Niger: effects of pretreatment, 3 Biotech 5 (2015) 1101–1106, https://doi.org/10.1007/s13205-015-0294-5.
[149] S.K. Panda, S.S. Mishra, E. Kayitesi, R.C. Ray, Microbial-processing of fruit and vegetable wastes for production of vital enzymes and organic acids: biotechnology and scopes, Environ. Res. 146 (2016) 161–172, https://doi.org/10.1016/j.envres.2015.12.035.
[150] V. Varadharajan, S.S. Vadivel, A. Ramaswamy, V. Sundharamurthy, P. Chandrasekar, Modeling and verification of process parameters for the production of tannase by Aspergillus oryzae under submerged fermentation using agro-wastes, Biotechnol. Appl. Biochem. 64 (2017) 100–109, https://doi.org/10.1002/bab.1451.
[151] V. Wagh, H. Patel, N. Patel, K.R. Vamkudoth, S. Ajmera, Pectinase production by Aspergillus Niger and its applications in fruit juice clarification, J. Pure Appl. Microbiol. 16 (2022) 2724–2737, https://doi.org/10.22207/JPAM.16.4.43.
[152] G.G. Raol, B.V. Raol, V.S. Prajapati, N.H. Bhavsar, Utilization of agro-industrial waste for β-galactosidase production under solid state fermentation using halotolerant Aspergillus tubingensis GR1 isolate, 3 Biotech 5 (2015) 411–421, https://doi.org/10.1007/s13205-014-0236-7.
[153] T. Sathish, R.S. Prakasham, Intensification of fructosyltransferases and fructo-oligosaccharides production in solid state fermentation by Aspergillus awamori GHRTS, Indian J. Microbiol. 53 (2013) 337–342, https://doi.org/10.1007/s12088-013-0380-5.
[154] S.S. Bhoyar, A.U. Chaudhari, M.A. Desai, R.V. Latpate, S.D. Sartale, K.M. Kodam, Wheat bran as an efficient agro-process waste for enhanced yellow laccase production by Lentinus tigrinus SSB_W2 and its application in anthraquinone dye degradation, 3 Biotech 14 (2024) 1–18, https://doi.org/10.1007/s13205-023-03881-9.
[155] N.A. Sagar, S. Pareek, S. Sharma, E.M. Yahia, M.G. Lobo, Fruit and vegetable waste: bioactive compounds, their extraction, and possible utilization, Compr. Rev. Food Sci. Food Saf. 17 (2018) 512–531, https://doi.org/10.1111/1541-4337.12330.
[156] H.K. Sodhi, K. Sharma, J.K. Gupta, S.K. Soni, Production of a thermostable α-amylase from bacillus sp. PS-7 by solid state fermentation and its synergistic use in the hydrolysis of malt starch for alcohol production, Process Biochem. 40 (2005) 525–534, https://doi.org/10.1016/j.procbio.2003.10.008.
[157] P.K. Meena, S.D. Awale, S. Kumar, D. Kumar, N. Kumar, Thermochemical conversion of agricultural residue for the production of hydrogen, methane, and biofuels: a comprehensive overview, Ind. Crops Prod. 221 (2024) 119340, https://doi.org/10.1016/j.indcrop.2024.119340.
[158] R.V. Srinadh, R. Neelancherry, Advancements in hydrogen production technologies from agricultural waste, in: R. Neelancherry, B. Gao, A.W. Jr (Eds.), Agricultural Waste to Value-Added Products, Springer Nature Singapore, Singapore, 2024, pp. 55–81, https://doi.org/10.1007/978-981-97-2535-9_3.
[159] S. Sharma, S. Basu, N.P. Shetti, T.M. Aminabhavi, Waste-to-energy nexus for circular economy and environmental protection: recent trends in hydrogen energy, Sci. Total Environ. 713 (2020) 136633, https://doi.org/10.1016/j.scitotenv.2020.136633.
[160] G.H. Dinesh, D.D. Nguyen, B. Ravindran, S.W. Chang, D.V.N. Vo, Q.V. Bach, H. N. Tran, M.J. Basu, K. Mohanrasu, R.S. Murugan, T.A. Swetha, G. Sivapraksh, A. Selvaraj, A. Arun, Simultaneous biohydrogen (H2) and bioplastic (poly-β-hydroxybutyrate-PHB) productions under dark, photo, and subsequent dark and photo fermentation utilizing various wastes, Int. J. Hydrogen Energy 45 (2020) 5840–5853, https://doi.org/10.1016/j.ijhydene.2019.09.036.
[161] K. Elsharkawy, M. Gar Alalm, M. Fujii, H. Afify, A. Tawfik, M. Elsamadony, Paperboard mill wastewater treatment via combined dark and LED-Mediated fermentation in the absence of external chemical addition, Bioresour. Technol. 295 (2020), https://doi.org/10.1016/j.biortech.2019.122312.
[162] Y. Zheng, Q. Zhang, Z. Zhang, Y. Jing, J. Hu, C. He, C. Lu, A review on biological recycling in agricultural waste-based biohydrogen production: recent developments, Bioresour. Technol. 347 (2022) 126595, https://doi.org/10.1016/j.biortech.2021.126595.
[163] N. Sharma, P.P. Sahota, M.P. Singh, Organic acid production from agricultural waste, in: B.K. Kashyap, M.K. Solanki, D.V. Kamboj, A.K. Pandey (Eds.), Waste to Energy: Prospects and Applications, Springer Nature Singapore Pte Ltd., 2021, pp. 415–438, https://doi.org/10.1007/978-981-33-4347-4_17.
[164] A. Blasi, A. Verardi, C.G. Lopresto, S. Siciliano, P. Sangiorgio, Lignocellulosic agricultural waste valorization to obtain valuable products: an overview, Recycling 8 (2023) 1–46, https://doi.org/10.3390/recycling8040061.
[165] R. Gnanasekaran, B. Dhandapani, K.P. Gopinath, J. Iyyappan, Synthesis of itaconic acid from agricultural waste using novel Aspergillus niveus, Prep. Biochem. Biotechnol. 48 (2018) 605–609, https://doi.org/10.1080/10826068.2018.1476884.
[166] D. Dasgupta, A. Sidana, P. Ghosh, T. Sharma, J. Singh, A. Prabhune, S. More, T. Bhaskar, D. Ghosh, Energy and life cycle impact assessment for xylitol production from corncob, J. Clean. Prod. 278 (2021) 123217, https://doi.org/10.1016/j.jclepro.2020.123217.
[167] A. Chandra, B. E, S. Chattopadhyay, A critical analysis on ion transport of organic acid mixture through an anion-exchange membrane during electrodialysis, Chem. Eng. Res. Des. 178 (2022) 13–24, https://doi.org/10.1016/j.cherd.2021.11.035.
[168] S. Kumar, N. Yadav, L. Nain, S.K. Khare, A simple downstream processing protocol for the recovery of lactic acid from the fermentation broth, Bioresour. Technol. 318 (2020), https://doi.org/10.1016/j.biortech.2020.124260.
[169] N. Sharma, P.P. Sahota, M.P. Singh, Organic acid production from agricultural waste, in: Waste to Energy: Prospects and Applications, Springer Singapore, 2021, pp. 415–438, https://doi.org/10.1007/978-981-33-4347-4_17.
[170] S.O. Kulkarni, P.P. Kanekar, J.P. Jog, S.S. Sarnaik, S.S. Nilegaonkar, Production of copolymer, poly (hydroxybutyrate-co-hydroxyvalerate) by Halomonas campisalis MCM B-1027 using agro-wastes, Int. J. Biol. Macromol. 72 (2015) 784–789, https://doi.org/10.1016/j.ijbiomac.2014.09.028.
[171] C. Maraveas, Production of sustainable construction materials using agro-wastes, Materials 13 (2020), https://doi.org/10.3390/ma13020262.
[172] J. Wang, S. Liu, J. Huang, Z. Qu, A review on polyhydroxyalkanoate production from agricultural waste biomass: Development, advances, circular approach, and challenges, Bioresour. Technol. 342 (2021) 126008, https://doi.org/10.1016/j.biortech.2021.126008.
[173] R. Yukesh Kannah, M. Dinesh Kumar, S. Kavitha, J. Rajesh Banu, V. Kumar Tyagi, P. Rajaguru, G. Kumar, Production and recovery of polyhydroxyalkanoates (PHA) from waste streams – a review, Bioresour. Technol. 366 (2022), https://doi.org/10.1016/j.biortech.2022.128203.
[174] M. Waqas, S. Hashim, U.W. Humphries, S. Ahmad, R. Noor, M. Shoaib, A. Naseem, P.T. Hlaing, H.A. Lin, Composting processes for agricultural waste management: a comprehensive review, Processes 11 (2023) 1–24, https://doi.org/10.3390/pr11030731.
[175] A. Sharma, R. Sharma, A. Arora, R. Shah, A. Singh, K. Pranaw, L. Nain, Insights into rapid composting of paddy straw augmented with efficient microorganism consortium, Int. J. Recycl. Org. Waste Agric. 3 (2014), https://doi.org/10.1007/s40093-014-0054-2.
[176] T. Sayara, R. Basheer-Salimia, F. Hawamde, A. Sánchez, Recycling of organic wastes through composting: process performance and compost application in agriculture, Agronomy 10 (2020), https://doi.org/10.3390/agronomy10111838.
[177] R.K. Saini, Y.S. Keum, Omega-3 and omega-6 polyunsaturated fatty acids: dietary sources, metabolism, and significance — a review, Life Sci. 203 (2018) 255–267, https://doi.org/10.1016/j.lfs.2018.04.049.
[178] N. Kannan, A.S. Rao, A. Nair, Microbial production of omega-3 fatty acids an overview, J. Appl. Microbiol. 131 (2021) 2114–2130, https://doi.org/10.1111/jam.15034.
[179] D.K. Saikia, C. Chikkaputtaiah, N. Velmurugan, Nutritional enrichment of fruit peel wastes using lipid accumulating aurantiochytrium strain as feed for aquaculture in the north-east region of India, Environ. Technol. 45 (2024) 1215–1233, https://doi.org/10.1080/09593330.2022.2139638.
[180] N. Swetha, S.K. Mathanghi, Towards sustainable omega-3 fatty acids production – a comprehensive review on extraction methods, oxidative stability and bio-availability enhancement, Food Chemistry Advances 4 (2024) 100603, https://doi.org/10.1016/j.focha.2023.100603.
[181] S.K. Panda, S.S. Mishra, E. Kayitesi, R.C. Ray, Microbial-processing of fruit and vegetable wastes for production of vital enzymes and organic acids: biotechnology and scopes, Environ. Res. 146 (2016) 161–172, https://doi.org/10.1016/j.envres.2015.12.035.
[182] N.A. Sagar, S. Pareek, S. Sharma, E.M. Yahia, M.G. Lobo, Fruit and vegetable waste: bioactive compounds, their extraction, and possible utilization, Compr. Rev. Food Sci. Food Saf. 17 (2018) 512–531, https://doi.org/10.1111/1541-4337.12330.
[183] R. Sahu, Dr P.L. Dhep, A One-Pot Method for the Selective Conversion of Hemicellulose from Crop Waste into C5 Sugars, 2012, pp. 751–761, https://doi.org/10.1002/cssc.201100448.
[184] P. Bhaumik, P.L. Dhepe, Exceptionally high yields of furfural from assorted raw biomass over solid acids, RSC Adv. 4 (2014) 26215–26221, https://doi.org/10.1039/c4ra04119d.
[185] D. Ghosh, D. Dasgupta, D. Agrawal, S. Kaul, D.K. Adhikari, A.K. Kurmi, P.K. Arya, D. Bangwal, M.S. Negi, Fuels and chemicals from lignocellulosic biomass: an integrated biorefinery approach, Energy Fuels 29 (2015) 3149–3157, https://doi.org/10.1021/acs.energyfuels.5b00144.
[186] M.S. Madhukumar, G. Muralikrishna, Fermentation of xylo-oligosaccharides obtained from wheat bran and bengal gram husk by lactic acid bacteria and bifidobacteria, J. Food Sci. Technol. 49 (2012) 745–752, https://doi.org/10.1007/s13197-010-0226-7.
[187] A.K. Samanta, N. Jayapal, A.P. Kolte, S. Senani, M. Sridhar, A. Dhali, K.P. Suresh, C. Jayaram, C.S. Prasad, Process for enzymatic production of xylooligosaccharides from the xylan of corn cobs, J. Food Process. Preserv. 39 (2015) 729–736, https://doi.org/10.1111/jfpp.12282.
[188] L. Bhatia, P.K. Sarangi, S. Nanda, Current advancements in microbial fuel cell technologies, in: S. Nanda, D.-V.N. Vo, P.K. Sarangi (Eds.), Biorefinery of Alternative Resources: Targeting Green Fuels and Platform Chemicals, Springer Nature Singapore Pte Ltd., 2020, pp. 477–494, https://doi.org/10.1007/978-981-15-1804-1_20.
[189] S. Rajesh, A.S. Kumawat, Opportunities for microbial fuel cells to utilize post-harvest agricultural residues, Ionics (Kiel) 29 (2023) 4417–4435, https://doi.org/10.1007/s11581-023-05175-9.
[190] R.N. Krishnaraj, S. Berchmans, P. Pal, The three-compartment microbial fuel cell: a new sustainable approach to bioelectricity generation from lignocellulosic biomass, Cellulose 22 (2015) 655–662, https://doi.org/10.1007/s10570-014-0463-4.
[191] S. Kondaveeti, G. Mohanakrishna, A. Kumar, C. Lai, J.K. Lee, V.C. Kalia, Exploitation of citrus peel extract as a feedstock for power generation in microbial fuel cell (MFC), Indian J. Microbiol. 59 (2019) 476–481, https://doi.org/10.1007/s12088-019-00829-7.
[192] M. Pal, R.K. Sharma, Development of wheat straw based catholyte for power generation in microbial fuel cell, Biomass Bioenergy 138 (2020) 105591, https://doi.org/10.1016/j.biombioe.2020.105591.
[193] S. Kondaveeti, A. Bisht, R. Pagolu, C. Lai, R. Lestari, A. Kumar, D. Das, V.C. Kalia, J.K. Lee, Mild alkaline pretreatment of rice straw as a feedstock in microbial fuel

cells for generation of bioelectricity, Indian J. Microbiol. 62 (2022) 447–455, https://doi.org/10.1007/s12088-022-01022-z.
[194] G.U. Raju, S. Kumarappa, V.N. Gaitonde, Mechanical and physical characterization of agricultural waste reinforced polymer composites, J. Mater. Environ. Sci. 3 (2012) 907–916.
[195] M.K. Saranya, M. Santhoshkumar, S. Sathish, S. Gopinath, P. Parimelashwaran, Recycling of bagasse ash and rice husk ash in the production of bricks, International Journal of Emerging Technology in Computer Science & Electronics (IJETCSE) 21 (2016) 976–1353.
[196] V. Charitha, V.S. Athira, V. Jittin, A. Bahurudeen, P. Nanthagopalan, Use of different agro-waste ashes in concrete for effective upcycling of locally available resources, Constr. Build. Mater. 285 (2021) 122851, https://doi.org/10.1016/j.conbuildmat.2021.122851.
[197] A. Wahane, A. Sahu, A. Verma, T. Dewangan, Evaluation of the physical and mechanical properties of composite board by utilizing agricultural waste, Mater. Today Proc. 84 (2022) 16–23, https://doi.org/10.1016/j.matpr.2023.04.142.
[198] Y.G. Yashas, S. Ballupete Nagaraju, M. Puttegowda, A. Verma, S.M. Rangappa, S. Siengchin, Biopolymer-based composites: an eco-friendly alternative from agricultural waste biomass, Journal of Composites Science 7 (2023), https://doi.org/10.3390/jcs7060242.
[199] S. Deepika, G. Anand, A. Bahurudeen, M. Santhanam, Construction products with sugarcane bagasse ash binder, J. Mater. Civ. Eng. 29 (2017) 1–10, https://doi.org/10.1061/(asce)mt.1943-5533.0001999.
[200] S. Langade, N. Gilke, K. Patil, Bagasse ash for manufacturing construction products, Mater. Today Proc. 5 (2018) 19954–19962, https://doi.org/10.1016/j.matpr.2018.06.361.
[201] K. Joshi, M.K. Meher, K.M. Poluri, Fabrication and characterization of bioblocks from agricultural waste using fungal mycelium for renewable and sustainable applications, ACS Appl. Bio Mater. 3 (2020) 1884–1892, https://doi.org/10.1021/acsabm.9b01047.
[202] S. Singh, S. Maiti, R.S. Bisht, N.B. Balam, R. Solanki, A. Chourasia, S.K. Panigrahi, Performance behaviour of agro-waste based gypsum hollow blocks for partition walls, Sci. Rep. 12 (2022) 1–16, https://doi.org/10.1038/s41598-022-07057-y.
[203] S.P. Raut, U.S. Patil, M.V. Madurwar, Utilization of phosphogypsum and rice husk to develop sustainable bricks, Mater. Today Proc. 60 (2022) 595–601, https://doi.org/10.1016/j.matpr.2022.02.122.
[204] N.V. Mohan, P.P.V.V. Satyanarayana, K.S. Rao, Performance of rice husk ash bricks, Int. J. Eng. Res. Afr. 2 (2012) 1906–1910.
[205] N.R. Aravind, D. Sathyan, K.M. Mini, Rice husk incorporated foam concrete wall panels as a thermal insulating material in buildings, Indoor Built Environ. 29 (2020) 721–729, https://doi.org/10.1177/1420326X19862017.
[206] B. Ambedkar, J. Alex, J. Dhanalakshmi, Enhancement of mechanical properties and durability of the cement concrete by RHA as cement replacement: experiments and modeling, Constr. Build. Mater. 148 (2017) 167–175, https://doi.org/10.1016/j.conbuildmat.2017.05.022.
[207] K. Rajashekhar Reddy, M. Harihanandh, K. Murali, Strength performance of high-grade concrete using rice husk ash (RHA) as cement replacement material, Mater. Today Proc. 46 (2021) 8822–8825, https://doi.org/10.1016/j.matpr.2021.04.332.
[208] R.S. Padhi, R.K. Patra, B.B. Mukharjee, T. Dey, Influence of incorporation of rice husk ash and coarse recycled concrete aggregates on properties of concrete, Constr. Build. Mater. 173 (2018) 289–297, https://doi.org/10.1016/j.conbuildmat.2018.03.270.
[209] J. Pandya, A. Bhogayata, Valorization of the wheat crop stubble ash in eco-efficient concrete, Mater. Today Proc. (2023), https://doi.org/10.1016/j.matpr.2023.03.573.
[210] S. Verma, H. Bajpai, S. Suresh, M. Mili, R.K. Gupta, R. Shetty, S. Kamble, M. A. Khan, S.A.R. Hashmi, A.K. Srivastava, Synthesis of advanced asbestos-free material using rice husk ash and marble waste for thermal insulation applications, Biomass Convers Biorefin 13 (2023) 8985–8998, https://doi.org/10.1007/s13399-021-01950-8.
[211] T. Bhuvana, A. Tiwari, C. Chandraprakash, Green fabrication of cellulose-rich agricultural residues for scalable and biodegradable acoustic boards, Ind. Crops Prod. 204 (2023) 117404, https://doi.org/10.1016/j.indcrop.2023.117404.
[212] A. Sharma, A.S. Brar, Investigations on in-situ paddy straw management technology implemented under different mechanical treatments for wheat establishment, Paddy Water Environ. 19 (2020) 649–660, https://doi.org/10.1007/s10333-021-00864-5.
[213] A. Sharma, A.S. Brar, Energy input–output modeling and sensitivity analysis for on-farm mechanically paddy straw bales formation, Paddy Water Environ. 20 (2022) 255–264, https://doi.org/10.1007/s10333-021-00888-x.
[214] P. Singh, A.S. Kalamdhad, A comprehensive assessment of state-wise biogas potential and its utilization in India, Biomass Convers Biorefin 13 (2023) 12557–12579, https://doi.org/10.1007/s13399-021-02001-y.
[215] T.J. Deka, A.I. Osman, D.C. Baruah, D.W. Rooney, Assessment of bioenergy and syngas generation in India based on estimation of agricultural residues, Energy Rep. 9 (2023) 3771–3786, https://doi.org/10.1016/j.egyr.2023.02.054.
[216] K.A. Motghare, A.P. Rathod, K.L. Wasewar, N.K. Labhsetwar, Comparative study of different waste biomass for energy application, Waste Manag. 47 (2016) 40–45, https://doi.org/10.1016/j.wasman.2015.07.032.
[217] K. Jana, S. De, Techno-economic evaluation of a polygeneration using agricultural residue - a case study for an Indian district, Bioresour. Technol. 181 (2015) 163–173, https://doi.org/10.1016/j.biortech.2015.01.060.
[218] N.N. Deshavath, V.V. Goud, V.D. Veeranki, Commercialization of 2G bioethanol as a transportation fuel for the sustainable energy, environment, and economic growth of India: theoretical and empirical assessment of bioethanol potential from agriculture crop residues, Biomass Convers Biorefin 14 (2024) 3551–3563, https://doi.org/10.1007/s13399-022-03039-2.
[219] M. Munagala, Y. Shastri, S. Nagarajan, V. Ranade, Production of Bio-CNG from sugarcane bagasse: commercialization potential assessment in Indian context, Ind. Crops Prod. 188 (2022) 115590, https://doi.org/10.1016/j.indcrop.2022.115590.
[220] P. Singh, A.S. Kalamdhad, Assessment of agricultural residue-based electricity production from biogas in India: resource-Environment-Economic analysis, Sustain. Energy Technol. Assessments 54 (2022) 102843, https://doi.org/10.1016/j.seta.2022.102843.
[221] P.K. Meena, A. Pal, S. Gautam, Zone-wise biogas potential in India: fundamentals, challenges, and policy considerations, Environ. Sci. Pollut. Res. Int. 31 (2024) 1841–1862, https://doi.org/10.1007/s11356-023-31328-4.
[222] R. Kumar, V. Kumar, A.S. Nagpure, Bio-energy potential of available livestock waste and surplus agriculture crop residue: an analysis of 602 rural districts of India, Sci. Total Environ. 889 (2023) 163974, https://doi.org/10.1016/j.scitotenv.2023.163974.
[223] J. Nagar, R. Kumar, Agricultural residue management in India: unlocking economic potential, International Journal of Research in Agronomy 7 (2024) 490–496, https://doi.org/10.33545/2618060X.2024.v7.i12Sh.2231.
[224] M. Hiloidhari, V. Vijay, R. Banerjee, D.C. Baruah, A.B. Rao, Energy-carbon-water footprint of sugarcane bioenergy: a district-level life cycle assessment in the state of Maharashtra, India, Renew. Sustain. Energy Rev. 151 (2021), https://doi.org/10.1016/j.rser.2021.111583.
[225] M. Hiloidhari, D. Das, D.C. Baruah, Bioenergy potential from crop residue biomass in India, Renew. Sustain. Energy Rev. 32 (2014) 504–512, https://doi.org/10.1016/j.rser.2014.01.025.
[226] K.S. Konde, S. Nagarajan, V. Kumar, S.V. Patil, V.V. Ranade, Sugarcane bagasse based biorefineries in India: potential and challenges, Sustain. Energy Fuels 5 (2021) 52–78, https://doi.org/10.1039/d0se01332c.
[227] Annual Report 2022-23, Ministry of New and Renewable Energy, Government of India, 2023.
[228] Creating Wealth from Agricultural Waste, Indian Council of Agricultural Research, New Delhi, 2020, p. 172.
[229] S. Soam, R. Kumar, R.P. Gupta, P.K. Sharma, D.K. Tuli, B. Das, Life cycle assessment of fuel ethanol from sugarcane molasses innorthern and Western India and its impact on Indian biofuel programme, Energy 83 (2015) 307–315, https://doi.org/10.1016/j.energy.2015.02.025.
[230] S. Soam, M. Kapoor, R. Kumar, P. Borjesson, R.P. Gupta, D.K. Tuli, Global warming potential and energy analysis of second generation ethanol production from rice straw in India, Appl. Energy 184 (2016) 353–364, https://doi.org/10.1016/j.apenergy.2016.10.034.
[231] S. Soam, M. Kapoor, R. Kumar, R.P. Gupta, S.K. Puri, S.S.V. Ramakumar, Life cycle assessment and life cycle costing of conventional and modified dilute acid pretreatment for fuel ethanol production from rice straw in India, J. Clean. Prod. 197 (2018) 732–741, https://doi.org/10.1016/j.jclepro.2018.06.204.
[232] K. Patel, S.K. Singh, Environmental sustainability, energy efficiency and uncertainty analysis of agricultural residue-based bioethanol production: a comprehensive life cycle assessment study, Biomass Bioenergy 191 (2024), https://doi.org/10.1016/j.biombioe.2024.107439.
[233] P. Mandade, B.R. Bakshi, G.D. Yadav, Ethanol from Indian agro-industrial lignocellulosic Biomass—A life cycle evaluation of energy, greenhouse gases, land and water, Int. J. Life Cycle Assess. 20 (2015) 1649–1658, https://doi.org/10.1007/s11367-015-0966-8.
[234] S. Uppalapati, S.P. Jani, J.B. Raj, C. Rajaganapathy, S. Murugapoopathi, S. Shangdiar, K.T.T. Amesho, Environmental impact and energy balance assessment in ethanol production from sugarcane molasses: a life cycle analysis in southern India, Renew. Sustain. Energy Rev. 204 (2024), https://doi.org/10.1016/j.rser.2024.114807.
[235] R. Kumar, A. Bhardwaj, L.P. Singh, Evaluating environmental impacts: a comprehensive investigation of sugarcane-based bioethanol production in northwest region of India, Sugar Tech 26 (2024) 180–193, https://doi.org/10.1007/s12355-023-01332-6.
[236] M.K. Hassan, R. Chowdhury, S. Ghosh, D. Manna, A. Pappinen, S. Kuittinen, Energy and environmental impact assessment of Indian rice straw for the production of second-generation bioethanol, Sustain. Energy Technol. Assessments 47 (2021), https://doi.org/10.1016/j.seta.2021.101546.
[237] A. Bhatnagar, P. Khatri, M. Krzywonos, H. Tolvanen, J. Konttinen, Techno-economic and environmental assessment of decentralized pyrolysis for crop residue management: rice and wheat cultivation system in India, J. Clean. Prod. 367 (2022), https://doi.org/10.1016/j.jclepro.2022.132998.
[238] S. Soam, P. Borjesson, P.K. Sharma, R.P. Gupta, D.K. Tuli, R. Kumar, Life cycle assessment of rice straw utilization practices in India, Bioresour. Technol. 228 (2017) 89–98, https://doi.org/10.1016/j.biortech.2016.12.082.
[239] G. Singh, S. Samuchiwal, P. Hariprasad, S. Sharma, Melioration of paddy straw to produce cellulase-free xylanase and bioactives under solid state fermentation and deciphering its impact by life cycle assessment, Bioresour. Technol. 360 (2022), https://doi.org/10.1016/j.biortech.2022.127493.
[240] V.S. Moholkar Umesh, 2G bioethanol for sustainable transport sector: review and analysis of the life cycle assessments, Curr. Pollut. Rep. 11 (2025), https://doi.org/10.1007/s40726-025-00340-2.
[241] N. Divyangkumar, N.L. Panwar, C. Agrawal, T. Gupta, G.L. Meena, M. Singh, Cradle-to-gate analyses of biochar produced from agricultural crop residues by vacuum pyrolysis, Clean Energy 8 (2024) 1–15, https://doi.org/10.1093/ce/zkae069.

[242] Sujata, A. Anand, P. Kaushal, Life cycle assessment of strategic locations to establish molasses based bioethanol production facility in India, Cleaner Environmental Systems 3 (2021), https://doi.org/10.1016/j.cesys.2021.100055.
[243] I. Tsiropoulos, A.P.C. Faaij, J.E.A. Seabra, L. Lundquist, U. Schenker, J.F. Briois, M.K. Patel, Life cycle assessment of sugarcane ethanol production in India in comparison to Brazil, Int. J. Life Cycle Assess. 19 (2014) 1049–1067, https://doi.org/10.1007/s11367-014-0714-5.
[244] K. Patel, M. Vashist, D. Goyal, R. Sarma, R. Garg, S.K. Singh, From waste to resource: a life cycle assessment of biochar from agricultural residue, Environ. Prog. Sustain. Energy (2025), https://doi.org/10.1002/ep.14558.
[245] K. Patel, S.K. Singh, Sustainable waste management: a comprehensive life cycle assessment of bioethanol production from agricultural and municipal waste, Environ. Sci. Pollut. Control Ser. 31 (2024) 51431–51446, https://doi.org/10.1007/s11356-024-34612-z.
[246] S.N. Joglekar, R.A. Kharkar, S.A. Mandavgane, B.D. Kulkarni, Sustainability assessment of brick work for low-cost housing: a comparison between waste based bricks and burnt clay bricks, Sustain. Cities Soc. 37 (2018) 396–406, https://doi.org/10.1016/j.scs.2017.11.025.
[247] 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.
[248] 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.v5i1.481.
[249] 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.
[250] 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.sbspro.2012.03.309.
[251] S. Sultan, Solid waste management in urban India: an overview, Int. J. Environ. Protect. Pol. 5 (2017) 61, https://doi.org/10.11648/j.ijepp.20170504.13.
[254] D.S. Pandey, E. Yazhenskikh, M. Müller, M. Ziegner, A. Trubetskaya, J.J. Leahy, M. Kwapinska, Transformation of inorganic matter in poultry litter during fluidised bed gasification, Fuel Process. Technol. 221 (2021) 106918.