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REVIEW ARTICLE

Biomass conversion of agricultural waste residues for different applications: a comprehensive review

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Abstract

Agricultural waste residues (agro-waste) are the source of carbohydrates that generally go in vain or remain unused despite their interesting morphological, chemical, and mechanical properties. With rapid urbanization, there is a need to valorize this waste due to limited non-renewable resources. Utilizing agro-waste also prevents the problems like burning and inefficient disposal that otherwise lead to immense pollution worldwide. In addition, conversion of biomass to value-added products like earthen cups, weaving baskets, and bricks is equally beneficial for the rural population as it provides secondary income, creates jobs, and improves rural people's lifestyles. This review paper will discuss an overview of different applications utilizing agro-waste residues. In particular, agro-wastes used as construction material, bio-fertilizers, pulp and paper products, packaging products, tableware, heating applications, biocomposites, nano-cellulosic materials, soil stabilizers, bioplastics, fire-retardant additive, dye removal, and biofuels will be summarized. Finally, several commercially available agro-waste products will also be discussed, emphasizing the circular economy.

Keywords Agro-waste · Value-added product · Green materials · Circular economy · Cellulose · Waste management

Introduction

Agricultural activities lead to the generation of some wastes or by-products known as agro-waste (Afolalu et al. 2021). These agro-wastes include residual straws, shells, stalks, manures, leaves, seeds, bedding, hulls, roots, husks, vegetable matter, and many other significant sources of agro-waste (Koul et al. 2022). Millati et al. reported that around 2 billion tons of agro-waste are generated worldwide annually, containing cellulose, hemicellulose, lignin, and extractive in different quantities (Millati et al. 2019). This lignocellulosic biomass is generally discarded by farmers and industrialists (Adeolu and Enesi 2013). Agro-waste is classified into two categories based on the origin of the waste, i.e., agro-residues (from agriculture fields) and industrial-residues (from industries after raw material processing). Agro residues can further be divided into field and process residues. Field residues are waste left on fields after crop harvesting, including husks, stalks, leaves, and stems. Process residues are field residue leftovers after the crop is converted to its final form, for example, seed leftovers from cotton linters. On the other hand, industrial residues are waste generated during any industrial or manufacturing activity, including potato peel, soybean oil cake, tea processing waste, and coconut oil cake; for example, the beverage industry generates waste like orange peels (Vandamme 2009; Sadh et al. 2018).

Several techniques are used to handle agro-waste, including burning, unplanned disposal, and feed supplements for ruminants and poultry (Kapoor et al. 2016). These waste disposal techniques impose numerous negative consequences: Burning agro-waste causes the generation of pollutants, emission of greenhouse gases, generation of aerosols like N_2O, CH_4, CO, NO_x, huge loss of microbial population, and soil nutrients (Porichha et al. 2021). At the same time, unplanned dumping of waste in open areas leads to rotting and associated environmental issues (Kapoor et al. 2016). The failure to manage waste can lead to water, air, and land pollution and become another reason for climate change

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(United Nations Environmental Programme (UNEP) 2009; Deshwal et al. 2021). Using agro-waste provides double benefits: it provides low-cost biodegradable raw materials, creates income, generates jobs, and prevents the harmful effects of agro-waste if left untreated, such as stubble burning, greenhouse gas emissions, and pollutants.

New era innovations make it possible to utilize this biomass as a raw material source for numerous value-added products that nourish the circular economy concept. The previous study showed that only 8.6% of the world's economy was circular by 2020, which means only a small fraction of waste was cycled (de Wit et al. 2020). The circular economy concept is based on a production and consumption model, which encompasses sharing, renovating, repairing, reusing, and recycling existing products as far as possible (Hamam et al. 2021). This approach minimizes waste and proposes a sustainable alternative to the current practices for handling waste. Researchers are making continuous efforts to valorize the agro-waste for producing value-added products like bio-diesel, bio-hydrogen, biogas, bricks, biodegradable cutlery and tableware, biochar, wall panels, biofertilizers, particle boards, baskets, earthen cups, candies, and juice by the banana stem (Sonite 2007; Eco India 2008; Green Science 2011; PaperWise 2015; Bio-lutions 2017; Varden 2020). Nevertheless, the waste valorization is limited to the lab-scale or small-scale businesses and can be further explored for novel applications that directly benefit the farmers and achieve a circular economy (Myclimate 2019; Paul and Sahni 2019).

Few researchers have recently reviewed articles on agro-waste utilization for human health and everyday lifestyle improvement (Dey et al. 2021), bioenergy (Chandra et al. 2021), and value-added chemicals (Kover et al. 2022). This review paper provides detailed studies utilizing agro-waste in different applications and value-added products. Valorization potential of agro-waste is presented in construction materials (Madurwar et al. 2013), energy production (Mahawar et al. 2015), pulp production of papermaking (Rousu et al. 2002), biofuel (Lee et al. 2019), packaging (Pratiwi et al. 2017), composites (Sanyang et al. 2017), cellulose nanomaterials (Mateo et al. 2021), biofertilizer (Chojnacka et al. 2020), dye removal (Bharathi and Ramesh 2013), and soil stabilizers (Kaur and Singh 2018). Moreover, various advantages of using agro-waste are also discussed. Some commercialized products utilizing agro-waste and their selection criteria as raw materials according to their morphological, chemical, and mechanical properties are also reviewed. Lack of awareness about technology and environmental concerns is critical, and this review attempts to provide techno-economic analysis of using agro-waste for environmental sustainability.

Selection criteria of agro-waste for different applications

There could be many selection criteria for agro-waste materials utilizing different applications depending on the chemical composition, morphological characteristics, and calorific value. The selection criteria based upon chemical composition are discussed. Agro-wastes include rice straw, wheat straw, banana stem, cotton stalks, sugarcane bagasse, hemp, reed, sugar beet waste, rye, cotton linters, corn stalks, and pineapple leaf. In Table 1, chemical composition of some agricultural wastes is mentioned and is divided into two groups, i.e., group A and group B.

Group A contains agro-waste materials with less than 40% cellulose, and group B contains raw materials with

Table 1 Chemical composition of the different agro-waste materials

Group	Agro-waste residues	Chemical composition (%)					References
		Cellulose	Hemicelluloses	Lignin	Ash	Moisture	
Group A	Sugar beet waste	26.3	18.5	2.5	4.8	12.4	El-Tayeb (2012)
	Sugarcane bagasse	30.2	56.7	13.4	1.9	8.34	El-Tayeb (2012)
	Sunflower	34.06	5.18	7.72	9.78	-	Raud et al. (2015)
	Rice straw	39.2	23.5	36.1	12.4	1.83	El-Tayeb (2012)
	Silage	39.27	25.96	9.02	-	-	Raud et al. (2015)
Group B	Amur silver grass	42	30.15	7	5.37	-	Raud et al. (2015)
	Rye	42.83	27.86	6.51	5.21	-	Raud et al. (2015)
	sawdust	45.1	28.1	24.2	1.2	1.12	El-Tayeb (2012)
	Banana stem	49.33	12.04	13.88	4.95	12.43	Subagyo and Chafidz (2020)
	Reed	49.4	31.5	8.74	-	-	Raud et al. (2015)
	Hemp	53.86	10.6	8.76	5.25	-	Raud et al. (2015)
	Corn stalks	61.2	19.3	6.9	10.8	1.92	El-Tayeb (2012)
	Pineapple leaf fiber	66.2	19.5	4.2	4.5	81.6	Daud (2014)

more than 40% cellulose. The raw material can be selected from this table depending upon the application. For example, if the product is designed to be used as cushioning material for packaging or in filling applications to retain the shape of products like shoes and bags, a high cellulose content is not needed. Hence, material can be selected from group A. Whereas, if the end-use of the product is designed to have high strength like carton boxes, printing, and writing papers, then it must have high cellulose content (Britannica 2017); in that case, the material must be selected from group B (El-Saied et al. 2012; Bharimalla et al. 2017). However, cellulose content is not the only selection criteria; morphological characteristics also play an important role in the final strength of the product. As mentioned in Table 1, banana fibers should have more strength than bagasse fibers due to higher cellulose content, but contradicting results were obtained in one study (Guimarães et al. 2009). Banana fibers cells were shown to be thick-walled, irregular, and non-spherical (Fig. 1a and b), whereas, in contrast, the cells of bagasse fibers (Fig. 1c and d) were shown to be thin-walled, regularly arranged, and nearly spherical. Thick-walled fibers are not conformable as they retain their tubular structure even after pressing. Due to this phenomenon, thick-walled fibers of banana possess lower surface area for bonding and hence achieved lesser tensile and burst strength in the developed paper. In contrast, thin-walled fibers of Bagasse do not retain their tubular structure after pressing and hence possess a higher surface area for bonding resulting in higher tensile and burst strength (Malik et al. 2004). It should be noted that other parameters will also play a significant role in the properties of the final product, but this shows how the material can be analyzed based on only its chemical composition and morphological characteristics for end-use application.

There are many similarities between wood and agro-waste, implying that agro-waste can replace woody raw material for paper making. In Table 2, numerous properties of fibers of different raw materials are shown like fiber length, fiber diameter, slenderness ratio, alpha-cellulose, and pentosan content. It can be observed that materials on the left resemble hardwood as their fiber length is mostly ranging between 1.3 and 2 mm is approximately the fiber length range of hardwoods (Riley 2012), whereas materials on the right resemble softwood as their fiber length ranges between 2 and 3 mm that is approximately the fiber length range of softwoods (Riley 2012). Therefore, one possible way to utilize this agro-waste would be to replace hardwoods and softwoods in producing papers with required end-use properties. In the past, several attempts were made to replace hardwoods and softwoods with agro-waste (Leão et al. 2012; Jani and Rushdan 2016).

Another selection criteria of agro-waste depend on the thermo-chemical properties used specifically for energy applications. One study found that raw materials containing a high fraction of fixed carbon can be utilized for charring operation. In contrast, raw materials containing high volatile matter, ash content, and fusion temperature may be used for combustor/gasifiers to generate energy (Jha 2010). Calorific value is also an important factor for combustion, and it was reported to be in the range of 14.3–25.4 MJ/kg for agro-waste residues (Gravalos et al. 2016). This range is due to differences in moisture, ash, and carbon content in different raw materials.

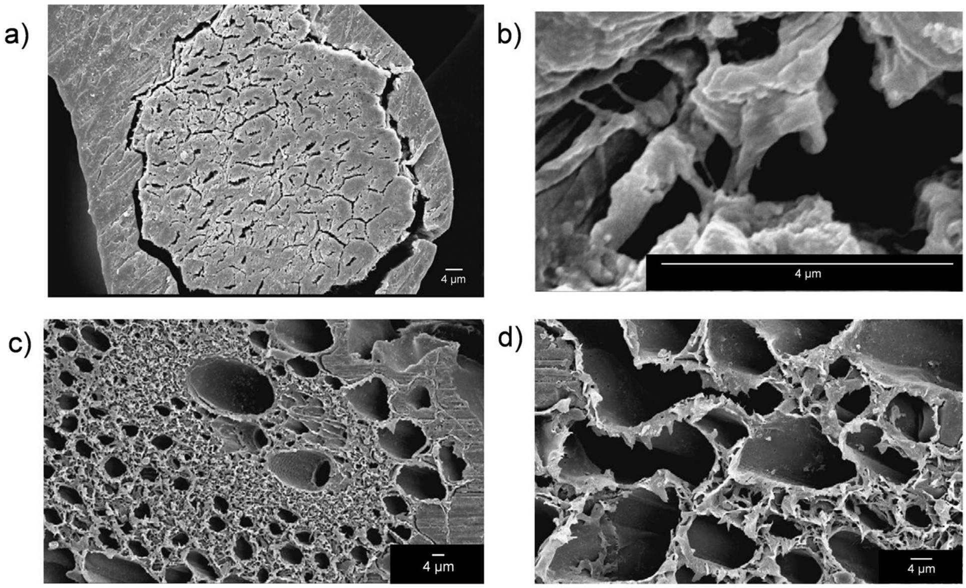

Fig. 1 Scanning electron micrographs of fiber cross-sections: banana (**a** and **b**, magnification); bagasse (**c** and **d**, magnification) (Guimarães et al. 2009)

Table 2 Similarity between woody and non-woody raw materials (Sridach 2010)

Properties	Unit	Rice straw	Wheat straw	Bagasse	Reed grass	Bamboo	Jute	Hemp	Kenaf
		Resembles hardwood					Resembles softwood		
1% NaOH solubility	%	57.7	43.6	33.9	34.8	24.9	28.5	-	28.4
Alcohol benzene soluble	%	0.6	4	1.7	6.4	2.3	2.4	2.6	2.1
Ash	%	15–20	4–9	1.5–5	3	1.7–5	1.6	5–7	2–5
Fiber diameter	mm	8	13	20	20	8–30	18	22	20
Fiber length	mm	1.41	1.48	1.7	1.5	1.36–4.03	2.5	2.0	2.74
Hot water soluble	%	7.3	12.3	4.4	5.4	4.8	3.7	20.5	5.0
L/d ratio		175:1	110:1	85:1	75:1	135–175:1	139:1	100:1	135:1
Lignin	%	12–16	16–21	19–24	22	21–31	11.5	2–4	15–18
Pentosans	%	23–28	26–32	27–32	20	15–26	24	4–7	21–23
Silica	%	9–14	3–7	0.7–3	2	1.5–3	< 1	< 1	-
α-Cellulose	%	28–36	29–35	32–44	45	26–43	61	55–65	31–39

Pretreatment of agro-waste

Agro-waste materials are suitable to replace common fuels used in several applications (Saleem 2022). It has enormous promise as a feedstock for bioconversion processes used to produce energy, fuels, and a wide range of chemicals. It is a renewable resource that is widely accessible, and the carbon dioxide released during its combustion does not affect atmospheric carbon dioxide because of its biogenic origin (Mankar et al. 2021). Despite these advantages, one of the biggest obstacles to its broad usage has always been its resistive nature in terms of its inherent qualities, which hinders its employment in conversion to value-added products. Therefore, agro-waste pretreatment is necessary as it involves structural alteration to overcome its recalcitrant character required for its conversion (Zhao et al. 2012). Additionally, pretreatment must not interfere with the native structure of biomass components. In this regard, the effectiveness of a pretreatment method depends on its ability to delignify the biomass without much alteration in the native structure of components, energy consumption, cost-effective operation, reduction in particle size of biomass, etc. (Park et al. 2016).

Generally, the pretreatment approaches can be categorized into physical, chemical, and biological approaches (El-Dalatony et al. 2017). The physical pretreatment concerns reducing the particle size of the biomass by employing millers, extruder screws, grinders, and ultraviolet or microwave radiations (S. Agu et al. 2019). The chemical pretreatment disrupts biomass structure by disrupting intra- and interpolymer bonds within the primary organic components (Norrrahim et al. 2021). Various studied compounds for chemical pretreatment were acid, organic solvent, alkali, and ionic liquids. In biological pretreatment, cellulose, hemicellulose, and lignin content of biomass are degraded, depolymerized, and cleaved by enzyme-producing fungi (Nadir et al. 2020). Assessing the effects of pretreatment on agro-waste biomass using cutting-edge analytical tools is essential to determining the best method for pretreatment (Anukam and Berghel 2021).

Agro-waste utilization for different applications and products

Some of the possible applications of agro-waste in different fields are shown in Fig. 2. Agro-waste can be used in heating applications after combustion and converted to biofuel using different enzymes. This biofuel can be further used in heat engines as a fuel source and produce mechanical work (Steeneken et al. 2011).

Moreover, this heat engine can be associated with a generator and produce electricity. In addition, agro-waste can undergo pulping and be converted to paper and packaging products like cartons, paper bags, and tableware (Kumar Sinha 1982; Vigneswaran et al. 2015). Agro-waste can also be used to produce biofertilizers that can nurture plant growth by supplying the primary nutrients (Chew et al. 2019) and they are also environmentally friendly compared to chemical fertilizers (Chew et al. 2019). When used with a binder, agro-waste makes it suitable for manufacturing bio-bricks (Gupta et al. 2020). Natural fiber polymer composites can also be produced by adding agro-waste as reinforcement in the polymer matrix. Agro-waste is also utilized to produce biopolymers like polylactic acid (PLA), which is used further in 3D printing applications (Green Science 2011). Table 3 summarizes the applications of agro-waste materials that are mentioned in this review paper.

Combusting agro-waste for energy applications

Fossil fuel is used for energy production but is not a long-term solution for increasing energy demand. Agro-waste is

Fig. 2 Agro-waste utilization for various end-use applications

an excellent renewable energy resource that can work with various energy conversion technologies. Apart from working as an energy source, agro-wastes can also generate employment for farmers and work as a carbon neutralizer (Singh and Raghuwanshi 2015). Mahawar et al. depicted that efficiently using 150 million tons of biomass can reduce CO_2 emissions by over 250 million tons each year. This study used coal and agro-waste (mustard crop residue) to produce energy, but both had different consequences (Mahawar et al. 2015). It was found that there is less emission to air in the form of NO_x, SO_x, and CO_2 in the case of mustard crop residue, hence supporting a clean environment. Moreover, the generation of ash content and water consumption in the power plant is lesser in this case. Furthermore, corn cobs were also utilized with tropic starch as a binder to produce briquettes in different concentrations of 6, 10, 14, and 19% and studied properties like moisture content, ash content, fixed carbon content, and bulk density from each of four samples (Zubairu and Gana 2014). A comparison was made between produced briquette with the briquette made from sugarcane bagasse and wood charcoal. It was found that the moisture in corn cobs briquettes was more than in wood charcoal briquettes and lesser than in sugarcane bagasse briquettes. Also, the heating value of corn cobs (32.43 MJ/Kg) briquette was higher than both wood charcoal briquette (8.27 MJ/Kg) and sugarcane bagasse (23.43 MJ/Kg) briquette. Another study incorporated cotton plant waste residues and pecan shells to produce briquettes (Coates 2000). Consequently, agro-waste converted to briquettes could be used in heating applications with promising results.

Biofuels

Biofuels may be in the form of solid, liquid, or gaseous fuel, and it consists of briquettes, bioethanol/bio-diesel, and bio-hydrogen/biogas, respectively. Biofuel is produced

Table 3 Summary of all the applications of agro-waste mentioned in the review paper

Material	Application	References
Rice straw and husk	Biofuel, packaging films, conducting paper, cellulose nanofibrils, cellulose nanocrystals, ceiling boards, soil stabilizer, paper, paperboard, tableware	Ajiwe et al. (1998); Abe and Yano (2009); Youssef et al. (2012); Lu and Hsieh (2012); Rosa et al. (2012); Wi et al. (2013); Harikumar et al. (2016); Pratiwi et al. (2017); Jayashree and Yamini Roja (2019); Liu et al. (2019); Rizal et al. (2020); Rattanawongkun et al. (2020); Saini et al. (2021)
Wheat straw	Biofuel, cellulose nanofibrils, cellulose nanocrystals, bricks, paper	Helbert et al. (1996); Nigam (2001); Deniz et al. (2004); Vargas et al. (2012); Hassan et al. (2018)
Sugarcane bagasse, rind	Biofuel, conducting paper, cellulose nanofibrils, cellulose nanocrystals, bricks, soil stabilizer, paper, tableware	Buaban et al. (2010); Youssef et al. (2012); Ali et al. (2014); Rahimi Kord Sofla et al. (2016); Liu et al. (2018); Novo et al. (2018); Srisuwan et al. (2018); Varghese et al. (2020)
Mustard crop residue	Energy	Mahawar et al. (2015)
Corn cobs, corn stalk	Energy, paper	Jahan and Rahman (2012); Zubairu and Gana (2014)
Cotton plant residues	Energy, biocomposite, building materials	Coates (2000); Algin and Turgut (2008); de Souza et al. (2020)
Cotton linters	Cellulose nanofibrils, cellulose nanocrystals	Montanari et al. (2005); Oun and Rhim (2015)
Pecan shells	Energy	Coates (2000)
Coconut shell	Packaging films, dye removal	Ahmadpour and Do (1996); Bernardo et al. (1997); Hayashi et al. (2000); Tanwar et al. (2021)
Coconut husk	Cellulose nanowhiskers, bricks, soil stabilizer	Nascimento et al. (2014); Srisuwan et al. (2018); Jagwani and Jaiswal (2019)
Pineapple peels and leaves	Packaging films, biocomposite	Hammajam et al. (2019); Kumar et al. (2021)
Banana pseudostem	Packaging films, cellulose nanofibrils, cellulose nanocrystals, soil stabilizer, paper	Mueller et al. (2014); Gobinath et al. (2020); Othman et al. (2020); Rattanawongkun et al. (2020)
Cassava waste	Biofertilizer, dye removal	Ogbo (2010); Isiuku et al. (2014)
Kenaf bast fibers	Cellulose nanocrystals	Kargarzadeh and Ahmad (2012)
Cocoa pod husk	Biocomposite	Sanyang et al. (2017)
Peach palm waste	Biocomposite	Leão et al. (2012)
Grape peels	Dye removal	Ma et al. (2018)
Dragon fruit peels	Dye removal	Jawad et al. (2018)

by thermochemical or biochemical conversion of biomass (Sarkar et al. 2012). When agricultural waste is used to produce biofuel, it is known as second-generation biofuels. First-generation biofuels are produced from starch, sugar, or oil extracted from vegetable oil and are not considered sustainable as they are directly competing with the food materials, but for second-generation biofuels, leftovers of agro-waste are used (Mohammed et al. 2018). Bioethanol from renewable feedstock sources such as rice straw, corn straw, sugarcane bagasse, and wheat straw (Sarkar et al. 2012) is a potential substitute for petroleum-derived fuels (Demirbas 2008). As depicted in Fig. 3, the bioethanol production process generally consists of pretreatment, enzymatic hydrolysis, and fermentation of biomass. Pretreatment is done with water, steam, and acid to ensure the delignification of the biomass, and a base may be added to maintain the ideal pH for maximizing the activity of the enzymes (da Silva et al. 2012). In the next step, enzymatic hydrolysis occurs, where cellulose and hemicellulose are broken down to glucose and xylose, respectively. Finally, the sugars produced are fermented where microorganisms (e.g., yeast and bacteria) metabolize plant sugars, forming alcohol and CO_2 following the distillation (Bayer et al. 2010). During distillation, ethanol emerges from the fermented mixture of ethanol and water (because ethanol evaporates faster than water), rises through a tube, collects, and condenses into another container. Finally, the bioethanol gets separated and can be used in further applications (Pocock 2008).

Sugarcane bagasse was utilized to produce biofuels (Buaban et al. 2010). Bagasse was ball milled so cellulose structure could become amorphous and easily attackable by hydrolytic enzymes. It was reported that saccharification yield for glucose was 84% and 70.4% for xylose. After enzymatic hydrolysis, fermentation of obtained sugar units resulted in ethanol with a concentration of 8.4 g/l and a conversion yield of 0.29 g ethanol per gram of fermentable sugars. In another study, wheat straw was utilized for ethanol production, implementing overliming with $Ca(OH)_2$ followed by boiling treatment, which enhanced the fermentability of

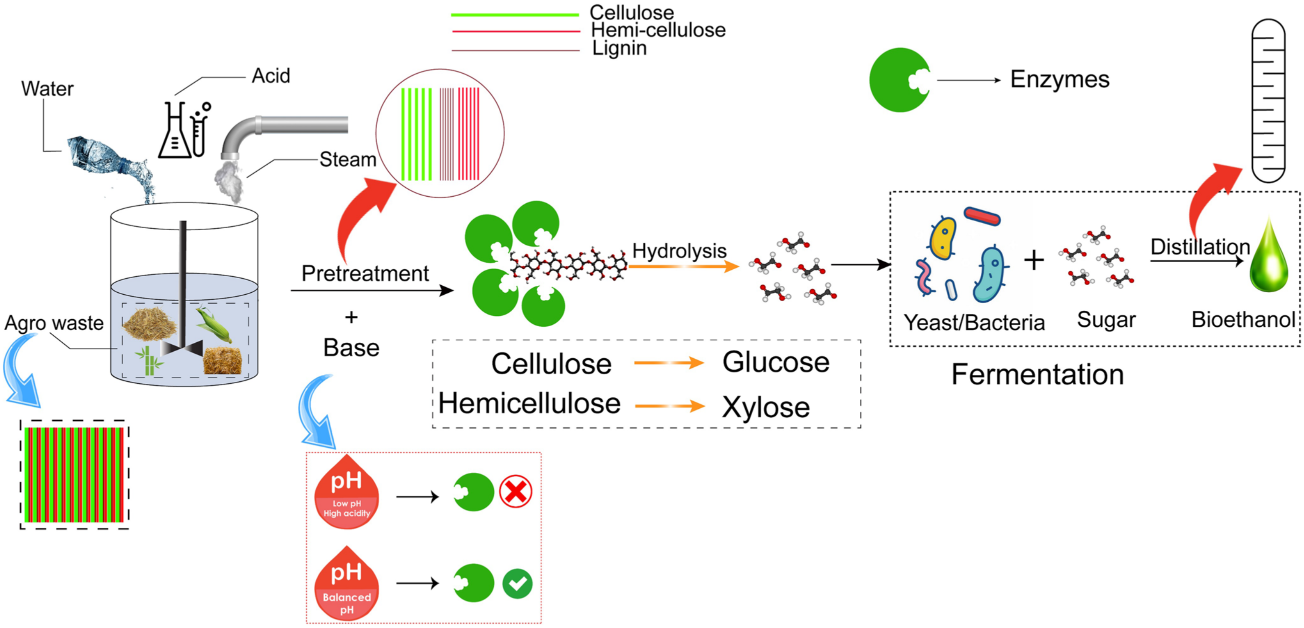

Fig. 3 Production process of bioethanol by agro-waste

hydrolysate as overliming was responsible for chemical conversion of inhibitors which inhibits enzymes activity and reduces their rate of reaction which resulted in 2.4 ± 0.1 fold increment in ethanol yield (Nigam 2001; Horváth et al. 2005; Sheikh and Bramhecha 2019). Rice straw was also utilized to produce ethanol and studied the effect of popping pretreatment in sugar recovery before enzymatic hydrolysis and fermentation, which resulted in yield increment from 0.270 g/gram of biomass to 0.567 g/gram of biomass (Wi et al. 2013). Changes in the surface area of rice straw after popping pretreatment were investigated. The surface area was increased twofold after pretreatment, making the substrate more accessible for enzymes and leading to more efficient hydrolysis of cellulose. Hence, fermentability of raw materials was improved. A comparison of sugar recovery was made between pre-treated and untreated rice straw. It was observed that sugar recovery was higher in pre-treated rice straw because cellulose to glucose conversion efficiency was increased due to popping treatment. It can be observed from these studies that milling, overliming, and popping treatments make the enzymes accessible for enzymatic hydrolysis is an important step in the formation of bioethanol. More attempts have been made to assess the availability of agro-waste for the production of bioenergy in Romania (Scarlat et al. 2011), Nigeria (Iye and Bilsborrow 2013), Zimbabwe (Shonhiwa 2013), Colombia (Gonzalez-Salazar et al. 2014; Patiño et al. 2016; Eras et al. 2019), China (Jiang et al. 2012; Qiu et al. 2014), etc.

Pulp production

For environmental and socio-economic issues, the use of agro-waste in papermaking is essential. Moreover, some agro-waste shows similar properties to woody raw materials, which justifies its utilization in papermaking (see Table 2). Figure 4 shows the typical pulp production by agro-waste using chemical pulping, but other pulping methods like mechanical pulping and Organosolv pulping can also be employed (Rodríguez et al. 2008; Saini et al. 2021). Generally, the agro-waste is collected and transported to the pulping facility, followed by the chemical pulping. After pulping, the pulp undergoes different bleaching sequences depending upon the final brightness required for the end-use applications, and finally, paper is produced on the paper machine. Chemical recovery of useful chemicals and wastewater treatment works simultaneously to improve the cost-effectiveness of the papermaking process and the compliance with the government norms for environmental concerns.

Many studies have been carried out by considering agro-waste as raw material for pulp, like rice straw (Rodríguez et al. 2008), canola (Kiaei et al. 2014), wheat straw (Berg et al. 2014), abaca (Jiménez et al. 2005), bagasse (Ferdous et al. 2020), kash (Ferdous et al. 2020), corn stalks (Ferdous et al. 2020), cotton linters (Abd El-Ghany 2009), *Miscanthus x giganteus* (Brosse et al. 2009), and pineapple leaf (Daud et al. 2015). Both writing and printing grade paper can be produced from agro-waste. Ruchira Papers Limited, India, founded in 1980 produces writing and printing grade papers with agro-waste residues like wheat straw, bagasse,

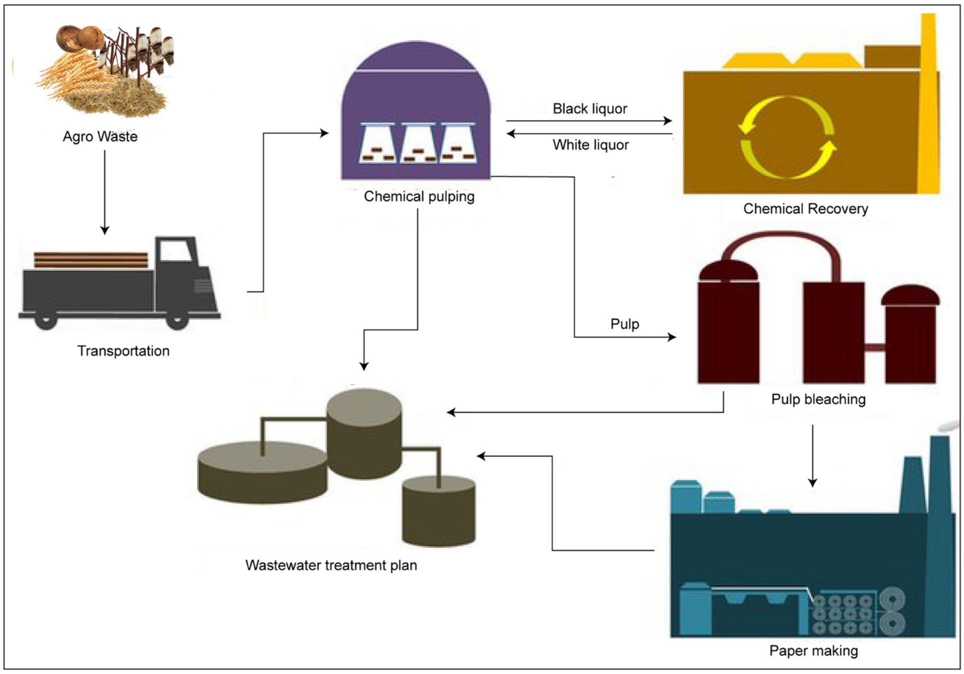

Fig. 4 Utilization of agro-waste in pulp and paper making (Chakraborty et al. 2019)

and *Tripidium bengalense* (Ruchira Papers 1980). Agro-waste can also be used to manufacture paper bags with good strength properties (Willamette Falls 2020).

Chemical pulping covers a major part of all pulping methods, so many studies have been reported. Jiménez et al. reported pulping conditions of abaca (Manila hemp) as soda concentration of 5–10%, pulping time 15–45 min, and temperature of 150–170 °C (Jiménez et al. 2005). The pulp's optimum properties were achieved at soda concentration, time, and high temperature of 7.5%, 30 min, and 170 °C, respectively. Pulp produced had a high kappa number (28.34), high yield (77.33%), and good strength properties like tear index, stretch, and breaking length. This pulp can have application in paper bags where strength is important, and the color is not a governing factor. In another study, chemical pulping on pineapple leaves was studied, and mechanical properties were compared with date palm rachis and palmyra fruit (Daud et al. 2015). The results revealed that the tensile index of pulp obtained by pineapple leaf was better than date palm rachis but lower than palmyra fruit. This difference could be due to cellulose content and/or morphological characteristics as explained in the selection criteria of raw material. Cellulose content and fiber length are as follows: palmyra fruit (53.4%, 50 mm) (Srinivasababu et al. 2014; Reddy et al. 2016); pineapple leaf (62.5%, 6 mm) (Asim et al. 2015; Mahardika et al. 2018); date palm rachis (41.2%, 1.3 mm) (Mahdavi et al. 2010; Ammar et al. 2012). Clearly, both cellulose content and fiber length are important in the final selection of the raw material for a specific application. Neutral sulfite semi-chemical (NSSC) pulping of the Canola plant was also studied, and properties like breaking length, tear index, burst index, stiffness were compared with mixed hardwood NSSC pulp (Kiaei et al. 2014). It was reported that the tensile and burst strength properties of canola NSSC pulp were enhanced than mixed hardwood NSSC pulp when they were used in corrugation application. Due to a lower Runkel ratio (0.47), the ratio of fiber cell wall thickness to lumen diameter, canola pulp fibers have good bonding ability since they collapse in ribbon-like structure and provide more surface area for bonding. NSSC pulping of sugarcane bagasse was also investigated and found that this raw material has promising properties to be used in conjunction with hardwoods, and softwoods and can be utilized in corrugated boards application (Samariha and Khakifirooz 2011).

Organosolv pulping is also excessively used on various raw materials to produce pulp as this is an environmentally benign process. In one study, the mechanical properties of sunflower stalks were determined after employing different pulping methods like soda, ASAE (alkaline sulfite-anthraquinone-ethanol), neutral sulfite, and peracetic acid (Barbash et al. 2016). Studies revealed that pulp obtained from ASAE is best because it had the lowest kappa number (i.e., an indication of remaining lignin content) at the same yield due to efficient delignification. The described reason for this delignification was the prevention of lignin condensation by the organic solvent and fragmentation of lignin by alcohol alkylation of hydroxyl groups in the alpha position. In another study, wheat straw and rye straw were taken as raw materials, and their pulp characteristics were compared after monoethanolamine/anthraquinone (MEA/AQ), soda, and soda/AQ pulping (Salehi et al. 2014). For the different MEA/water and bath ratios, delignification behavior was observed, and the effect of the addition of KOH in pulping liquor was also observed. It was revealed that adding KOH to pulping liquor has no significant effect. For an equal degree of delignification, MEA/AQ pulp showed 10% more yield than soda and soda/AQ pulp due to the high selectivity of monoethanolamine. As the MEA/water ratio decreased, yield and kappa number increased, but optimum results were obtained at a ratio of 50/50. Rye straw pulp was found superior in mechanical properties, yield, and bleachability to wheat straw pulp. Additionally, solvent pulping with pre-hydrolysis of cotton linter was studied and compared to commercial softwood pulp (Abd El-Ghany 2009). It was concluded that prehydrolyzed cotton linter pulp had lower hot alkali solubility, higher α-cellulose content, and higher crystallinity than the commercial softwood pulp. It is depicted in these studies that pulps produced by agro-waste incorporating Organosolv pulping undergo efficient delignification, show good mechanical properties, and contribute to a greener approach to pulp production.

Tableware

Plastic products are extensively used in several fields, such as the food industry, packaging, electronics, and construction (Gu and Ozbakkaloglu 2016). A report stated that people use 500 billion single-use plastic cups every year, and this data is sufficient to know the dependency on plastics for producing tableware (Fact sheet 2018). The disadvantage of using plastic is that it takes many years to degrade; that is why agro-waste, a biodegradable material, is getting popular for producing tableware (Leblanc 2021). These tablewares are produced by the pulp thermoforming technique, consisting of steps like mixing, forming, drying, pressing, and trimming (SPI 2018). In this manufacturing technique, raw materials are first diluted in water and deposited on the porous mesh via applied vacuum to form a pulp preform of the desired shape. The preforms are dried in molding dies under high temperature, pressure, and trimmed if necessary, to achieve the required features in the final pulp-based tableware. In a study, rice straw was suggested to produce food carrying bowl (Saini et al. 2021). Refiner mechanical pulping (RMP) and chemical pulping were used to produce paperboard, later pressed into bowls. Paperboard made up of RMP was of lower mechanical strength, better smoothness, and porosity than chemical pulping. Although the tensile and burst index of the RMP paperboard was equivalent to that of grade III kraft paper as specified in IS 1397:1990. Even after being lower in mechanical strength, bowls produced through RMP were suitable for food serving applications. Sugarcane bagasse was also utilized for pulp-based tablewares (Liu et al. 2018). The strength properties of bagasse-based tableware were reported to be increased with the bamboo fibers as reinforcement by interwinding with bagasse fibers (Liu et al. 2020). The degradation time of tableware was expected to be 60 days, whereas this degradation time for plastic is way more than this. As a concluding remark, biodegradable tableware is not only utilizing the otherwise burned waste but is also good for the environment as it degrades very fast compared to synthetic plastics. However, currently, the cost of biodegradable tableware is more than the conventional plastic tableware, which is a huge concern for consumers, and researchers must work on the economic viability of the tableware (YutoEco 2022).

Packaging industry

Packaging plays an important role in commercializing any product, especially in the consumer-packed goods industry, and significantly affects consumers' buying decisions (Mohebbi 2014). Various commercial packaging products are cartons, films, paperboards, containers, corrugated film boards, kraft bags, etc. Molded pulp packaging is in huge demand due to its environmental advantages and is synthesized by fibrous materials like recycled paper and natural fibers. This molded pulp packaging makes thermoformed products like egg cartons, fruit trays, food packaging, shoe inserts, glass bottle packaging, and electronic appliances packaging (QTM 2018; Pulp2Pack 2021). Out of these packaging, food packaging is the most crucial packaging application as it directly affects consumer health. Food packaging must provide mechanical support to food product and defends foods from external influences like microbial contamination, light, insects, water vapor, oxygen, and dirt and dust particles (Lee and Rahman 2014). The most commonly used technique for producing films in labscale is solvent casting, as shown in Fig. 5a (Suhag et al. 2020). Also, the tradition of active compounds obtained from natural resources (agro-waste) is in trend now as chemical compounds like BHA (butylated hydroxyanisole) and BHT (butylated hydroxytoluene) can cause health risks that are toxic for human consumption. Various bioactive compounds are responsible for the antioxidant properties in different waste, such as extracts from pineapple peel and coconut shells, as shown in Fig. 5b. In a study, agro-food waste, i.e., coconut shell, was successfully valorized in packaging applications as an active antioxidant agent (Tanwar et al. 2021). Polyvinyl alcohol and starch were used as a biocomposite matrix and incorporated coconut shell extract in 3, 5, 10, and 20%. For increasing barrier and mechanical properties, sepiolite clay was also added. Films were developed using the solution casting technique, and fabricated films showed enhanced antioxidant activity due to the catechin and phenolic compounds in coconut shell extract. These films were used as antioxidants for lipid-based food, fried products, and food vulnerable to oxidation. In another study, Pineapple peel

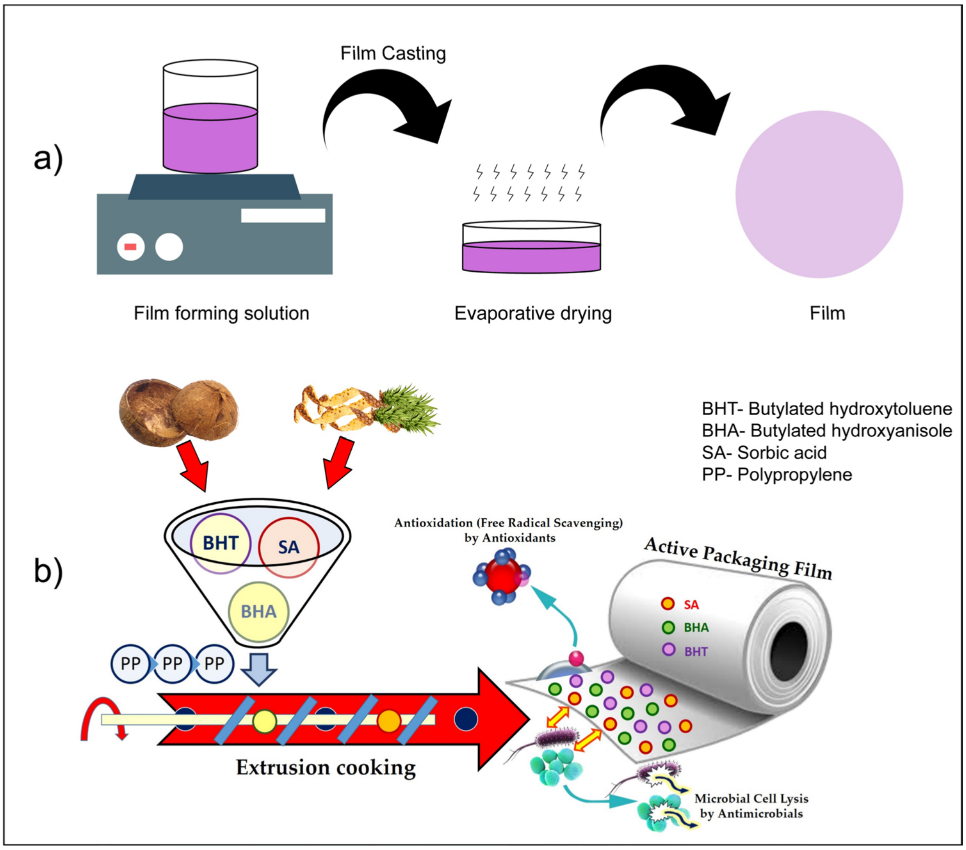

Fig. 5 **a** Solution casting technique for production of films. **b** Incorporation of agro-waste in production of active packaging films (Peighambardoust et al. 2021)

extracts were also utilized in polyvinyl alcohol (PVOH) and corn starch (ST) packaging films (Kumar et al. 2021). The films were developed using the solution casting by adding 5, 10, 15, and 20% (v/v) pineapple peel extracts into the PVOH/ST matrix. Films obtained possess antioxidant activity confirmed by the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay. Compounds such as catechins, ferulic acid, and gallic acid were responsible for the antioxidant activity. The thermal stability in developed films was also enhanced due to the incorporation of pineapple peel extracts.

The utilization of rice straw was analyzed as a potential material for packaging applications (Pratiwi et al. 2017). Chitosan and cellulose extracted by rice straw in different proportions were selected to produce a bioplastic using phase inversion and solvent casting technique. Mechanical properties like tensile strength, modulus of elasticity, elongation at break, and water absorption were studied. It was found that at a chitosan/cellulose ratio of 3:10, the water absorption of produced bioplastic is highest. This property will help bioplastic degrade quickly compared to synthetic plastics like polyethylene terephthalate and polypropylene. At the same time, the mechanical properties were found to be highest at ratio 4:10. In another study, banana pseudostem was incorporated with starch in different percentages (0, 10, 20, 30, 40%) to produce a biocomposite film for food packaging (Othman et al. 2020). Films were made using solvent casting, and films' optical, mechanical, and barrier properties were analyzed. The film's mechanical and optical properties increased when the percentage of banana waste increased from 10 to 40%, but it is always lower than neat starch film. This effect was attributed to the weak intermolecular interaction between banana waste and starch in lower percentages of banana pseudostem (Shapi'i and Othman 2016). However, favorable results were found in barrier properties like WVTR (water vapor transmission rate) and OTR (oxygen transmission rate). Both OTR and WVTR decreased with an increase in banana pseudostem waste, which validates their use as a replacement for non-biodegradable food packaging material. In a study, conducting paper was synthesized by agro-waste (rice straw and bagasse) coated with conductive polymers (polyaniline, PANi) via In-situ emulsion polymerizations. Obtained hybrid product was also suggested as an anti-bacterial packaging material (Youssef et al. 2012). As the ratio of PANi increased, the electrical conductivity of paper increased, but on the other hand, mechanical properties decreased. The reason for this decrement was the inherent brittleness of PANi, so when it intercalates between cellulosic fibers, it decreases the mechanical properties (Youssef et al. 2012). Hence, it is clear that agro-waste was used in almost all kinds of packaging like cartons, packaging films, and paper packaging.

Biofertilizers

Biofertilizers consist of living microorganisms that increase soil fertility and plant growth by supplying the required nutrients to the plant. As shown in Fig. 6, many conversion methodologies of agro-waste into biofertilizers like anaerobic digestion, chemical hydrolysis, in-situ degradation, and direct burning, resulting in products like digestate soil conditioner, soluble biowaste substance, degraded crops, and minerals, respectively. These products can be used as biofertilizers in soil (Du et al. 2018). Anaerobic digestion (AD) is a natural organic matter degradation process in the absence of oxygen in environments such as the bottom of lakes and the intestines of animals. The key objective of AD is to treat waste streams and generate biogas. In addition, the solid residue of AD could be further processed into a biofertilizer or soil conditioner (Tampio et al. 2016; Ndubuisi-Nnaji et al. 2020). In chemical hydrolysis, biomass is treated via acid or alkaline hydrolysis at moderate temperature, resulting in a soluble bio-waste substance. This soluble bio-waste substance is then dried to form a solid product used as a biofertilizer (Rosso et al. 2015; Du et al. 2018). In-situ degradation is a low-cost option to generate an organic fertilizer as it returns all nutrients to soil on site. In-situ degradation uses only indigenous microorganisms that take considerable time, generally 3–6 months. This long decaying period restricts the amount of residue loaded into the field (Du et al. 2018). In contrast, the direct burning of agro-waste is the fastest way of transferring the nutritional content of agro-waste to the soil (like potassium), which transforms almost all organic matter into gaseous oxides and a few mineral elements, but its benefits are limited in soil nutrient enrichment and cause severe air pollution, erosion, soil organic matter loss, and loss of microbial population (Du et al. 2018).

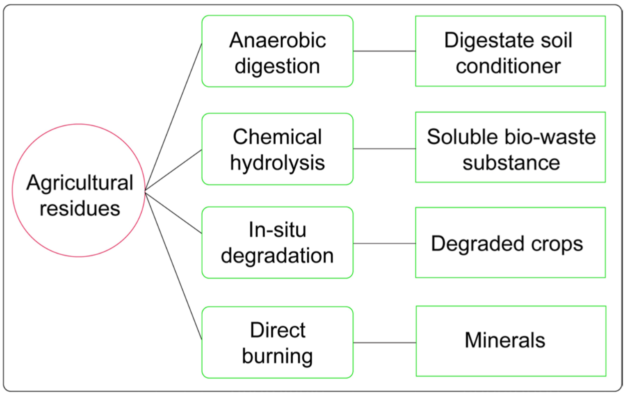

Fig. 6 Conversion methodologies of agro-waste to biofertilizer (Du et al. 2018)

In a study, biofertilizers were produced from five agro-wastes (Kanmani et al. 2009; Lim and Matu 2015), utilizing watermelon, papaya, pineapple, citrus orange, and banana. Fermentation was done in two batches, and analysis was done separately to observe the effect. The fermentation time of the second batch is lower than the first batch because the first batch's precursor increases the reaction rate. After applying the biofertilizer of different agro-wastes to a mustard plant, potassium content, pH, average weight, and the average length of the longest root were analyzed. Citrus orange waste had the lowest pH and potassium content. High acidity affected plant growth, and hence citrus orange waste was not suggested to be used as a biofertilizer. Conversely, bananas, papaya, and melon had higher pH and potassium content, so they were advised to be used as biofertilizers. Due to lower acidity and higher potassium content, gain in plant weight and increased average longest root length was reported compared to untreated plants. In another study, banana pseudostem was reported to synthesize biofertilizer incorporating cellulolytic bacteria (Mahalakshmi and Naveena 2016). It was discovered that cellulolytic bacteria degraded banana pseudostem and released the bound potassium, an essential nutrient for plant growth. In another study, cassava waste was valorized to biofertilizer using different fungi incorporating semi-solid fermentation (Ogbo 2010). It was reported that biofertilizer produced by fungi *Aspergillus niger* improved the growth of pigeon pea significantly, but fungi *Aspergillus fumigatus* failed to show this growth. It is depicted that biofertilizers are always preferred over chemical fertilizers, and agro-wastes are used with or without fungi to produce the biofertilizers.

Cellulose nanomaterials

Nanocellulose is a natural nanomaterial extracted from the plant cell wall, with one or two dimensions (length or diameter) ranging from 1 to 100 nm. There are two main nano-cellulose materials: cellulose nanofibrils (CNF) and cellulose nanocrystals (CNC). Due to several interesting properties such as high aspects ratio, high strength, high surface area, and excellent stiffness (Phanthong et al. 2018), they are utilized in applications like paper and packaging, hygiene products, food sector, skincare products, healthcare, paints, artificial kidneys, sensors, and tissue engineering applications (Mishra et al. 2018). Some of the recent applications of nanocellulose are shown in Fig. 7, consisting of applications in emulsifiers (Goi et al. 2019), carbon dots anchoring (Jiang et al. 2016; Gea et al. 2018), biomedicines (Lin and Dufresne 2014), biocomposites (Omran et al. 2021), etc. Nanocellulose works as a particle stabilizer in emulsions, and it attracted huge attention among all-natural biomacromolecules due to its renewable, economic, and non-toxic characteristics. In addition, it is also readily accessible to physical or chemical modifications (Li et al. 2021). CNF can be synthesized by agro-waste and incorporated as

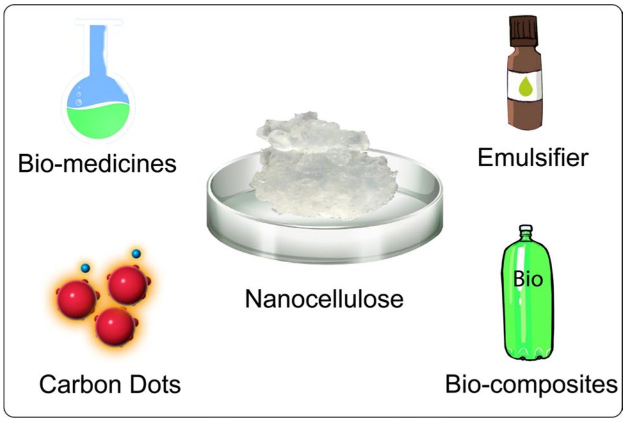

Fig. 7 Applications of nanocellulose in different domains

reinforcing filler in biocomposites (Alemdar and Sain 2008). In transparent nano cellulosic film, the carbon dots enhance UV blocking characteristics and protect from microbial growth (Feng et al. 2017). A recent study developed a fluorescent hydrogel of nanocellulose based on carbon dots for enhanced adsorption and sensitive sensing of heavy metals (Guo et al. 2019; Kousheh et al. 2020). Nanocellulose also has application in the development of biomedical materials from the molecular level of cellular cultivation to macroscopic biomaterials consisting of substitute implants, drug delivery, tissue repair, regeneration, etc. (Lin and Dufresne 2014).

Sugarcane bagasse was suggested to extract cellulose nanofibrils (CNF) and cellulose nanocrystals (CNC) (Kumar et al. 2014; Rahimi Kord Sofla et al. 2016). The process employed to extract CNF was ball milling; for CNC, it was conventional acid hydrolysis. It was revealed that CNC had higher crystallinity than CNF because most of the amorphous region was eliminated from microfibrils during acid hydrolysis. It was also depicted that CNC and CNF had higher crystallinity than raw bagasse due to the removal of lignin and hemicellulose. CNC was found to have a needle-like structure and a low aspect ratio, whereas CNF was a rope-like structure having a higher aspect ratio. CNCs were observed to have higher thermal stability when compared to native cellulose fibers. Kenaf bast fibers were also used for extracting cellulose nanocrystals (Kargarzadeh and Ahmad 2012). It was reported that crystallinity increases during early durations of hydrolysis, but as this duration increases beyond 40 min, crystallinity reduces along with thermal stability. Unripe coconut husk fibers were also exploited to extract cellulose nanowhiskers (CNW) (Nascimento et al. 2014), utilizing the Organosolv pulping, alkaline bleaching of pulp with H_2O_2 and NaOH, and finally hydrolyzing with sulfuric acid. Other than the mentioned raw materials, researchers also extracted CNC and CNF from agro-wastes like soy hulls (Pires et al. 2013), rice straw and potato tuber (Abe and Yano 2009), rice straw (Lu and Hsieh 2012), rice husk (Rosa et al. 2012), cotton linters (Montanari et al. 2005; Oun and Rhim 2015), banana plant (Mueller et al. 2014), pineapple leaf (Cherian et al. 2010), and wheat straw (Helbert et al. 1996).

Biocomposites

Composites are generally produced by combining two or more different materials with different properties to get the combined properties in the same material. Waste plastics can be incorporated with natural materials like coconut, banana, sisal, bamboo, curaua, jute, and pineapple, to produce low-cost, superior, and biodegradable composites (Leão et al. 2012). Figure 8a shows the possible ways to utilize organic waste and residues in natural fiber polymer composites (NFPCs). It is shown that fiber reinforcement is done in the polymer matrix; these fibers can be used directly or processed by anaerobic digestion. The digestion releases biogas, which produces energy for thermal conversion. In addition, agro-waste can be directly burned to produce energy for thermal conversion and generate biochar, which is sometimes added to increase the thermal stability of NFPCs (Väisänen et al. 2016). For extracting polymer, the fiber digestate is gone under thermal conversion in which the polymeric materials are dissolved in liquid and can be fragmented and purified for further use. The synthesized polymer is then reinforced with fibers and additives, producing NFPC. Figure 8b shows the typical dog bone-shaped composites produced by reinforcing latania natural fiber in polypropylene (PP)/ethylene-propylene-diene-monomer (EPDM) (Nasihatgozar et al. 2016).

In a study, cotton waste and paper industry waste were used to produce nanocellulose (de Souza et al. 2020). Cotton waste nanocellulose (CW-N) and industrial waste nanocellulose (IW-N) were integrated with poly(lactic acid) matrix, and mechanical properties were analyzed. Both CW-N and IW-N showed similar physiochemical properties, but morphology was very different; CW-N was found to be nano fibrillar with a mean diameter of 30 nm, and IW-N was spherical and irregular structure having a mean diameter in the range of 60–200 nm. Biocomposite synthesized from both CW-N and IW-N was obtained with enhanced tensile strength due to efficient stress transfer to the filler. This biocomposite was advised to be used in food packaging and biomedical applications. Cocoa pod husk (CPH) was also used as a natural filler in many studies with polymer matrix of polylactic acid (Sanyang et al. 2017), polypropylene (Chun and Husseinsyah 2016), polyurethane (El-Shekeil et al. 2014), and epoxy resins (Imoisili 2013). For CPH/PLA composite films with 0, 5, 10, and 15 wt% fillers (Sanyang et al. 2017), tensile strength increased with the fillers from 0 to 10% (good dispersion of filler in the polymer matrix)

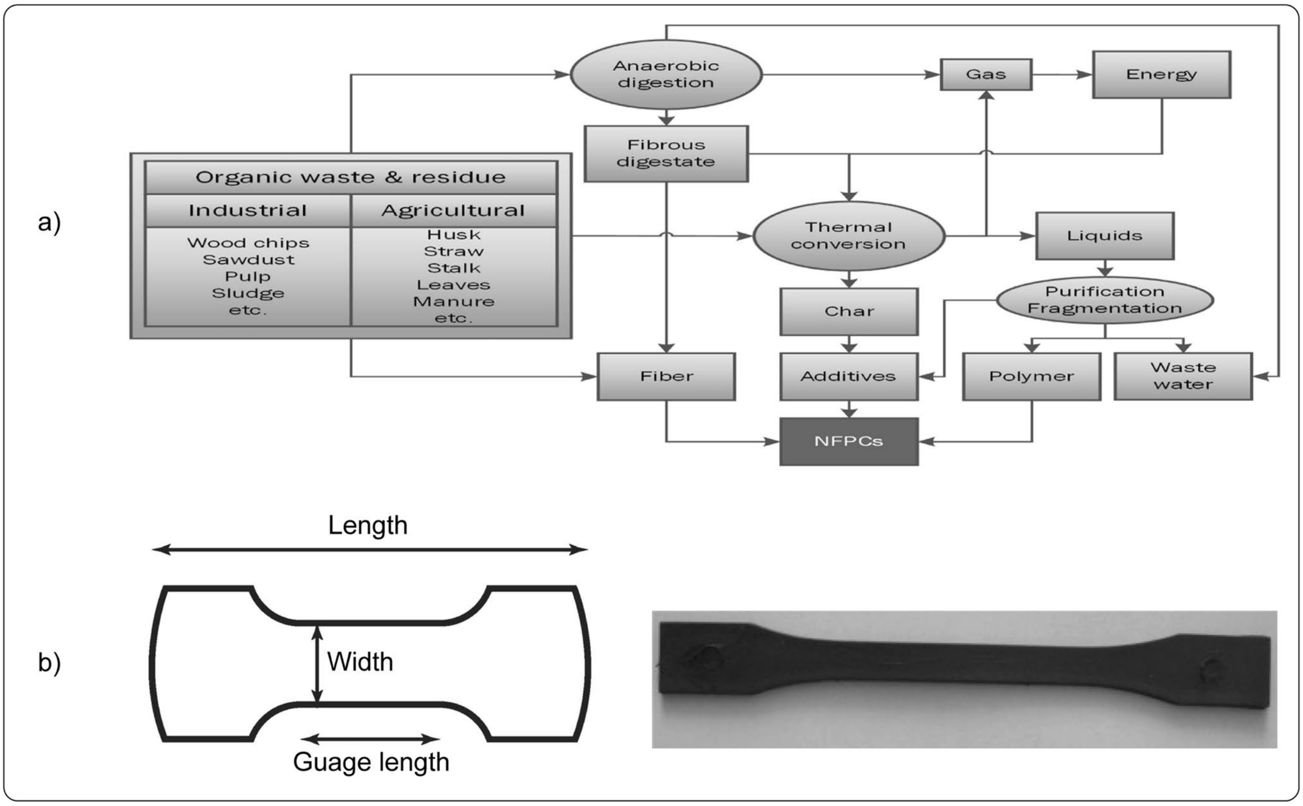

Fig. 8 **a** Possible ways to utilize organic waste and residues in natural fiber polymer composites (NFPCs) (Väisänen et al. 2016). **b** Picture of dog bone shape composite made up of agro-waste (Nasihatgozar et al. 2016)

and decreased when filler loading increased to 15%, possibly due to agglomeration of CPH in the polymer matrix and bad interfacial adhesion between CPH (hydrophilic) and polymer matrix (hydrophobic) (Chun and Husseinsyah 2016). Whereas, for corn husk flour/PLA composites (Jagadeesh et al. 2013), only flexural modulus increased, and other mechanical properties like impact, tensile, and flexural strength were reduced. This reduction in tensile strength was attributed to the irregular shape of filler as moderate spaces were generated in interfacial bonding of polymer matrix and fiber, and they become unable to support stresses that are transferred from the polymer matrix. One more possible reason for reduced tensile strength in the case of corn husk composites could be the high ash content (24.9%) in comparison to cocoa pod husk with lower ash content (12.3%). Ash is an inorganic material that does not contribute to bonding. Plastic waste was also utilized along with peach palm waste (shells and sheaths) as reinforcement for synthesizing composite panels (Leão et al. 2012). It was deduced that fraction of added peach palm waste was crucial in determining the suitability of composites, as the sample where the percentage of natural material was less than plastic waste (60% plastic waste + 40% natural material) showed good physical properties and thickness swelling was also in the acceptable range that is maximum 8% for high-density panels. Pineapple leaf fibers (Munawar et al. 2015) and millet husk fiber (Hammajam et al. 2019) were also utilized as reinforcement in PLA. Referring these studies, it can be observed that many kinds of agro-waste are being used as reinforcement in biocomposites and performing well in terms of strength.

Construction materials

As the population increases, the need for more and more construction is arising, due to which more cement, bricks, mortar, and other related materials are required. The cement industry, for example, causes a lot of greenhouse gas emissions and CO_2 footprints, i.e., 5–8% (Zhang et al. 2014; Kajaste and Hurme 2016); hence, there is a need to use some other raw materials for construction purposes, and agro-waste is studied extensively for this work. In Fig. 9, it is shown that agro bricks and agro cement can also be produced by agro-waste, which can be further used in construction applications.

Different agro-wastes (coconut husk, grass, and sugarcane bagasse) were used to produce fired clay bricks in different fractions from 0 to 7.5 wt% (Srisuwan et al. 2018).

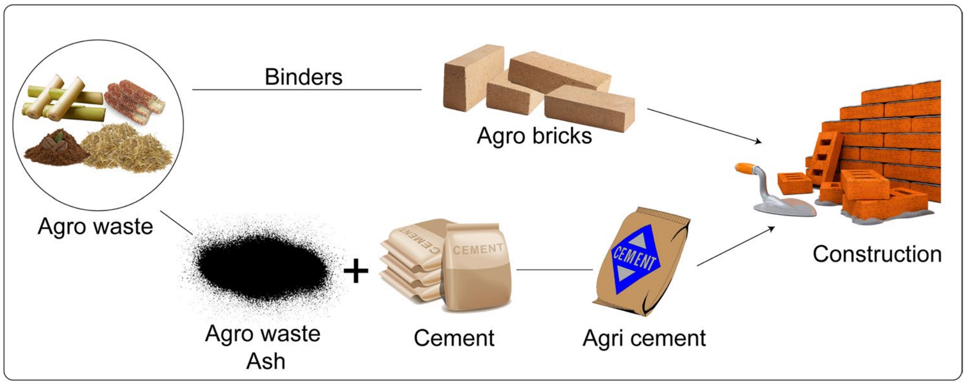

Fig. 9 Utilization of agro-waste in construction applications

The concept was to create some porosity in the structure (during firing of bricks at high temperatures, agro-waste is sacrificed), so lattice vibration in brick can be minimized, making its thermal conductivity less and working as a thermal insulator. However, due to the open structure of agro residues, the porosity of brick was more; therefore, it can result in more water absorption, which is a question of the durability of bricks. It was reported that there is a significant decrement in the compressive strength of bricks after mixing this agricultural waste. In addition, it was revealed that as the waste percentage increases in bricks, shrinkage also increases due to more pores and more space available for grain growth of particles during firing, and simultaneously bulk density was decreased due to more porosity. In another study, bagasse and wheat straw were utilized as an additive in the fired bricks up to 5% together with 0.5% polystyrene (PS), and then bricks were fired at 1250 °C for 2 h (Hassan et al. 2018). Unlike the previous study, polystyrene is added with agro-waste to increase the porosity further, resulting in a large decrease in thermal conductivity, enabling it to work as a lightweight thermal insulator.

Besides bricks, agro-waste also found its application in agro-cement, ceiling boards, and other building materials. In a study, agro-waste was represented as sustainable pozzolans in cement, and filler in the concrete mixture, which partially replaced the cement used in construction (He et al. 2020). It was reported that agro-cement could be produced by burning the crushed agro-waste to ash and mixing it with cement. Ceiling boards were also manufactured with agro-waste (rice husk, as a matrix material) in two categories (Ajiwe et al. 1998; Rizal et al. 2020). In the first category (C1), sawdust was used as filler and glue as a binder, whereas glue was only used in the second category (C2). Properties like water absorption, tensile strength, and moisture content of produced ceiling boards were compared with commercial ones. The tensile strength of C1 was higher than both C2 and commercial ceiling boards. This increment was explained by higher silica content due to sawdust in C1 as small silica particles provide a higher surface area that enhances interfacial adhesion between matrix and filler, so better load transfer and results in increased tensile strength. Limestone waste (LSW) and cotton waste (CW) were also reported to manufacture lightweight and cheap building materials (Algin and Turgut 2008). Properties like flexural strength, compressive strength, unit weight, and water absorption were reported to satisfy international standards. It was observed that if CW largely replaces LSW, its energy absorption capacity increases. Hence, the composite does not fail due to brittle fracture even after surpassing the failure stress limit. This strategy reduces the weight of building material and increases smoothness compared to existing concrete bricks. It was advised to use this building material to replace wooden blocks, ceiling panels, concrete bricks, etc. Agro-waste also finds application in floor and roof tiles using sawdust, rice husks, palm fibers, and corn cob (Saravanan 2017; Zulkefli et al. 2017; Tayade et al. 2019).

Dye removal

As anthropogenic activities increase, industrial growth occurs, but the industry generates much wastewater parallelly. This wastewater sometimes contains dyes and has harmful effects if not removed. To treat wastewater, adsorption of the dyes is necessary, and activated carbon is an excellent adsorbent for this purpose, but it has limited use due to its higher cost (Salleh et al. 2011; Yagub et al. 2014; Chikri et al. 2020). Many researchers have converted agricultural waste like coconut shells and sawdust into activated carbon by physical and chemical activation (Ahmadpour and Do 1996; Bernardo et al. 1997; Hayashi et al. 2000) and found satisfying results. In a study, grape peels were incorporated for methylene blue (dye) adsorption, where the peel was treated by microwave hydrothermal process at 180 °C for 3 min (Ma et al. 2018). Optimum operating conditions were achieved at an adsorbent dosage of 250 g/L. The effect of dragon fruit peels in methylene blue removal was also studied, and the optimum conditions were achieved at an adsorbent dosage of 600 mg/L (Jawad et al. 2018). Methylene blue was also removed using raw sawdust (agro-waste) and treated sawdust (enzyme + NaOH) (Bhikhu and Gaurav

2016). The treated sawdust provided better dye adsorption than untreated sawdust, which might be due to the increased porosity of sawdust upon hemicellulose and lignin removal. Similarly, sawdust was utilized with chemical activation with phosphoric acid (H_3PO_4) for dye removal (Zhang et al. 2008). In further studies, chemical activation of sawdust was done by impregnating it in zinc chloride (Zhang et al. 2008). Moreover, other dyes like Methyl orange dye were removed by using Pisum sativum peels (Prasad et al. 2017). In this study, the dye was degraded for its removal, where magnetic nanoparticles of Fe_3O_4 were responsible for the reaction. Tao et al. used the activated carbon synthesized from the shaddock (pomelo) peel to adsorb the methyl orange (Tao et al. 2019). In this study, biomass waste was carbonized at high temperatures and activated with phosphoric acid. The Methylene red dye removal was done by Isiuku et al. by employing NaOH-activated carbon made from cassava peels, and optimum conditions were achieved at 200 mg/L feed concentration and 13 ml/min flow rate (Isiuku et al. 2014). The mentioned literature depicted that agro-waste can be utilized for dye removal with or without chemical activation and enzymatic treatment.

Soil stabilizers

Soil stabilization can be defined as the physical or chemical treatment of soil that may increase or maintain soil stability, leading to enhanced engineering properties such as improved strength, fatigue strength, higher resistance to fracture, enhanced resilience, reduction in swelling, and resistance to the bad effects of moisture (Arroyo Torralvo et al. 2017; Firoozi et al. 2017). Some parameters to judge soil properties are expansive index and plasticity index. The expansive index represents the swelling and shrinking potential of soil when water volume variation occurs, and the plasticity index represents the water range where soil exhibits plastic properties, and if the plasticity of soil increases, it becomes weak and can cause structural damage to lightweight structures such as sidewalks hence the soil is stabilized to decrease the plasticity and expansive index of soil (Viswanadham et al. 2009). In a study, bagasse ash was utilized as stabilizing soil material for expansive soil. Bagasse ash was used in proportions of 0, 4, 8, and 12%, and properties like expansive index and plasticity index were determined (Ali et al. 2014). It was found that adding bagasse ash in any proportion decreased expansive index and plasticity index as bagasse ash reduced the uplifting pressure of soil. In another study, bagasse ash was utilized as an admixture in lime (costly soil stabilizer) for soil stabilization (Srinivasa Reddy et al. 2017). Three samples were made, where 15% bagasse ash, 3% lime, and 15% bagasse ash along with 3% lime were taken, and maximum dry density (MDD), California bearing ratio (CBR), and plasticity index were determined. It was depicted that the MDD was decreased in each case, which means the soil is less susceptible to settlement when used as filling material because bagasse ash has decreased the number of voids in the soil. It was also revealed that the combination of lime and bagasse ash had dramatically increased CBR value which is a measure of soil strength, and hence, bagasse ash was also beneficial to increasing soil strength. Similarly, rice husk ash and lime (Harikumar et al. 2016; Jayashree and Yamini Roja 2019; Liu et al. 2019), banana fiber (Gobinath et al. 2020), coconut husk (Jagwani and Jaiswal 2019) were also studied in soil stabilizing. These studies confirm the utilization of agro-waste as a cheap and effective soil stabilizer.

Miscellaneous applications

Today, plastic materials have a wide range of applications in every field, but the problem with plastic is its non-biodegradability. Here, bioplastics come into the picture and can be described as either bio-based or biodegradable plastics (Chan et al. 2021). Polylactic acid is a bioplastic derived from lactic acid, and its global demand is increasing with an expected reach of 1.96 megatons by 2025 (Azaizeh et al. 2020). Lactic acid was derived from agro-waste like sugarcane bagasse (Rojan et al. 2005; Wischral et al. 2019), cassava bagasse (John et al. 2006), wheat bran (Naveena et al. 2005), corn fiber (Saha and Nakamura 2003), banana peduncles, sugarcane, and carob (Azaizeh et al. 2020).

Vegetable scraps and spent brewer's yeast were utilized as a nucleic acid (NA) source and used as a fire-retardant additive in cotton fabric (Bosco et al. 2017). NAs were extracted from both wastes and performed a flammability test, and their fire behavior was compared. It was found that NAs recovered from spent brewer's yeast performed better as it provided self-extinction and fire retardant characteristics that can only be achieved by expensive purified DNA.

In a study, graphene oxide (GO) was synthesized using sugarcane bagasse via an oxidation process (Somanathan et al. 2015). It was reported that the synthesized graphene oxide had a well-graphitized structure and the method used was also environmentally friendly. Application of the derived GO may be found in functional devices or sensors.

Benefits of incorporating agro-waste in the valorization of value-added products

There are many advantages of using agro-waste as raw material for different value-added products, as listed in Fig. 10. As stated earlier, agro-waste produces secondary income for farmers and reduces dependency on woody biomass. Also, incorporating agro-waste makes it possible to produce biodegradable products, reinforcing the circular

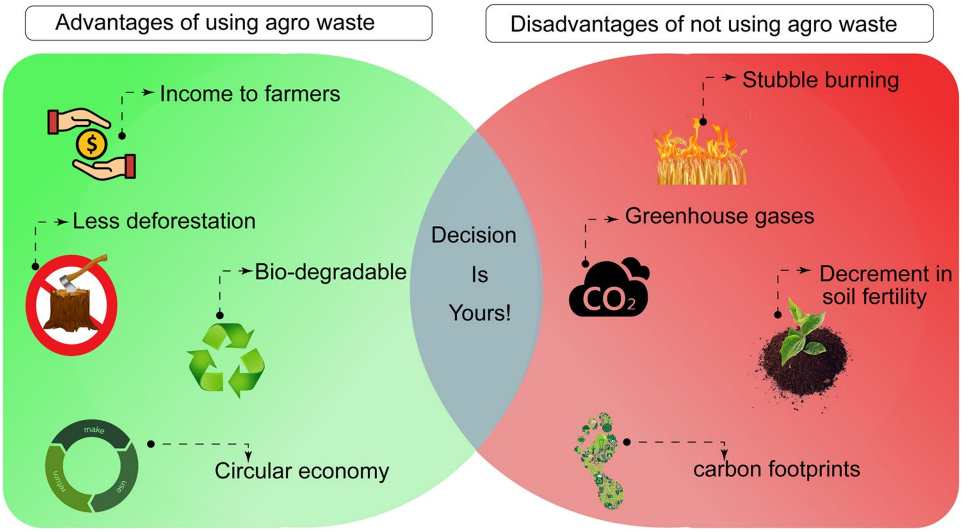

Fig. 10 Advantages of using agro-waste and disadvantages of not using agro-waste in the valorization of value-added products

economy concept. Moreover, it contributes to the evolution of new green markets, conversion of agro-waste to animal feed, the foundation for more jobs, and bioenergy production (McCormick and Kautto 2013; Scarlat et al. 2015; Oluseun Adejumo and Adebukola Adebiyi 2021). There are various disadvantages also if agro-waste is left unused (Fig. 10). Stubble burning is the major issue as rice straw, and wheat straw are generally burned after crop harvesting. Indian Ministry of New and Renewable Energy (MNRE) revealed that India generates 500 million tons of agricultural waste annually and a massive loss of nutrients occurs due to burning agricultural waste. For example, if 1 tonne of rice straw is burned, there will be a loss of 2.3 kg phosphorus, 1.2 kg sulfur, 5.5 kg nitrogen, and 25 kg potassium (Porichha et al. 2021). Moreover, crop burning is also responsible for the emission of greenhouse gases, an immense amount of particulates, pollutants, aerosols like N_2O, CH_4, CO, and NO_x, and many other hydrocarbons. It was found that upon rice straw burning, 70% of carbon in rice straw is emitted as CO_2, 7% as CO, and 0.66% as CH_4 (Jain et al. 2014). Due to the burning of crop residues, soil temperature also increases, causing a huge loss of microbial population in the soil, which is necessary for the root development of plants.

Energy shortages for countries in Africa and Asia are a big hurdle in their socio-economic development. According to the current report, approximately 660 million people will still not have electricity in 2030 (Li et al. 2021). In this modern era, agro-waste is available as a resource that can be utilized as biofuel and can fill this huge gap in energy shortage and reduce the dependency on imported crude oil. Biofuels are carbon–neutral, as the amount of carbon dioxide consumed by plants throughout their life cycle is almost equal to carbon dioxide released when the plant is burned as fuel; hence, agro-waste in biofuel can reduce CO_2 emissions (Paul and Sahni 2019). There is a substantial agricultural waste generation in family farms that are neither utilized nor treated, which causes severe environmental pollution. This waste may be used as fertilizer and can help farmers both environmentally and economically. The incorporation of manure biogas digestor was suggested to be very helpful for family farms to improve sustainability by reducing pollution and decreasing input and resource losses (Yang et al. 2021). Besides all the environmental advantages of utilizing agro-waste, the nation also gets huge economic benefits. Nassar et al. reported the comparison in economics when bagasse is used in conjunction with either banana stem or softwood for papermaking. It was analyzed that if 80% of bagasse pulp is used in conjunction with 20% of banana stem pulp (in contrast to 80% bagasse pulp + 20% softwood pulp), it can result in savings of 6.256 million dollars per year (Nassar et al. 2021) also obtained with higher double fold and tensile properties with a manageable decrease in brightness.

Commercialized products from agro-waste material

Many agro-wastes are already valorized into useful products, as listed in Table 4, which are either commercialized or awaiting commercialization. The raw material used for the specific product and the benefits is also discussed, giving a brief idea about the product usage. These value-added products include handmade paper, biocomposite tiles, earthen cups, biochar, fortified baked products, candies and cookies, banana central core stem juice, decorative wall panels, tableware, biofertilizer, green particle boards, porous bricks, and baskets. Jute waste and mulberry bark have been used to produce handmade paper, requiring approximately 50% less energy and 75% less water

Table 4 Valorization of agro-waste into commercialized or awaiting commercialized products

Value-added product	Source of raw material	Picture	Reference
Handmade Paper	Jute Waste		(Kimothi et al. 2020; Varden 2020)
Kulhad (Earthen cups) Making	Corn Cob Powder		(Kimothi et al. 2020)
Biocomposite Tiles	Rice husk		(Sonite 2007)
Biochar	Agricultural Waste Material		(Kimothi et al. 2020)
Oyster Mushroom Cultivation	Coconut waste		(Kimothi et al. 2020)
Paper Plates	Natural Fiber Biomass		(Kimothi et al. 2020; PaperWise 2015; Phillipson 2015; Bio-lutions 2017)
Fortified Baked Products	Cabbage waste		(Kimothi et al. 2020)
Candy and Cookies	Banana Central Core Stem		(Kimothi et al. 2020)
Banana Central Core Stem Juice	Banana Central Core Stem		(Kimothi et al. 2020)
Biofertilizer	Sugarcane and sugarbeet		(Al-Aees 2019)
Decorative Wall Panels	Banana Pseudo-stem Fibers and Natural Binders		(Al-Aees 2019)
Porous bricks	paddy straw, wheat straw, sawdust, and hemp		(Kimothi et al. 2020; GreenJams 2019)
Weaving Baskets	Cymbidium Orchids Leaves		(Kimothi et al. 2020)
Green Particle Board	Cassava Stems using Bioadhesives		(Kimothi et al. 2020)

*All figures indicated in the table are provided as examples and are not taken from the references mentioned than by incorporating virgin fiber (India, Thailand) (Eco India 2008; Varden 2020; HMPC 2021). These handmade papers have aesthetic value and help in resource conservation, generate fewer pollutants, reduce deforestation, and require less energy in production than virgin paper. Earthen cups are very popular and manufactured using corn cub powder with mud (Kimothi et al. 2020). Agricultural waste, in conjunction with mud, is utilized to make these cups, which is an alternate solution for the problem of corn cob residues (India). More than 100 million tons of husk are produced globally and take a long time to decompose, and thus are not appropriate for composting or manure. As a solution, biocomposite tiles are made by Sonite Surfaces (Thailand) using rice husk (Sonite 2007). Biochar is a fine-grained, carbon-rich, and porous material produced by pyrolysis of agro-waste. This biochar can be further used as a carbon sequestration agent and fertilizer (India) (Kimothi et al. 2020; Amin et al. 2016). Agro-waste is also commercialized as a substrate for cultivating edible oyster mushrooms with many health benefits (India) (Kimothi et al. 2020). Paper plates are fabricated from different agro-waste traditionally made of plastic (Germany and Netherlands) (PaperWise 2015; Phillipson 2015; Bio-lutions 2017). This is a biodegradable product with an aesthetic look that safely stores food items. Fortified baked products like biscuits, bread, and rusk are also produced by cabbage waste, whose protein and crude fiber content increase by replacing refined wheat flour with a powdered cabbage leaf (India) (Kimothi et al. 2020). Moreover, total antioxidant activity increases due to fortification. The banana's central core stem produces candies/cookies and juice, which is a good source of nutrition and helps dissolve kidney stones (Kimothi et al. 2020). Biofertilizers are manufactured using sugarcane and sugar beet, increasing crop yield and adding nutrients to the soil (India) (Kimothi et al. 2020). Also, the decorative wall panels are manufactured by the pseudo banana stem, which provides a great acoustic property that confirms the good response of panels to sound waves and excellent workability to be cut in any shape and size (Africa) (Al-Aees 2019). Bricks are manufactured using different agro-waste raw materials with higher porosity, lower weight, density, labor charges, and transportation than conventional bricks (India) (GreenJams 2019). In rural areas, baskets are made with the help of cymbidium orchids leaves (India) (Kimothi et al. 2020). Green particle boards have been manufactured by cassava stems using bioadhesives which is traditionally made up of synthetic polymers that cause formaldehyde emission, which creates environmental issues (India) (Kimothi et al. 2020).

Challenges during waste transformation

There are many challenges regarding agro-waste transformation to value-added products. The density of agro-waste biomass is lesser than woody biomass; hence, it needs huge transportation facilities and more manpower for the same amount of raw material. But at the same time, it is easily available in every region, which again makes the transportation cost less, so there should be some efforts to make pellets of this kind of biomass before transporting them to regions where the agro-waste raw materials are unavailable (Greinert et al. 2019). After reaching the conversion facility, agro-waste pretreatment is also necessary as it involves structural alteration to overcome its recalcitrant nature required for its transformation, so it is a challenge to find suitable and economic pretreatment methods for a particular raw material. Also, agro-waste raw materials contain a high amount of moisture, negatively affecting their calorific value for heating purposes (Burubai and Okpala 2017). Moreover, the food and beverage industry generates a sizable quantity of bio-waste that may be used to create energy, but in most cases these feedstocks have a high moisture content and are not appropriate for thermo-chemical conversion processes (Mahro and Timm 2007). Nevertheless, certain companies in this industry have a lot of low-moisture solid biomass resources that are ideal for burning (e.g., rice husks, olive stones, nut shells, or pine cones). Another challenge is yield; researchers reported that agro-waste raw materials consist of silica and other inorganic constituents than woody raw materials, so the yield of final products is also low. The research is going on to meet these challenges and make the agro-waste raw material easy to transform in every aspect.

Future perspectives of biomass conversion of agricultural waste residues

A variety of technological, environmental, social, and economic factors should be taken into account while promoting the industrial use of biomass. For the continued use of solid biomass energy, each industrial sector has its unique difficulties. The pulp and paper companies can expand their conventional raw material to agro-waste and torrefied biomass to boost the efficiency and profitability of their traditional core business (Proskurina et al. 2017). Better energy intensity and use of by-products can lead to a carbon–neutral situation (Wesseling et al. 2017), and new separation and drying technologies can be used to lower the energy intensity of the pulp and paper business. Developing and testing biomass gasification systems to produce energy more effectively is one of the main research fields. Additionally, waste heat recovery is an energy-efficient method, and utilizing remaining ash after burning biomass might help reduce the environmental effects of cement manufacturing (Rajamma et al. 2009; Carrasco et al. 2014; Paris et al. 2016). Gasification of biomass or co-gasification of biomass with coal is another way to boost biomass usage in the non-metallic mining industry. High capital costs, appropriate feedstock, and on-site biomass storage are major obstacles. Furthermore, biomass availability and supply are not assured, and the supply infrastructure is poor or non-existent. The sole renewable carbon source is biomass, which is required for producing iron, but there is still much to learn about many ways to use biomass in the iron and steel sector (Mousa et al. 2016). Because of its chemical, physical, and mechanical characteristics, raw biomass cannot be effectively used in the steel industry. Therefore, it is preferable to employ torrefied biomass, semi-charcoals, or charcoals. To reduce the cost of using biomass and increase CO_2 reductions, steel mills might be combined with the production of chemicals and upgrading of biomass (Ghanbari et al. 2015).

Conclusion

Presently, agro-waste is handled by unplanned disposal and feed supplements for ruminants and poultry. Other than that, whatever waste is remaining burned on fields. These handling practices threaten the environment as they lead to the generation of pollutants in air and water, greenhouse gas emissions, microbial population loss, and soil nutrients. However, from the discussed studies in this review, agro-waste could be utilized as a resource of the new era contributing to immense applications. Various approaches to valorizing the agro-waste were discussed in this review article: construction material, biofertilizers, paper and packaging products, heating applications, composites, nano cellulosic materials, soil stabilizers, biofuel, and dye removal. The physical and chemical properties of agro-waste were made suitable for cellulosic raw material. The studies confirmed that products made with agro-waste had properties very similar or even superior to their non-renewable raw material. Conversion of biomass to value-added products was also beneficial for the rural population as it provides secondary income, creates jobs, and improves the lifestyle of rural people. The utilization of agro-waste was discussed as the key to solving waste disposal problems, pollution due to burning, deforestation, greenhouse gas emissions, and carbon footprints. Several value-added products from agro-waste were already commercialized, and as a customer, one should opt to buy these products, which helps maintain the environmental sustainability. The awareness and importance of agro-waste utilization are increasing slowly, so capital investment must be made to commercialize the value-added products produced entirely or partially by agro-waste.

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