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Valorization of agro-industrial wastes for biorefinery process and circular bioeconomy: A critical review

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Abstract:

Energy recovery from waste resources is a promising approach towards environmental consequences. In the prospect of environmental sustainability, utilization of agro-industrial waste residues as feedstock for biorefinery processes have gained widespread attention. In the agro-industry, various biomasses are exposed to different unit processes for offering value to various agro-industrial waste materials. Agro-industrial wastes can generate a substantial amount of valuable products such as fuels, chemicals, energy, electricity, and by-products. This paper reviews the methodologies for valorization of agro-industrial wastes and their exploitation for generation of renewable energy products. In addition, management of agro-industrial wastes and products from agro-industrial wastes have been elaborated. The waste biorefinery process using agro-industrial wastes does not only offer energy, it also offers environmentally sustainable modes, which address effective management of waste streams. This review aims to highlight the cascading use of biomass from agro-industrial wastes into the systemic approach for economic development.

Keywords: Biorefinery; Agro-industrial waste; Valorization; Circular economy; Energy

1. Introduction

Owing to more industrialization and populace expansion, the generation of waste materials has emerged as a serious issue among researchers (Varjani and Upasani, 2021). As industries counts have been increased, employability, expectancy, land utilization, global trade, etc are few outcomes (Jahnavi et al., 2020; Shah et al., 2021). Major residues are produced by the agro-industries every year. Cereal industries producing husks as waste materials, coffee companies releasing waste in the form of coffee pulp, peels of fruits and vegetables are few examples of agro-industries releasing residues (Cusenza et al., 2021). Energy is required for developing industries and the economy (Yaashikaa et al., 2020). The increase in demand for energy in traditional sources for fulfilling the human requirement resulted in an exploration of all feasible techniques of energy harvesting from various sources (Siwal et al., 2021; Kundariya et al., 2021).

The utilization of agricultural wastes is one technique applied in rural areas for energy production. Bio-based energy is renewable energy obtained from living organisms mainly from agricultural wastes (Anwar et al., 2014; Koyande et al., 2020; Yaashikaa et al., 2019). Wastes from the agricultural sector can be utilized to produce many value-added products such as generating power, biofuel production and generation of biogas (Mohanty et al., 2021). Various substrates possess many properties in them for producing different types of products. Organic compound wastes though toxic to an ecosystem can be used for the production of foodstuffs and other value-added products such as animal feed, biofuels, and biofertilizers (Mishra et al., 2020; Patel et al., 2021). These materials serve as a rich source of minerals, proteins, and sugars. These agricultural residues can't be termed as wastes rather than labelled as raw materials for the production of value-added products (Usmani et al., 2021). These nutrition-rich materials help in microbial growth also that in turn utilizes these materials.

The disposal and release of these untreated residues into the environment will result in the deposition of contaminants into the ecosystem and finally affecting humans and other living beings (Varjani, 2017; Saravanan et al., 2017; Carolin et al., 2017). These residues or agro- industrial wastes are left either untreated or unutilized hence disposal is being done through dumping into the land, burning, or landfilling. These dumped wastes produce adverse effects on the environment like an increase in temperature, greenhouse gases, etc. For this reason, the development of sustainable management is required. For the exploitation of renewable resources, an integrated form of waste management has to be put forward in the postulation of the circular economy. It is based on the biorefinery idea and the concept of the 3R's (reduce, reuse and recycle) with the main focus to utilize the raw materials from the agricultural sector (Islam et al., 2021). A new methodology to solve the agricultural issues is the development of an agricultural circular economy. Though the method developed many fields, an efficient strategy is still required for accessing its environmental advantages.

The research in this agricultural circular economy is not completely resolved. LCA (life cycle assessment) is best suited for estimation of impact on the ecosystem at all stages of the agricultural circular economy. This system included the utilization of advanced technologies for reducing wastes using a closed-loop system (Cong and Thomsen, 2021). For efficient progress towards the circular economy, it requires technologies for maintaining the balance between economic and industrial development, protection of the ecosystem with effective utilization of resources.

This review is mainly focused on usage of potential agro-industrial by-products for the production of biobased products under economically feasible and eco-friendly biorefinery process. As of now, there are various ideas of biorefinery process being worked on. The present review comprehensively described possible valorization of agro-industrial wastes and their utilization for generation of renewable energy products. In addition, the review covers various methods of conversion of agro-wastes to value-added products. This paper systematically reviews management of agro-industrial wastes and products from agro- industrial waste valorization for their extensive application(s). Also, application of life cycle assessment (LCA) in agricultural circular bioeconomy has been discussed providing a profound knowledge into

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where future innovative work should be coordinated towards in order to maximally use biogas and its by-products.

2. Biorefinery concept and management

The current population size has resulted in maximum utilization of available resources for developing sustainable agricultural practices to lead a defensible life. Hence it is important to set bio-refineries that make use of raw materials mainly biomass, animal, and human wastes (Dragone et al., 2020; Varjani et al., 2020a). Majorly a successful bio- refinery based on energy, food, and chemical production relies on human and government organizations. The product formation depends on the composition of biomass utilized during the production process (Varjani et al., 2021a). A well-established bio-refinery is present in various regions that aids to have a maintainable ecosystem, people, animal life, and land. Plants generate energy in the form of biomass and it is stored in chemical form. The ultimate aim of the biorefinery is to utilize this energy stored for maintaining sustainable life (Parada et al., 2017; Rajendran et al., 2021).

The major concern in biorefinery management is making sure self- efficacy in the field of energy, manure production, and food with a socio-economic approach. For this wide knowledge in biomass accessibility and availability, soil type and fertility, population expansion, availability of land, agricultural outcomes, etc., are required (Shahid et al., 2021; Varjani et al., 2020b). The organizational committee members of bio-refinery management may be expert members and advisors from various governmental institutions, local communities, and business people. Bio-refinery involves few sectors namely: farming sector distressed with soil fertility, production of biomass, land utilization, yield and control of pest and weed, bioprocessing sector deals with excess crop utilization and conversion of agricultural waste into useful products and wastewater monitoring sector for controlling the waste discharged into the ecosystem (Sharma et al., 2013). Table 1 depicts biorefinery products from agro-industrial biomass using different conversion technologies.

Table 1
Agro-industrial biomass biorefinery products by employing different conversion technologies.

Biomass	Technology used for conversion	Microorganism	Product	Yield	References
Corn fiber	Enzymatic hydrolysis and biodetoxification	–	Bioethanol	70.2 g/L	Zhang et al., 2021
Grape pomace	Solid state fermentation	*Saccharomyces cerevisiae*	Bioethanol	0.419 g/g	Rodriguez et al., 2010
Corn stover	Saccharification and Solid state fermentation	*Saccharomyces cerevisiae*	Bioethanol	37.8 g/L	Buruiana et al., 2014
Cotton stalk	Solid state fermentation	*Actinobacillus succinogenes*	Succinic acid	63.0 g/L	Li et al., 2013
Sugarcane bagasse	Fermentation	*Gluconobacter oxydans*	Gluconic acid Xylooligosaccharides	96.3 % 39.1 %	Zhou and Xu, 2019
Sweet sorghum bagasse	Fermentation	*Saccharomyces cerevisae Clostridium acetobutylicum*	Ethanol Butanol	144.8 g/kg 17.3 g/ kg	Su et al., 2020
Wheat bran	Fermentation	*Lactobacillus pentosus*	Lactic acid	0.73 g/g	Tirpanalan et al., 2015
Oil palm empty fruit bunches	Fermentation	*Klebsiella pneumoniae*	2,3-butanediol	75.03 g/L	Rehman et al., 2021
Sawdust	Enzymatc hydrolysis	–	Bioethanol	351 L/ton	Abdou Alio et al., 2021
Spent coffee grounds	Fermentation	*Clostridium beijerinckii*	Biobutanol	7.1 g/L	Lopez-Linares et al., ´ 2021
Chestnut shells	Fermentation	*Saccharomyces cerevisae*	Bioethanol	14.6 g/L	Morales et al., 2018
Grass silage	Fermentation	*Cupriavidus necator*	poly-3-hydroxybutyrate	22 g/L	Schwarz et al., 2018
Pomegranate peels	Fermentation	yeast	Bioethanol	80 g/kg	Talekar et al., 2018
Cheese whey	Fermentation	Psychrophilic GA0F bacterium	Hydrogen Ethanol 2,3 Butanediol	73.5 cm^3/g 0.24 g/ g 0.42 g/g	Alvarez-Guzman ´ et al., 2020
Corn cob molasses	Fed batch fermentation	*Klebsiella pneumoniae*	2,3 Butanediol	1.35 g/lh	Wang et al., 2010

3. Sources and effects of agro-industrial waste

Agro-industrial waste refers to materials obtained as wastes from the agricultural field and agriculture-related industries from various processes such as the production of agricultural outcomes such as fruits, meat, vegetables, dairy products, etc. Agricultural wastes can be differentiated as livestock wastes, agro-industrial wastes, crop residues, and fruit and vegetable waste (Zihare et al., 2018; Cusenza et al., 2021). Production of livestock and cultivation of crops facilitates sustenance for farmers worldwide. Application of manure from livestock as an energy source is feasible and, in many regions, it is applied practically for producing biogas or just processing for burning purposes (Khoshnevisan et al., 2021). Livestock waste such as animal slurry, chicken litter, straw, etc can be utilized as combustible for producing heat energy and generating power. This is economically possible if places are well established for the production of heat and processing of by-products.

The power generated and heat produced can be utilized in farms themselves. The agricultural industrial wastes comprise of wastes generated during processing such as residues and by-products from various processing industries such as animal skin, vegetable, and fruit peel, eggs, meat, sugarcane bagasse, starch processing generates starch residues, etc (Naqvi et al., 2020). Sugarcane bagasse is a dry fibrous waste obtained once the juice has been extracted from sugarcane and this ranks top among agro-industrial wastes. Fruit peel from orange, pomegranate, banana, apple, etc comes under agro-industrial wastes. The waste materials that are obtained directly from the agricultural field are considered crop residues. They are the widely available and cheapest waste that can be converted into value-added products (Prasad et al., 2020). The most commonly obtained crop residues for the production of bioethanol include rice straw, corn straw, and wheat straw. Of the three crops, rice straw is the most value-added and promising biomass produced in large quantities throughout the world (Tajmirriahi et al., 2021). These crops are widely available throughout the entire year and the only minimum is utilized for bioethanol production while the major part is left unutilized and burnt causing environmental problems.

Corn straw is the most common biomass utilized for the production of lingo-cellulosic ethanol. Residues from sorghum, barley, and oats are also according to agriculture industrial wastes. All unprocessed vegetables and fruits such as orange, jack fruit, tomato, banana, etc comprised of agro-industrial wastes (Pandey et al., 2000). These wastes are generated from marketplaces and food processing industries. As these materials are easily and quickly perishable, they stand as a severe threat to the ecosystem since the chance of contamination is high. The generation of this fruit and vegetable waste from various units such as processing, packing, distributing, and consuming is high in most countries. The annual generation of these wastes is more and disposal is by dumping which is not proper and cause pollution (Sridhar et al., 2021).

Agro-industries like the food sector generate vast quantities of multi-component waste in the form of solid, liquid, or gaseous state from processing, treatment, and disposal methods. The quantity and components of agro-industrial waste materials depend on the type of operation involved, various steps involved in processing, characteristics of raw materials used, and type and nature of products obtained (Nayak and Bhushan, 2019). Table 2 shows the composition and elemental analysis of agro and industrial waste biomass. The major components present in wastes from the food processing sector include fat, carbohydrate, oil, protein, etc. These compounds are rich in eco-characteristics such as suspended solids, biological oxygen demand (BOD), and chemical oxygen demand (COD). As these agro-industrial waste materials have high nutritional value, improper treatment or disposal of these materials may result in the occurrence of environmental pollution such as the release of waste effluent, air pollution, discharge of solid waste, etc (Sadh et al., 2018).

Food industries release huge quantities of waste and wastewaters every year as residues. These waste residues act as energy carriers and can be regenerated to meet the demand raised due to the increasing population (Ng et al., 2020). Carbon, lignin, cellulose, nitrogen, etc are few compositions of industrial waste materials and they can be reduced and regenerated to produce value-added products such as bioethanol, biogas, etc. The agricultural process turns to be the main source of pollutant causing sector due to the application of chemical fertilizers, herbicides, and pesticides (Ugwu and Enweremadu, 2020). Developing and developed nations are very much dependent and in need of these fertilizers and pesticides for increasing agricultural productivity. But the application of these chemically formulated products results in depleting soil characteristics and fertility. Application of these chemically filled fertilizers and pesticides results in water pollution also. So, the agro- industrial waste materials can be reused and converted as bioenergy in the form of biofertilizers and biopesticides to avoid these environmental problems.

4. Methodologies for valorization of Agro-industrial waste

There are various methods of conversion of agro-wastes to value- added products or energy. Few methodologies include mechanical (Pelletization – a multi-step process for producing energy carrier), thermo-chemical, and bio-chemical are discussed below.

Table 2

Biomass feedstock	Chemical Composition	Elemental analysis	Reference
Corn stover	Glucan (34.8); Xylan (19.0); Arabinan (1.9); Galactan (1.7); Ash (2.4); Acidinsoluble lignin (21.0)	Carbon (43.92); Hydrogen (6.01); Nitrogen (0.42); Sulfur (0.07); Oxygen (40.44)	Liu et al., 2013; Tumuluru 2015
Wheat straw	Extractives (7.3); Ash (4.2); Lignin (17.3); Holocellulose (74.7)	Carbon (42.9); Hydrogen (5.7); Nitrogen (0.62); Oxygen (38.25); Chlorine (0.17)	Jablonsky et al., 2015; Dedovic et al., 2012
Oat straw	Polysaccharides (51.0); Lignin (19.6); Extractives (20.5); Ash (8.9)	Carbon (48.17); Nitrogen (0.03); Hydrogen (6.23); Sulphur (0.02); Oxygen (45.55)	Motasemi et al., 2015; Krongtaew et al., 2010
Barley straw	Ash (10.34); Holocellulose (56.3); Lignin – acid (18.2); Lignin – water (1.0)	Carbon (47.20); Nitrogen (0.15); Hydrogen (6.01); Sulphur (0.03); Oxygen (48.36)	Motasemi et al., 2015; Serna-Díaz et al., 2020
Rice straw	Cellulose (39.04); Hemicellulose (21.64); Lignin (16.2); Ash (18)	Carbon (38.55); Hydrogen (5.50); Oxygen (55.34); Nitrogen (0.60)	Ma et al., 2009; Younas et al., 2017
Coffee husk	Lipids (0.5–3); Protein (8–11); Minerals (3–7); Cellulose (43); Hemicellulose (7); Lignin (9)	Carbon (46.51); Hydrogen (6.77); Oxygen (46.20); Nitrogen (0.43); Sulphur (0.09)	Gouvea et al., 2009; Rodriguez & Gordillo, 2011

4.1. Combustion

Combustion is the widely utilized commercial method for igniting the biomass in presence of air. The chemical energy contained in the biomass gets converted into electricity, mechanical power, or heat energy. The agro-industrial waste materials are purposefully and technically valorized through the course of direct combustion to produce geomaterials as debris. The combustion process is usually performed in turbines, boilers, or electric furnaces (Shen et al., 2016; Yuan et al., 2019). In boilers, the production of electricity is facilitated by burning the biomass for the generation of the high-pressure steam for the turbine to operate which is connected to a generator. Kumar et al., 2015 reported that the efficiency of conversion for combustion of biomass was found to range from 20% to 40% and with the system above 100 MWe. The biomass with high moisture content was found to fit better for these conversion methods.

4.2. Gasification

Gasification involves the conversion of biomass to the mixture of gases containing methane, nitrogen, carbon monoxide, nitrogen, etc. with the help of gasifiers that ranges from 20 to 500 kW (Pacioni et al., 2016). The process includes the utilization of gasifying media as heat, oxygen and steam. The selection of biomass gasification technique is depends on the application of steam and types of gasification agent utilized (Fang et al., 2021). The conversion to a vaporous fuel gives a more extensive selection of innovations for electricity and heat generation for small to large scale industrial applications. The heat needed for drying could be resultant from different phases of the gasification cycle. The dried biomass goes through thermal degradation through the

pyrolysis interaction at a temperature in the range of 200 °C and 650 °C.

Cotton stalk	Cellulose (41.6); Hemicellulose (21.6); Lignin (34.0); Ash (0.37); Extractives (6.16)	Carbon (48.6); Hydrogen (5.3); Nitrogen (1.0); Sulfur (0.2); Oxygen (44.9)	Karthyani et al., 2017; Çetin and Durusoy, 2017
Sorghum stalk	Extractives (Water: 12.1, Ethanol: 2.92); Cellulose (36.3); Hemicellulose (22.2); Lignin (18.2)	Carbon (40); Nitrogen (0.5)	Deshavath et al., 2017
Groundnut shell	Cellulose (38); Hemicellulose (36); Lignin (16); Ash (5)	Carbon (81.78); Hydrogen (2.11); Nitrogen (1.15); Oxygen (11.05)	Gajula et al., 2011
Sugarcane bagasse	Cellulose (44); Hemicellulose (27); Lignin (13); Ash (4)	Carbon (47.50); Hydrogen (5.48); Nitrogen (0.51); Oxygen (46.51)	Behnood et al., 2016; Guida and Hannioui 2017
Tamarind seed	Moisture (11.2); Protein (20.23); Ash (2.50); Fiber (3.0)	Carbon (99.5); Nitrogen (0.3)	Mohamed et al., 2015; Munusamy et al., 2011
Oil palm	Cellulose (31); Hemicellulose (19.2); Lignin (14); Ash (12.0)	Carbon (30.02); Hydrogen (3.81); Nitrogen (0.89); Sulfur (0.19); Oxygen (23.35)	Abdullah et al., 2007; Lim et al., 2012
Corn cob	Ash (1.33); Lignin (35.2); Cellulose (41.5); Hemicellulose (13)	Carbon (42.70); Hydrogen (6.49); Oxygen (50.41); Nitrogen (0.25); Sulfur (0.15)	Garadimani et al., 2015; Kpalo et al., 2020
Grape pomace	Crude protein (14.1); Ether extract (9.5); Crude fibre (27.5); Ash (7.8); Hemicellulose (8.4); Cellulose (12.6)	Carbon (52.27); Nitrogen (2.91); Hydrogen (5.38)	Calderon-Cortes et al., 2018; Deiana et al., 2014
Almond hull	Crude protein (3.2); Crude fibre (13); Hemicellulose (2.1); Cellulose (12); Ash (8.4)	Carbon (48.9); Hydrogen (6.2); Nitrogen (0.18); Oxygen (43.5)	Abid et al., 2019; Rapagna et al., 2018

Composition and elemental analysis of agro-industrial waste biomass. The char is gasified in the range of 700 °C and 1000 °C to deliver syngas. Producer gas or syngas is produced during the process with a calorific value of 4.0 to 5.0 MJ/m^3 (Kosov et al., 2015).

4.3. Pyrolysis

Pyrolysis is a technique which breaks the organic materials in the non-appearance of oxygen, might give a promising valorization way to deal with produce gaseous, biochar and liquid coproducts. The process conditions of pyrolysis can be improved to deliver a solid (biochar), liquid (bio-oil) and gaseous (syngas) demonstrating that a pyrolysis reactor can act as a powerful waste-to-energy converter (Varjani et al., 2019). This process occurs in presence of a very high temperature of 300 to 800 °C without an oxygen supply (Cusenza et al., 2021). Residence time and temperature are major operating conditions for the composition of the products obtained from the pyrolysis process. There are different types of pyrolysis processes suitable for producing various products. Slow pyrolysis is used for producing biochar whereas flash pyrolysis aids in producing bio-oil (Santos et al., 2015).

4.4. Fermentation

The fermentation process is utilized for producing biofuels like bioethanol by employing microorganisms to convert starch, cellulose, or sugar into recoverable products for example ethanol (Cherubini, 2010). Initially, the biomass is crushed and with the application of enzymes, the starch content is converted to sugar (Munasinghe and Khanal, 2010). Finally, yeasts help in the conversion of these sugars to bioethanol. The purification step of obtained product was performed using distillation process is considered as an energy utilizing phase. The solid matter obtained during the process can be utilized as animal feed and bagasse acquired from sugarcane can be utilized as a boiler fuel during the gasification process.

4.5. Transesterification

Transesterification is the process in which oil or fat reacts with the alcohol group to form glycerol and ester. Biodiesel is produced using biomass in presence of a catalyst such as sodium or potassium hydroxide and methanol or ethanol. Biodiesel can be used for running any diesel engines or fuel for vehicles. It is produced using animal fats, oils, etc., through the transesterification and esterification process (Encinar et al., 2021). The by-product obtained as a result of this process is glycerol that has applications in pharmaceuticals, cosmetics, etc.

4.6. Anaerobic digestion

Anaerobic digestion involves the degradation or decomposition of organic matter such as agri-waste, food-waste, etc in absence of oxygen to produce products (Pan et al., 2021). Methanogenesis, acidogenesis, hydrolysis, and acetogenesis are the four main processes involved in anaerobic digestion. The parameters influencing the anaerobic digestion process include temperature, pH, total solids, retention time, volatile solids, etc (Cremonez et al., 2021). There are vast benefits of anaerobic digestion for the valorization of agricultural waste such as being cost- effective, simple, and no power requirement. Anaerobic digestion is currently being utilized as a method for valorizing agricultural waste materials typically wet materials with a high organic content into a biogas that can be directly utilized as a substitution for gaseous petrol (Macias-Corral et al., 2008). Anaerobic digestion breaks biodegradable biomass by microbes in anaerobic encompassing at the processing temperature ranges from 30 to 65 °C. One normal result of these cycles is biogas that can be moved up to biomethane, an alternative in contrast to petroleum gas (Cherubini, 2010). Another advantage is that the emission of gaseous pollutants is less compared to other methods. The drawback hindering the application of agricultural waste as a substrate in the process of anaerobic digestion is the pre-treatment process. Agri- wastes require pre-treatment before the main process that makes the whole process complex.

5. Management of Agro-industrial wastes

Agro-industrial waste management promotes economic advantages like waste conversion to value-added products, cost reduction in the waste treatment process; prevent environmental pollution and other related problems (He et al., 2019). Agro-industrial waste management can be classified into four namely reduction or minimization of waste, conversion, segregation and waste utilization. Waste reduction or minimization is the first type where various steps are to be taken into account including in-plant modification (Hiloidhari et al., 2014; Rao and Rathod, 2018). The important step to be considered as an effective measure of minimizing waste generation is waste conversion. Segregation of waste must be properly done. The solid and other waste must be segregated properly for proper management (Mostafa et al., 2018; Leong et al., 2021).

Waste utilization is an important step in the waste hierarchy. The waste materials must be properly recovered, recycled, and reused as they can be used for the production of value-added products. The utilization efficiency of agricultural waste is influenced by the local environment, population, and development of agricultural activities and industries. There are many methods for recycling agricultural waste like gasification, use of crops as feed or fertilizer, and production of manure (Siddiqui and Dincer, 2021). The recycling of agricultural wastes can be done using two sources: farmers and industries.

Agriculture residues can be additionally divided into process residue and field residue. The process residues are residues present even after the harvest is prepared into substitute important asset while the field residues are deposits that present in the field after the course of yield harvesting. These field residues comprise of leaves, stalks, seed cases, and stems. Agricultural wastes are found to have enhanced potential value as they can be converted and reutilized. The utilization outcomes must be cost-effective, high quality, can be commercialized, multifunctional, etc. The practice of burying, discarding, or burning agricultural waste is quite common and only a minimum quantity is utilized for energy processing. Agricultural waste pollutants possess four features such as less cost, low quality, high quantity, and instability. The recycling pathways were titled after fertilizer, biomass energy, material, and feed. For maintaining the economy, saving resources, and preserving the ecosystem, the recycling of agricultural wastes must be enhanced (Wang et al., 2016; Rene et al., 2020). The utilization efficacy of agricultural wastes is less. The input and output sources must be built to enhance the efficiency of the utilization of agricultural wastes.

6. Products from Agro-industrial wastes

Agro-industry produces a large number of different forms of waste, which mostly came out from waste management processes. The generated waste might be multi-stage and may comprise multi-segment. The possible methods of converting waste materials into useful products using biological principles are investigated.

6.1. Application as the substrate for SSF

Agro-industrial wastes are utilized for producing value-added products. The biomass or agricultural wastes generated can be used for bioenergy production such as biofuels, biogas, etc. Depending on the composition of the substrate, the products are produced with different compositions. Solid waste from various industries such as beer, paper, wine, textile, detergent, agriculture, etc is utilized as substrates for solid substrate fermentation (SSF). Solid materials with low moisture content are considered suitable substrates for SSF. Few examples of agricultural waste utilized as substrates include rice straw, wheat straw, peanut cake, etc (Mohapatra et al., 2020; Sala et al., 2021). A research study was conducted using tan agro-industrial waste for its accessibility and availability as carrier material for fungal immobilization in SSF. Few materials were found to be efficient for utilizing as immobilization carriers in SSF owing to their water absorption ability and effective support medium for the vast growth of microorganisms (Orzua et al., 2009).

6.2. Production of biofuel

Biofuels are used as a substrate for fossil fuels. Many studies have been conducted utilizing agro-industrial waste such as sugarcane bagasse, sugar beet waste, rice straw, potato, and sweet potato waste, etc as a substrate for biofuel production (Yogalakshmi et al., 2022). The utilization of agricultural residues minimizes deforestation as human dependency on forest waste gets reduced and also harvest time required for field residues is less. Many researchers have proposed biofuel mainly bioethanol production using lignocellulosic materials and other agricultural residues. The second generation of bioethanol production was successfully proposed by Saini et al. (2014). The study used the lignocellulosic composition of various agro-industrial wastes in producing bioethanol that serves as a better alternative to fossil fuels such as petrol and diesel. These lignocellulosic materials are a cost-effective, eco- friendly and useful alternative energy source. Another study showed the production of biogas using different agricultural residues and weeds (Paepatung et al., 2009).

Owing to vast industrialization and population expansion, the demand for low-cost energy sources is increasing. An enormous amount of waste materials is available for biofuel production. Bioethanol was produced using vegetable waste by fermentation using *Saccharomyces cerevisiae* (Mushimiyimana and Tallapragada, 2016). Peels of onion, carrot, and potato were used in this study, and bioethanol production is the only best alternative for maximum utilization of agricultural residues. As the banana pseudostem is an easy and vast available waste, it can be effectively used for bioethanol production by pre-treating with *Aspergillus* species (Ingale et al., 2014). Butanol was also produced from agricultural residue using *Clostridium* species (Maiti et al., 2016). Hence agricultural waste serves as an eco-friendly and cost-effective material for the production of biofuels thus fulfilling the energy requirements.

6.3. Production of antibiotics

Antibiotics are those substances that are synthesized by the microbes that kill or stop the growth of other harmful microorganisms at low concentrations (Tripathi, 2008). Studies showed the utilization of various agro-industrial wastes for antibiotics production. Few materials like sawdust, rice straw, rice hull, wheat straw, corn cob, etc can be used for producing antibiotics. Of all the agro-industrial waste materials, groundnut shells and coconut oil cake produced antibiotics at high concentrations. External energy was provided for increasing production. The antibiotic oxytetracycline was produced using groundnut shells as raw material through SSF. *Streptomyces rimosus* was used for this production process (Asagbra et al., 2005; Tobias et al., 2021).

6.4. Production of enzymes

The different composition of agro-industrial waste helps the growth and development of microbes for the production of enzymes through the fermentation process (Viveka et al. 2020). Table 3 demonstrates enzymes produced from agro-industrial wastes. The growth rate of microbes can be increased with the help of these raw materials. Kalogeris et al. (2003), demonstrated the production of cellulolytic enzymes like β-glucosidase and endoglucanase using fungal strains. Another study showed the utilization of corn cob for phenolic production through SSF (Topakas et al., 2004). Raw materials from food industries such as oil

Table 3
Enzymes produced from agro-industrial wastes.

Enzyme	Agro-industrial residue	Microorganisms	Reference
Mannase, Xylanase	Rice straw, Soybean meal	*Paenibacillus polymyxa BTK01 and Bacillus subtilis BTK07*	Chantron et al., 2021
Peroxidase (LiP), Manganese peroxidase (MnP), Laccase	Corncob	*Phanerochaete chrysosporium*	Sosa-Martínez et al., 2021
Laccase, Xylanase, Amylase	Oil palm biomass	*Trametes lactinea FBW and Pycnoporus sanguineus FBR*	Naidu et al., 2020
Cellulase	Banana peel	*Trichoderma viride* GIM 3.0010	Sun et al., 2011
Cellulase	Mango peel	*Trichoderma reesei*	Saravanan et al., 2012
Laccase	Bagasse, Cornstalk and Rice husk	*Trametes versicolor*	Perdani et al., 2020
Inulinase	banana peel, wheat bran, rice bran, orange peel and bagasse	*Saccharomyces* sp.	Onilude et al., 2012
Inulinase	Coconut oil cake	*Pencillium rugulosum* (MTCC-3487)	Dilipkumar et al., 2014
Mannanase	Apple pomace and cottonseed powder	*Aspergillus niger* SN-09	Yin et al., 2013

Mannanase	Lime, grape, tangerine and sweet orange peels	*Penicillium italicum and Trichosporonoides oedocephalis*	Olaniyi et al., 2014
Mannanase	Palm kernel cake	*Aspergillus terreus* SUK-1	Rashid et al., 2013
Laccase	Fermented ragi	*Trametes versicolor*	Atilano-Camino et al., 2020
b-glucanase	Oat meal	*Rhizomucor miehei* CAU432	Yang et al., 2015
b-glucanase	Orange peel waste	*Tricoderma viride* MBL	Irshad et al., 2012
Laccase	Tea residue	*Trametes versicolor*	Xu et al., 2020
β-glucosidase	white and red grape marc, vine shoots trimming and grape stalks, organic crude olive pomace, crude olive pomace and exhausted olive pomace and brewer's spent grain	*Aspergillus ibericus, Rhizopus oryzae, Aspergillus niger*	Leite et al., 2019
Pectinase	Citrus peel and sugar cane bagasse	*Aspergillus oryzae*	Biz et al., 2016

cakes, peels of fruits and vegetables, field residues, etc are effectively utilized for the production of glucoamylase and amylase enzymes using bacterial species (Suganthi et al., 2011; Negi and Banerjee 2009). Salim et al. (2017), showed that *Bacillus* species produced four enzymes namely cellulase, protease, pectinase, and amylase utilizing agricultural residues such as wheat bran, maize bran, sunflower meal, and olive oil cake. Chemical pretreatment was done for obtaining maximum production.

Amylase was produced using four different agricultural wastes such as wheat bran, wheat flour, sugarcane bagasse, and soybean meal. These materials were rich in carbon sources and *Rhizopus microspore was* utilized for this study. Of these materials, wheat bran showed maximum production. Buenrostro-Figueroa et al. (2013) showed production of ellagitannins using agro-industrial waste such as coconut husks, corn cob, and sugarcane bagasse. It was found that corn cob resulted in maximum production of enzyme followed by sugarcane bagasse and coconut husks. Oil cakes were used for producing lipase enzyme and maximum production of lipase was obtained when palm kernel oil cake was used particularly (de Oliveira et al., 2017).

6.5. Production of phytochemicals

The requirement for phytochemicals derived from plants is increasing due to their potential applications in allopathy. The extract from plants can be used directly or the specific compound can be isolated, purified, and then utilized for desired purposes (Mopuri and Islam, 2017; Saravanan et al., 2021). Through various chemical drugs are available commercially, the use of these natural compounds serves as the source of new drugs. Due to this, plant waste materials are generated in huge quantities resulting in pollution. For example, mango leaves are used for spiritual purposes and are left untreated or burning after usage which results in environmental pollution. These leaves are found to possess therapeutic properties. The dried mango leaves are rich in antioxidants, antiviral, and antitumor properties and it contains a valuable compound mangiferin (Imran et al., 2017). This compound is rich in antioxidant and anti-diabetic properties which can be used widely for treating diseases. Recently compounds derived from natural materials are widely used as antioxidants.

Phenolic compounds are beneficial phytochemicals widely used for treating human disorders and diseases due to their antioxidant properties (Singh et al., 2018). These bio compounds effectively interact with molecules like lipids, DNA, and proteins for framing natural therapeutic compounds. Few industrial phenolic compounds include tannins, flavonoids, alkaloids, and anthocyanins that are obtained from plants, fruits, shells, leaves, roots, etc. The agro-industrial waste such as vegetables, fruits, and crop residues are subjected to various extraction procedures for isolating bioactive compounds (Arun et al., 2020). One example is the tomato processing industry where huge quantities of tomato seeds and peels are released as waste materials. The seeds and tomato peels are rich sources of bioactive compounds such as sterols, terpene, polyphenol, etc. Similarly, coffee production also eliminates waste residues that are rich in tannin and phenolic compounds.

Agro-industrial waste can be sued as a feedstock for microbes, which produce bio pigments either by solid substrate fermentation or submerged fermentation. Chemically synthesized pigments may be toxic and cause health effects when consumed while natural pigments are non-toxic and safe. Natural pigments such as chlorophylls, melanin, carotenoid, etc can be obtained directly from plants while pigments like xanthophylls, phytocyanin, etc are obtained using microbes by fermentation process (Panesar et al., 2015). Astaxanthin and beta- carotene compounds produced by algae and cyanobacteria are of industrial importance owing to their maximum production and commercial value. Another important pigment is melanin, naturally present in humans, animals, plants for protection against harmful UV radiation. Agro-industrial waste such as fruit and vegetable peels are a significant choice for melanin production for commercial applications. Another important molecule is a peptide that is encoded within protein sequences and found to have a role in human health disorders such as hypertension, cancer, diabetes mellitus, etc. The peptides are of different sizes and a molecular weight that suits for food and pharmaceutical industries. Waste residues produced by agro-industrial wastes such as oiled plant residues, soybean meal, etc are rich in the protein source.

6.6. Production of biofertilizers

Nutrients such as nitrogen, potassium, and phosphorous are required for growth and plant development (Varjani et al., 2019). These nutrients must be present in the soil and their level gets decreased once the crops are harvested. Hence remuneration of these nutrients into the soil is required either by natural method or through the addition of fertilizers. Chemical fertilizers have been utilized progressively in recent times to enhance agricultural production and manage pests. Though, most chemical fertilizers have injurious impacts to both plants and microbes present in the soil. The application of organic fertilizers allows the microbes to break down the organic compounds that improve the physical, chemical, and biological characteristics of soil (Varjani and Upasani, 2019; Varjani et al., 2021b). The enhancement rate depends on the quality of organic fertilizers used and also the fertilizer composition.

Agro-industrial waste materials possess a high concentration of soil nutrients such as nitrogen, phosphorous, and potassium helpful for enhancing soil fertility and yield (Beesigamukama et al., 2021; Mohanty et al., 2021). They serve as a better alternative to chemical fertilizers in minimizing environmental pollution and managing sustainable agricultural soil (Adesra et al., 2021; Varjani et al., 2021b). Animal manure can be widely utilized as fertilizer and is rich in phosphorous content having a direct impact on plant growth. This also alters the physicochemical properties of soil such as increasing cation exchange capacity of soil, stability, and water holding ability resulting in increased productivity (Varjani and Upasani, 2019). Aggro-waste like compost of rice straw pretends to be a better inoculant carrier material. The energy for heterotrophic bacteria is provided through the biodegradation of complex molecules to simple sugars. This aids in increasing the soil nutrients helpful for plant absorption. The utilization of microbial inoculants in managing soil fertility and characteristics has been practiced continuously in recent years.

7. Application of LCA in agricultural circular bioeconomy

Life cycle assessment has emerged as an important technique for finding eco-friendly and economical outcomes and is mainly aimed at the agro-industrial sector. Major agricultural life cycle assessment analysis was dealt with either anyone concern about the agricultural sector. Studies were very limited on agricultural circular bioeconomy like examining the impact of using waste from the agricultural sector. Various contaminants are also released from different components of the agricultural system. Examining the agricultural circular bioeconomy completely alone can help in the identification of its effect on the ecosystem accurately (Sauve et al., 2016). Hence involving lifecycle assessment in analysing the influence of agricultural circular economy is considered to be a quantitative as well as a complete process. Fig. 1 demonstrates that LCA in agro-industrial circular bioeconomy.

The agricultural sector is more complex compared to the industrial sector due to many reasons: soil plays a major role in the agricultural sector, uncontrollable, diverse outcomes, data collection is difficult and also agricultural sector consists of various vague issues. So, when lifecycle assessment is established in the agricultural sector many issues such as complexity in data collection, diversity, and evaluation system. The agricultural circular economy is focused to produce more ecological advantages and economic benefits through the utilization of energy and materials effectively. It aids in minimizing ecological degradation, solving the problem of food safety, and reducing the energy crisis (Fang et al., 2021). Agricultural circular bioeconomy differs with climatic conditions and economic development. Models used for an agricultural circular economy are complex, consist of industries related to agriculture, cropping, fermentation, sewage plants, etc. This is important to examine the correlation between the other components before initiating lifecycle assessment.

The outcome units in the agricultural circular bioeconomy must be fitted into the sub-components properly, the flow of materials and energy among the sub-components must be monitored and finally, the input and outcome of the circular system between the ecological system must be described. By fitting these steps, the lifecycle assessment analysis tends to become more feasible and accurate by examining the circular economy model. Defining goals and scope are considered to be a significant factor in lifecycle inventory examination and assessing its effect. A component boundary between the original system and investigated component is depicted by the energy and material flow. For data comparison, a functional unit is used and is chosen for examination and ecological impact. The application of lifecycle assessment in agricultural systems directs to analyse the efficacy of agricultural outcomes in the environment and find out appropriate measures for enhancing the overall ecological efficacy of the agricultural outcomes and the progression of agricultural methods. The agricultural circular economy is a difficult system that follows the law of energy and material flow patterns. Henceforth it is mandatory to perform a lifecycle assessment of the agricultural system on a circular bioeconomy level.

Lifecycle inventory is more time-consuming and goes through the stage while performing lifecycle assessment owing to the collection of data and tends to become feasible once valid information is available. For data collection, three databases are available currently like registered database, public database, and restricted database. The database available for the agricultural system is less compared to the industrial sector. Few agricultural databases include Swiss Agricultural Life Cycle Assessment Databases and Denmark LCA food databases. These available databases can be utilized as a reference or as a comparative source as agricultural development and environmental conditions may vary among different countries. The information of agricultural lifecycle assessment is from the survey in agricultural fields, reference sources such as data collected by the release of carbon, nitrogen, etc, and yearbooks. However, the collection of data through these methods seems to be complex.

Lifecycle Impact Assessment involves three steps as Categorization, Characterization, and Normalization for examining and knowing the ecological effects. Categorization is the process of allocation and classifying the gathered data. Characterization is the method of assessing the quantity of every impact to its respective ecological impacts. It can be directly compared with the lifecycle inventory analysis. In normalization, the ecological impacts are made in comparison with others.

The examination of ecological impact can be accomplished through local levels such as effects from waste, universal levels such as global warming, and regional level such as acidification. Quantifying the amount of nitrogen oxide is the difficult part of agriculture. Assessment can be done through experts' examination, estimation of cost, and target distance. Of three methods, analysis of expert is considered to be feasible as the other two methods require problem of data collection. Lifecycle assessment interpretation is the method of elucidating results from lifecycle assessment inventory and for enhancing the technique and outcomes. A significant characteristic of the agricultural circular economy is the variance of outcomes in agricultural products. By framing proper data collection methods for the agricultural circular economy, lifecycle assessment can be made by researchers by avoiding difficulties in data collection and comparability. Introducing a multi-functional system in the agricultural circular economy can make the lifecycle assessment more extensive and structural which resembles a new way in this sector.

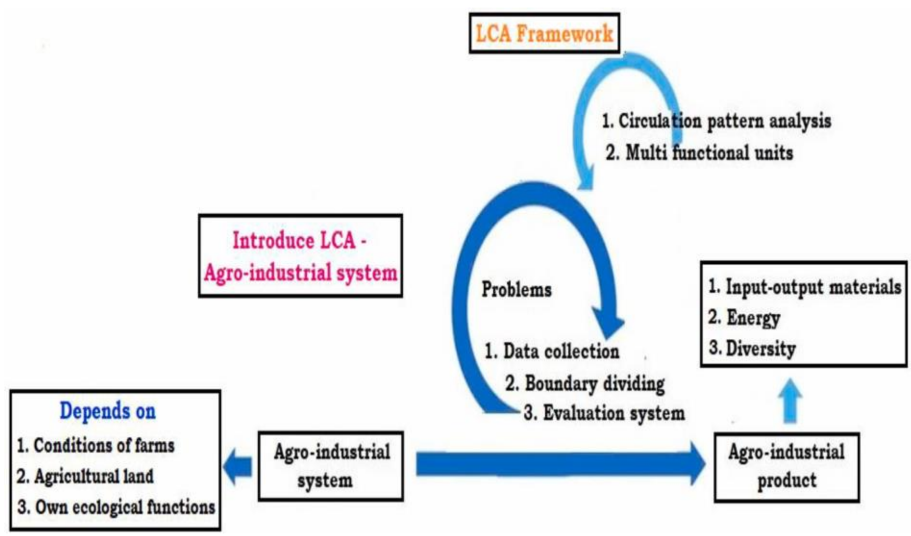

Fig. 1. LCA linkages with agro-industrial circular bioeconomy.

8. Novel methodologies, challenges and future perspectives

There exists a demand for development of novel outcomes and tools for examining and analysing agro-industrial waste valorization in circular bioeconomy. Efforts have been made to generate lignocellulose- based methodologies from agro-waste materials for production of value-added products such as fuels, chemicals, etc (Yaashika et al. 2019; Markande et al., 2021; Prajapati et al., 2021). The production of biofuels and energy from lignocellulosic biomass depends on two primary processes (i) Biochemical (ii)

Thermochemical. Biorefinery techniques provide efficiency to produce green, less cost, value-added products from widely available agro-industrial wastes. The important outcome of agro-waste obtained through fermentation is biohydrogen. Present commercially available hydrogen generation methods depend on water electrolysis and are energy-concerted (Pooja et al. 2021). In contrast, the production of biohydrogen and its application is environmentally friendly, green, feasible substitute for other fossil-based fuels. Agro- industrial wastes contain a rich source of biologically active species like antioxidants. Agro-industrial wastes can be drawn as a great origin for many bioactive components by using the concepts of circular bioeconomy and biorefinery. For a reliable future, there is a need to shift towards the 3Rs concept - Reduce Recycle and Reuse system. The primary challenge to developing lignocellulosic biomass is to low cost techniques to isolate significant components of lignocellulosic biomass (lignin, hemicellulose, and cellulose) and convert fractionated lignocellulosic biomass to monomeric substrates that can be directly utilized for chemical conversion to produce green products such as biofertilizers, platform chemicals, bioenergy, etc (Nagarajan et al., 2021). Combinations of mechanical and chemical methodologies have been considered to address this part of lignocellulosic biomass usage, with some interaction adaptability needed to address the way that various sources of lignocellulosic biomass have distinctive explicit lignin, hemicellulose, and cellulose content. To finish up, there is a critical need to renovate current biorefinery methodologies or create a sustainable biorefinery approach for utilization of agro-industrial wastes and expedite the large- scale production of biofuel.

9. Conclusions

Agro-industrial wastes have a huge potential to be revalorized for energy generation, and obtaining distinctive bioactive compounds. The reliability between agro-industrial waste management and its operative use is fundamental for fortifying world's economy to circularity. This review pinpointed that agro-industrial waste holds incredible potential to be used as an efficient alternative to fuel derivatives. Agro-industrial waste-based biorefineries are economically feasible as they escalate waste usage and recovery of bio based products. Furthermore, agro- industrial waste biorefineries contribute more to the circular bioeconomy and have expanded potential outcomes towards commercialization.

CRediT authorship contribution statement

P.R. Yaashikaa: Writing – original draft, Data curation. **P. Senthil Kumar:** Conceptualization, Supervision, Writing – original draft, Resources. **Sunita Varjani:** Conceptualization, Supervision, Writing – original draft, Resources.

Declaration of Competing Interest

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.

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