19 Agro-industrial Residues: An Eco-friendly and Inexpensive Substrate for Fungi in the Development of White Biotechnology

Akshaya Gupte, Darshankumar Prajapati, Ashish Bhatt, Shreya Pandya, Mehul Raghunathan, and Shilpa Gupte

Abstract

The population growth in the twenty-first century, constant exploitation of natural nonrenewable resources, and industrial pollution have forced humanity to look for alternative renewable resources, and so far the agro-industrial residues are one of the most suitable alternatives. Being rich in carbohydrates (cellulose and hemicellulose) and novel biochemical compounds (polyphenolics), agro-residues can be utilized by agricultural, biotechnological, pharmaceutical, and manufacturing industries. Being available abundantly in nature, they are cost-effective, renewable, low carbon-emitting, and eco-friendly in nature. These features make their way to bio-based refinery, and it is also one of the best ways toward green technologies and agro-waste utilization for the generation of value-added products. This chapter describes the wide range of agro-residues available and their application in the context of fungal white biotechnology.

Keywords

Agro-industrial residue · Renewable resources · Fungal white biotechnology · Polyphenols · Sugarcane bagasse · Biorefinery · Biofuel

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A. Gupte (✉) · D. Prajapati · A. Bhatt · S. Pandya · M. Raghunathan
Vallabh Vidyanagar, India
e-mail: akshaya@nvpas.edu.in

S. Gupte
Ashok and Rita Institute of Integrated Study and Research in Biotechnology and Allied Sciences, New Vallabh Vidyanagar, India

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19.1 Introduction

The rapid expansion of population and the constant growth of global economy have increased energy demand, and nearly 80% of this demand is met by using nonrenewable energy resources [1]. Fossil fuel consumption has resulted in greenhouse gas emissions, which have drastic effects on the climate. They are limited in nature and may even deplete in the near future [2]. Lignocellulosic biomasses are regarded as an effective and sustainable solution to this problem as they can fulfill the energy demand as well as reduce net carbon emission. Lignocellulosic biomass (LCB) is abundantly available in nature. LCB is a highly renewable, economical, and eco-friendly feedstock containing sugar polymers along with organic moieties such as lignin and suberin that can be processed to generate value-added products such as second-generation biofuels, organic acids, animal feeds, and bio-sourced compounds [3].

LCB has a complex three-dimensional structure, in which cellulose fibers are enveloped by the condensed structure formed by hemicellulose and lignin (Fig. 19.1). Cellulose is a homopolymer of glucose molecules which are linked by β-1,4-glycosidic linkage whereas hemicellulose is a heteropolymer which consists of a variety of sugars such as xylose, mannose, arabinose, and galactose. Lignin is composed of polyphenolic compounds (coniferyl alcohol, sinapyl alcohol, and coumaryl alcohol) that act as cementing material between cellulose fibers [4]. LCB can be categorized into biomass, virgin biomass, and energy crops. Trees, bushes,

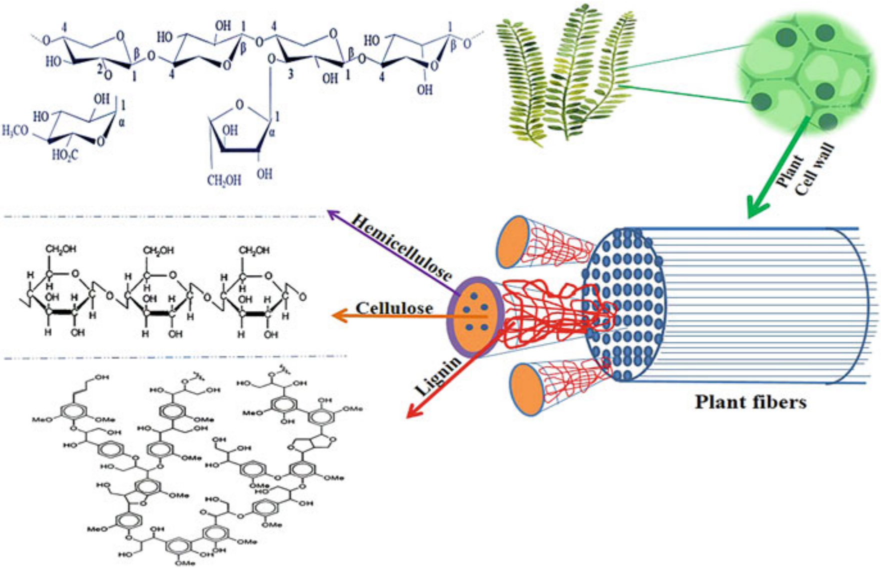


Fig. 19.1 Schematic representation of lignocellulosic biomass composition

and sand grasses are examples of virgin biomass, whereas agricultural residue, stover, and bagasse are examples of waste biomass. Energy crops are raw materials grown specifically for the production of second-generation biofuels as they offer high biomass to fuel conversion [5]. The conversion of LCB for the production of biofuels and energy is based on two main approaches. The use of biochemical processes involving enzymatic and microbial conversion is employed when LCB substrate has C/N ratio below 30 and humidity content above 30%. For the LCB substrates having C/N ratio higher than 30 and humidity content lower than 30%, thermochemical processes can be utilized. In recent years, attempts have been made to produce a wide range of new-generation biofuels such as biohydrogen, ethanol, butanol, dimethylfuran, levulinic acid, and gamma-valerolactone from LCB [6].

LCB is considered a good sustainable resource because of its abundant availability, renewability, low cost, and global mass production. Apart from biofuels, LCBs are used in wood processing industries, paper and pulp industries, biotechnological industries as well as nutrient-rich animal feed production. According to Qaisar et al. [7], the annual global production of LCBs was more than 180 billion tons and most of it remains unutilized. A small fraction of unutilized LCBs has been used as fodder for animals [8] or dumped in landfills. However, due to high transportation costs, the major part is incinerated on-site, which leads to severe problems of greenhouse emission and high particulate matter in the air. Therefore, utilization of LCBs for white biotechnological purposes will be a truly holistic and green approach, as it will not only provide the substrate for the production of value-added products but also reduce the problem of solid waste disposal land and air pollution.

19.2 Types of Agro-industrial Residues

In recent years, there has been a growing tendency toward more effective use of agro-industrial residues such as cassava bagasse, sugarcane bagasse, sugar beet pulp, coffee pulp/husk, apple pomace, and so on.

19.2.1 Sugarcane Bagasse

Saccharum officinarum is the scientific name for sugarcane, which belongs to the Gramineae family. It may be found in tropical and subtropical regions all over the world. It may reach a height of 8–20 feet and is roughly 2 in. thick. There are several distinct horticultural types, each with its unique stem color and length. About 200 nations grow sugarcane, and Brazil is the world's largest producer, accounting for roughly 25% of global output. India, Pakistan, China, and Thailand are the next major producers. India is the world's second-largest sugarcane producer. Sugarcane is commonly used to make falernum, sugar, rum, soda, molasses, and ethanol for transportation. Bagasse has a low ash content, which makes it ideal for use in bioconversion processes involving microbial cultures. Bagasse may also be regarded a rich solar energy reservoir in comparison to other agricultural residues due to its high yields (about 80 tons/ha vs. 1 ton/ha for wheat, 2 tons/ha for other grasses, and 20 tons/ha for trees, respectively) and yearly regeneration ability [9].

Sugarcane bagasse is very rich in cellulose and hemicellulose content, i.e., 50% and 25%, respectively. It also contains about 25% of lignin as well as minimum ash content. To be more specific, there is about 50% α-cellulose and 30% pentosans, with 2.4% ash content [9]. Because of having very high amount of cellulose and hemicellulose, sugarcane bagasse is considered one of the most promising sources of carbon and energy. Sugarcane bagasse, a rich source of energy and carbon, is widely utilized as raw material for the production of various biotechnologically significant products such as organic acids [10], enzymes [11], animal feed [12], mushrooms [13], bioplastics [14] as well as biofuels [15]. Moreover, it is also used for the generation of electricity and paper production.

19.2.2 Cassava Bagasse

Cassava (*Manihot esculenta* Crantz) is a short-lived perennial that grows 1– 5 meters tall and belongs to the Euphorbiaceae family. Cassava is originated in South America, most likely in eastern Brazil. It is a bushy plant with aerial and subterranean portions that produce tubers. With a trunk and branches, the height of the aerial section can reach up to 4 meters. The subterranean portion is composed of two types of roots: those that provide nourishment to the plant and those that are arranged axially around the stem. These are known as tubers and are the plant's edible portions. After rice and corn, the tropical root crop cassava (*Manihot esculenta* Crantz) is the third most important source of calories in the tropics [16].

Industrially, cassava tuber processing is mostly done to extract flour and starch, which results in more liquid and solid residues (processing for flour produces solid residues, while processing for starch produces liquid residues) [17]. Brown peel, inner peel, useless roots, bagasse, and flour trash are examples of solid residues, with bagasse being the most common solid residue. Apart from this, cassava bagasse has also been used for the preparation of nanofibers [18].

19.2.3 Oil Cakes

Oil cakes are solid remnants leftover after expulsion or solvent extraction of oil from a plant component like a seed. Edible oil cakes are made from edible oil-bearing seeds that are utilized to cover a portion of the nutritional needs of either animal feed or human consumption. On the other hand, nonedible oil cakes are made from seeds that do not contain poisonous chemicals or other contaminants [19]. The chemical composition of different oil cakes are described in Table 19.1.

Nonedible oil cakes, made from neem, castor, mahua, and karanja, are commonly utilized as manures. Soybean cake, rapeseed cake, cottonseed cake, groundnut cake, sunflower cake, copra cake, and linseed cake are the most popular edible oil cakes in the world [21]. Soybean cake accounts for 54% of the overall production volume of

Table 19.1 Chemical composition of major oil cakes (adapted from [20])

Oil cakes	Dry matter (%)	Carbohydrate (%)	Crude protein (%)	Fat (%)	Crude fiber (%)	Ash (%)
Sunflower	93	23.0	35.6	1.68	28.41	7.36
Copra	89.9	42.4	20.9	8.0	11.5	5.5
Sesame	93.9	21.0	48.2	2.3	6.4	12.6
Soybean	90.3	23.6	51.8	0.9	17.8	7.3
Rapeseed	90.75	32.2	42.8	4.1	12.1	7
Olive oil	72.8	10.1	4.77	8.72	49.14	2.36
Linseed	88.9	36.0	33.2	2.8	8.1	5.4
Groundnut	90	14.1	45.6	2.47	8.3	5.02
Safflower	93.1	20.1	44	5.9	12.1	7.2
Palm kernel	93	45.5	17.5	7.4	11.9	4.8
Cottonseed	91.53	27.0	41.5	5.75	14.67	6.46

the different types of oil cakes mentioned above, with rapeseed cake accounting for 10% and cottonseed cake accounting for 10%.

Oil cakes have major potential for the production of various industrially significant products. Various microbial enzymes including amylase [22], lipase [23], xylanase [24], tannase [25], protease [26], and phytase [27] have been produced using a single type of oil cakes or with a combination of different oil cakes, as a raw agro-industrial residue. Oil cakes have been used not only as raw materials but also as media supplements, by extracting them in the form of soy peptone trypticase soy agar, soy protein isolate or concentrate as well as soy flour, which supplements the needs of nitrogen sources in the culture media [28]. Moreover, oil cakes have also been used for the production of secondary metabolites. Soybean cake and cottonseed cake were used as nitrogen sources for the production of antibiotics [29]. In addition, oil cakes have also been explored for the production of secondary metabolites such as biosurfactants, which have potential applications in bioremediation, microbial enhanced oil recovery (MEOR), and food processing industries [30].

19.2.4 Cereal Straw and Bran Residues

Cereal straw is one of the world's most abundant and renewable lignocellulosic waste materials with a great potential in white biotechnology. The estimated global yield of cereal straw is 2.9 billion tons per annum [31], which directly displays the abundance of agricultural waste biomass available to be utilized as a renewable resource. There are various crops such as wheat, barley, rice, oats, and rye, which are incorporated under the title "cereals." The nonedible parts of these crops, straw and bran, are important agro-residues. Cereal straw is made up of a high percentage of biological macromolecules such as lignin, cellulose, and hemicellulose. Both cellulose and hemicellulose are polymers of sugar monomers linked via glycosidic

Table 19.2 Chemical composition of various agro-residues

Agro-industrial substrate	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Cellulose/ lignin	References
Wheat straw	31.5–39.5	21.2–29.0	5.6–15.0	2.2–5.3	[33]
Rice straw	22.8–38.4	17.7–28.5	6.4–18.0	3.6–5.9	[34]
Rice husk	28.0–43.0	17.5–20.6	21.5–22.5	1.3–1.9	[35]
Corn stover/husk	36.4–40.0	25.0–29.0	13.0–21.0	2.1–2.3	[36]
Corn cobs	28.0–45.0	35.0–43.0	11.0–17.0	2.5–2.7	[37]
Cotton hulls	52.0–90.0	5.0–20.0	4.0–12.0	5.0–11.2	[38]
Sugarcane bagasse	26.6–40.0	19.0–30.0	19.0–23.3	1.4–2.2	[39]
Soft wood chips/ sawdust	37.7–49.5	10.7–25.0	26.1–29.5	1.4–1.7	[40]
Hard wood chips/ sawdust	42.9–45.1	22.0–33.0	24.0–26.0	1.7–2.0	[41]
Coffee pulp/husk	23.0–29.1	15.1–17.1	13.0–26.0	0.89–0.94	[42]

linkages. Upon hydrolysis, some sugars can be fermented into various products such as acetic acid, levulinic acid, ethanol, and acetone. Moreover, these sugars can also be used for the fermentation of antibiotics and enzymes [32].

Chemically, agro-residues are mainly composed of cellulose, hemicellulose, and lignin, where their proportion varies with different types of residual substrates (Table 19.2).

Cereal straws such as rice straw, wheat straw, barley straw, oats straw, and rye straw as well as bran residues are one of the most abundant agricultural residues in the world. For long, humans have used these residues for various purposes.

Since ancient times, people are used to burning the residual biomass on the fields and also utilizing as a firewood fuel to generate energy as the direct combustion is easy and economic. However, the incomplete combustion imposes serious environmental pollution problems due to low combustion efficiency. Recently, researchers have been working on improving calorific values and combustive efficiency of various straw and bran residues [43], which may enhance the usage of straw for the production of industrially significant products. Moreover, the agro-waste and fibrous lignocellulosic materials have been intensively utilized in paper and pulp industries since the third century BC [44]. Paper and pulp industries are always interested in the cellulosic portion of the lignocellulosic biomass. Thus, the remaining part containing lignin and hemicellulose is almost wasted in the form of black liquor. This black liquor also contains strong acids and alkali, which not only cause severe water pollution problems but also increase the cost of the process. Thus, researchers are involved in the development of some novel biotechnological processes that may be cost-effective as well as eco-friendly. Such biotechnological processes may involve the application of fungal enzymes, organic acids, and biosurfactants.

In addition, cereal straws and bran residues have also been used as animal feed. Some countries such as Australia and New Zealand have enough grasslands which can afford forage-based animal husbandry whereas other developed countries such as Switzerland and the United States can meet the expense for grain-based animal husbandry. In contrast, countries such as India and China have high population-to-land ratio; thus they cannot afford forage or grains for their fast-growing animal husbandry [45, 46]. Therefore, abundant straw and bran residues can be considered as sustainable resources for animal feed. However, the direct usage of such residues as animal feed is limited due to their complex composition having higher amounts of lignin and lower amounts of proteins, which results in poor digestibility and, as a result, lower nourishment [47]. It is reported that ruminants such as sheep and cattle can only digest about 50% of the ingested straw; on the other hand, pig can digest maximally up to 25% [48]. Thus nowadays it has become necessary to improve the digestibility and protein content of straw residues using various straw processing technologies such as silage and straw ammonization.

19.2.5 Banana Pseudostem

Banana is one of the tallest monocotyledons herbaceous plants [49]. The banana plant belongs to the Musaceous family. Banana is the oldest and most economically significant cultivated crop in the world. The banana plant is also known as a cash or staple crop. Bananas originated from Southeastern Asia and the Western Pacific region [50]. Banana plants are also referred to as a "Kalpathru," a plant of virtues [51]. The meaning of banana is a finger, and the word comes from Arabic "Banaana" or "Banaan" which means finger tiles [52]. The banana plant is grown all over the world. Banana is the fourth largest cultivated fruit in the world after grapes, citrus, and apple fruit [53]. India, China, Philippines, and Brazil are the maximum banana-producing countries. In 2020, the production of banana fruit in the world reached 20 million tons. India produced 32 million metric tons of banana in 2020. India contributes 26% of the world's banana production.

Banana pseudostem is made up of tightly packed, overlapped twisting leaf sheaths with a central core and because of this, the stem of banana is called "Pseudostem" [54]. Banana plants produce only one bunch of bananas during the life cycle. After harvesting the bunch of bananas, the residues (banana pseudostem) are left on the plantation as a waste. It generates disposal and environmental problems [55]. Such problems can be reduced by using banana pseudostem in the preparation of value-added products. Banana pseudostem is also used in solid-state fermentation as a solid material.

Each part of the banana pseudostem is useful in the preparation of value-added products. Li et al. [56] reported that the banana pseudostem is a good source of holocellulose and low amount of lignin which make the banana pseudostem an excellent source for pulping and papermaking. Sap, fibers, central core, and sutures are four parts of banana pseudostem that can be utilized in order to prepare value-added products such as mordants, liquid fertilizers, microcrystalline cellulose, fabric, yarn, candy, pickles as well as compost.

Banana pseudostem sap is an extract of banana pseudostem which is brown in color. Banana pseudostem is known for its medicinal and industrial applications.

Thorat and Bobade [55] reported that the juice of the banana pseudostem is beneficial in dissolving the stone in the kidney and urinary bladder. The sap of the banana pseudostem is also effective against the jaundice. In addition, sap has also been used as a natural mordant in the dying processes [57].

Banana pseudostem is made up of 14-18 leaf sheaths which are mainly divided into three parts, i.e., outer sheath, intermediate sheath, and central core. The fibers of the outer sheaths are very brittle and can be easily broken down. The central core is a pulpy matter which is not useful for fiber extraction. Thus only the intermediate sheaths are used for the production of fibers. The fibers can be extracted either mechanically, chemically, or enzymatically using fungal enzymes such as laccases, pectinases, and cellulases. This banana fiber has many applications such as in the preparation of yarns, handicrafts, handbags, ropes, purses, carpets, tissue papers, microcrystalline cellulose (MCC), and doormats [52, 58]. Many researchers reported that the banana pseudostem fibers are rich in cellulosic content [54, 59]. In particular MCC can be prepared by treating α-cellulose by using chemical or biological or physical treatment [60]. MCC has an excellent property in pharmaceutical, food, and cosmetic industries. MCC is used in pharmaceutical industries as a binder or adsorbent, in food industries as a stabilizer, thickener, emulsifier, anticaking or bulking agent due to the excellent binding property, and in polymer composite as a mechanical reinforcing agent [61].

19.3 Lignocellulosic Biomass-Based Biorefinery: A Circular Economy Approach

A circular economy is “a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible” [62]. Fungal biotechnology has the ability to utilize the agro-industrial waste and the ability for sustainable production of irrepressible sources of feed, food, fuels, chemicals, construction materials, textiles, automotive and transportation industries and beyond. As well as it can advance the transition from petroleum-based economy into a bio-based circular economy [63].

Biorefinery is an emerging concept which is an amalgamation of biomass conversion processes and industrial facility for the production of producing fuels, power, chemicals, and a variety of other value-added products from biomass, using a wide range of technologies (Fig. 19.2) [5]. Consequently, the concept of biorefinery is considered analogous to that of petroleum refinery with the main difference of using renewable plant-derived materials instead of nonrenewable fossil-derived petroleum crude [64, 65]. The wide range of technologies employed in biorefinery can provide bio-based products such as biomaterials (fibers and pulp for paper industries, composite materials, hydrogels), biofuels (ethanol, biodiesel, butanol, and methane), and a variety of biochemical compounds (levulinic acid, acetic acid, polysaccharides, etc.) through fractionation, fermentation, and purification processes. Therefore agro-industrial residues have a wide range of application as

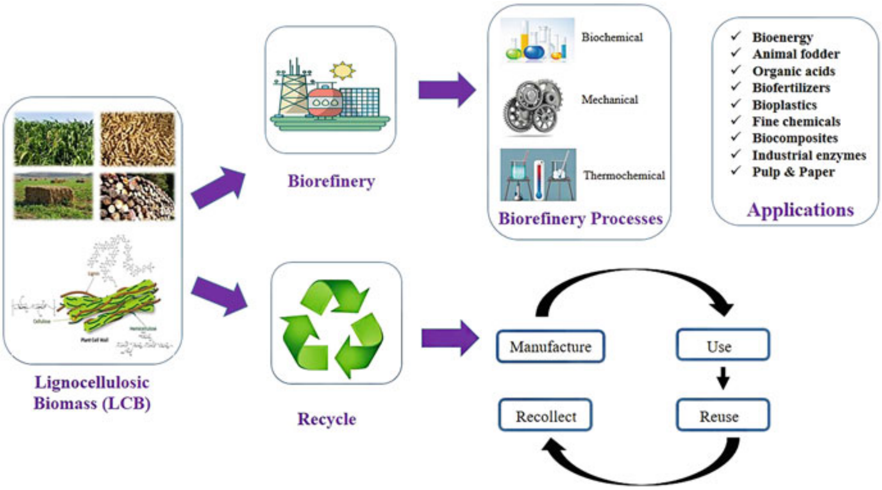


Fig. 19.2 Bio-based refinery processes and their applications

an alternative to nonrenewable resources which makes it a valuable commodity around the globe [66].

19.4 Major Applications of Agro-industrial Residues

19.4.1 Agro-residues in Biotechnologically Significant Enzyme Production

Agro-residues are a rich source of nutrients which can be utilized to support the growth and development of microbes for the purpose of production of various enzymes such as laccase, xylanase, cellulase, and xylosidases[67]. Table 19.3 is a compilation of enzymes produced from various agro-industrial wastes.

19.4.1.1 Laccase

Laccases produced by fungi are very crucial and more important at the industrial level. Laccases have wide applications in various fields such as textile, pharmaceutical and chemical industries, food industry, wood processing, and many more. Laccases (E.C. 1.10.3.2) belong to the class oxidoreductase, which has the ability to oxidize diphenols as well as can use the molecular oxygen as electron acceptor. Laccases belong to a category of polyphenol oxidases which contain copper atom in the catalytic center and therefore are called multicopper oxidases [81]. Fungal genera belonging to Ascomycetes, Deuteromycetes as well as Basidiomycetes have been reported for their laccase production capabilities.

Rebhun et al. [82] reported laccase production using agro-industrial waste with the help of white-rot basidiomycetes such as *Cerrena unicolor* and *Cucurbita*

Table 19.3 Production of industrially significant enzymes from LCB using fungi

Agro-industrial substrate	Fungal species	Enzymes	References
Wheat straw, rice straw, wheat bran, rice bran	*Fusarium incarnatum* UC-14, *Trametes versicolor,* *Phanerochaete chrysosporium,* *Pleurotus ostreatus* HP-1	Laccase	[68–71]
Finger millet, bajra, barnyard millet, paddy, maize stover, jowar, foxtail millet, proso millet straw	*Aspergillus flavus* *Ganoderma lucidum* IBL-05 *Phanerochaete chrysosporium*	Lignin peroxidase	[72, 73]
Wheat, straw, oil palm empty fruit bunches	*Aspergillus tubingensis* JP-1 *Aspergillus sp.* LPB-5	Xylanase	[74, 75]
Wheat bran, textile wastes consisting of cotton and polyester	*Trichoderma reesei* NCIM 1186 *Penicillium citrinum* NCIM 768 *Aspergillus niger* CKB	Cellulase	[76, 77]
Wheat bran, mosambi peel, mosambi bagasse, lemon peel, rice bran, banana peel, sugarcane bagasse	*Aspergillus oryzae*	Pectinase	[78]
Oil palm cake	*Pseudolagarobasidium sp.* PP17-33	Manganese peroxidase	[79]
Lime, grape, tangerine, and sweet orange peels	*Penicillium italicum* and *Trichosporonoides oedocephalis*	Mannanase, xylanase	[80]
Barley bagasse	*Trichoderma koningiopsis 2OI2A1M*	β-xylosidases, xylanase, β-glucosidases	[17]

maxima and conclude that wheat bran was the excellent substrate for growth and for fermentation by *C. unicolor*, enabling a better production of laccase (87.450 IU/L on day 7). Freixo et al. [83] utilized tomato pomace as the only carbon source and reported the maximum laccase production after the third day (362 U/L of fermentation broth). Birhanli et al. [84] utilized lignocellulosic wastes such as sunflower receptacle, apricot seed shell, and bulrush for laccase production under semisolid-state and submerged fermentation (SMF) conditions from *Trametes trogii* (Berk.). Wang et al. [85] reported the increased laccase production by *Trametes versicolor* using corn steep liquor as both nitrogen source and inducer. At present the focus has been on using a mixture of agro-residues, instead of individual ones. An et al. [86] reported that laccase production in *P. ostreatus* was improved after inclusion of cottonseed hulls with corncob and straw. In a recent study involving the use of *Lentinus strigosus* isolated from Amazon, a total of 176.23 U/mL laccase activity was reported after 6 days and as a substrate mixed lignocellulosic biomass was used, which is composed of cellulose (19.16%), hemicellulose (32.83%), and lignin (6.06%) [87].

19.4.1.2 Cellulase

Cellulose is one of the most plentiful carbohydrates in plants. Structurally, cellulose is a linear biopolymer of hydroglucose units linked by the β-1,4-glycosidic linkages. The enzyme employed for cellulose hydrolysis is cellulase (E.C. 3.2.1.4), which decomposes cellulose into shorter oligomeric chains like cellodextrin, cellobiose, and monomeric sugar units like glucose. Depending on the structure and function, cellulases can be categorized into three categories, viz. endoglucanases, exoglucanases or cellobiohydrolases, and β-glucosidases or cellobiases. In spite of being classified into different categories, these enzymes work collaboratively and in a coordinated manner to catalyze the hydrolysis of the complex cellulose. According to the classical hydrolysis theory, endoglucanases randomly hydrolyze the cellulose chains along the amorphous regions by a mechanism of adsorption and desorption and in turn produce cellodextrin. On the other hand, cellobiohydrolases gradually hydrolyze the crystalline cellulose regions from either the reducing or nonreducing end that liberate cellobiose as their main product whereas β-glucosidases hydrolyze the released soluble cello-oligomers to monomeric glucose units [88].

Picart et al. [89] using rice straw produced cellulase by *Penicillium* sp. And the enzyme reported was stable at temperature 65 °C and pH 4–5. Waghmare et al. [90] compare various agriculture wastes like sorghum husks, grass powder, corn straw, paddy straw, sugarcane bagasse, and sugarcane barbojo for cellulolytic enzyme production; the best carbon sources for enzyme production was grass powder and sugarcane barbojo. Olajuyigbe et al. [91] reported the production of thermostable crude cellulase enzymes on corncob by *Sporothrix carnis*. The highest production of enzyme achieved was at 96 h with 2.5% inoculum, activity (285.7 U/mL), pH 6.0, and temperature 80 °C. Perez et al. [92] isolated thermophilic fungi *Myceliophthora thermophila* and reported 18.75 U g^{-1} d^{-1} cellulase activity using sugarcane bagasse and wheat bran as a substrate. Rayhane et al. [93] utilized a mixture of lignocellulosic residue consisting of vine shoots, jatropha cake, olive pomace, and olive oil to produce cellulase using *Trichoderma asperellum*. In one of the important studies recently, Laothanachareon et al. [94] investigated the effect of various agro-residues on cellulase production by using 23 different strains of *Aspergillus niger* and concluded that CMCase and β-glucanase activity as only appeared when carbon source was switched from basal sugar medium to agro-residue biomass (sugarcane bagasse).

19.4.1.3 Hemicellulases

Hemicellulases are a group of enzymes that break down hemicellulose, which is a major component of plant cell walls. Hemicellulases target different types of hemicelluloses such as pentosans, xylans, galactans, mannans, and glucans. Hemicellulases are equipped with functional modules that are capable of digesting glycosidic bonds as well as esterified side chain groups. Acetyl and feruloyl esterases hydrolyze acetate or ferulic acid side groups in the plant cell wall structure. Some of the most common hemicellulases that act upon glycosidic bonds include α-glucuronidases, α-arabinofuranosidases, α-d-galactosidases, and mannanases.

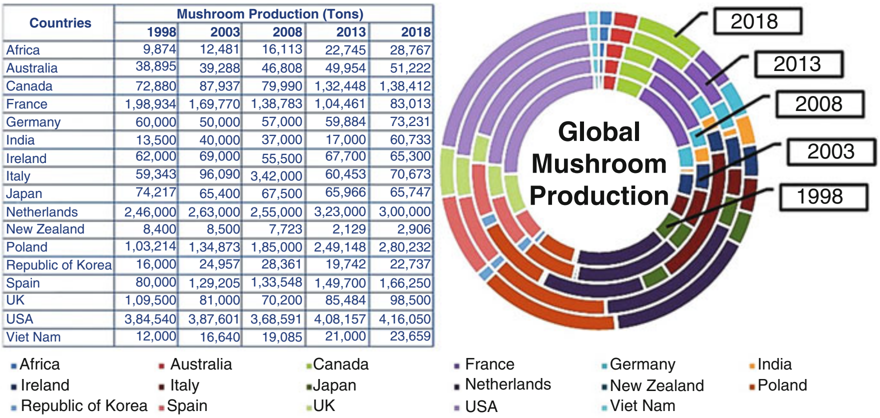
Among hemicellulases, xylanase (EC 3.2.1.8) is a class of enzymes that degrade the linear polysaccharide xylan into xylose, thus breaking down hemicellulose, one of the major components of plant cell walls. Xylans principally consist of D-xylose as its monomeric unit and traces of L-arabinose [95]. The use of easily available and cost-effective agriculture residues such as wheat bran, corncobs, and wheat straw provides suitable methods to achieve higher xylanase yields. Gawande et al. [96] evaluated many lignocellulosic residues such as wheat bran, sugarcane bagasse, rice straw, and soya bean hulls for xylanase production from *A. terreus* and *A. niger*. Highest xylanase production was observed in wheat bran. Milagres et al. [97] showed the production of high level of thermostable xylanase (1597 U/g xylanase activity) after 10 days of SSF from *Thermoascus aurantiacus*. Patel and Prajapati [98] reported wheat husk, rice bran, and rice straw as efficient agro-residues for xylanase production by using *Cladosporium sp.,* and the maximum xylanase activity was found with rice bran. Cunha et al. [99] optimized the production of xylanase by *Aspergillus foetidus* using soybean residues and achieved 13.98 U/mL enzyme activity. Most recently Ismail et al. [100] isolated *Aspergillus flavus* AW1 which was able to produce xylanase using corn cobs as a substrate.

19.4.1.4 Pectinase

Pectinases are a group of enzymes that break down pectin, a polysaccharide found in plant cell walls, through hydrolysis, transelimination, and deesterification reactions. Among the agro-residues fruit waste and peels are a rich source of pectins and potentially can be used for the production of pectinase. Rangarajan et al. [101] suggested orange peel as an important agro-residue that can be used to produce pectinase and reported exopectinase activity of 6800 IU/g with orange peel extract using *Aspergillus niger*. Satapathy et al. [102] were able to produce 1366.30 U/mL pectinase using *Aspergillus parvisclerotigenus* KX928754 in liquid static surface fermentation, 973.12 U/mL with sugarcane bagasse, and 686.7 U/mL with spent tea residues.

19.4.2 Agro-industrial Residues in Mushroom Cultivation

A large quantity of agricultural crop residues in terms of lignocellulosic waste as well as organic content rich agro-industrial by-products is generated annually, which are worth getting recovered and transformed into value-added products. These agro-residues have been utilized for the production of industrially significant organic acids, biosurfactants, enzymes, biofertilizer or biopesticide, flavors, ethanol, bioactive secondary metabolites, animal and aquaculture feedstocks, therapeutic compounds as well as edible and medicinal mushrooms, and also for bioremediation of hazardous compounds, biological detoxification of agro-industrial residues, and



Countries	Mushroom Production (Tons)				
	1998	2003	2008	2013	2018
Africa	9,874	12,481	16,113	22,745	28,767
Australia	38,895	39,288	46,808	49,954	51,222
Canada	72,880	87,937	79,990	1,32,448	1,38,412
France	1,98,934	1,69,770	1,38,783	1,04,461	83,013
Germany	60,000	50,000	57,000	59,884	73,231
India	13,500	40,000	37,000	17,000	60,733
Ireland	62,000	69,000	55,500	67,700	65,300
Italy	59,343	96,090	3,42,000	60,453	70,673
Japan	74,217	65,400	67,500	65,966	65,747
Netherlands	2,46,000	2,63,000	2,55,000	3,23,000	3,00,000
New Zealand	8,400	8,500	7,723	2,129	2,906
Poland	1,03,214	1,34,873	1,85,000	2,49,148	2,80,232
Republic of Korea	16,000	24,957	28,361	19,742	22,737
Spain	80,000	1,29,205	1,33,548	1,49,700	1,66,250
UK	1,09,500	81,000	70,200	85,484	98,500
USA	3,84,540	3,87,601	3,68,591	4,08,157	4,16,050
Viet Nam	12,000	16,640	19,085	21,000	23,659

Fig. 19.3 Worldwide mushroom production (Data source: FAOSTATS—Food and Agriculture Organization [111])

biopulping under solid-state fermentation (SSF) with the help of fungi from Ascomycetes and Basidiomycetes [103–107].

Cultivation of mushrooms is one of the prominent biotechnological processes for agro-waste valorization. Mushroom cultivation is an economically feasible and widely performed SSF process in which nutrients available in lignocellulosic material are transformed into mushrooms [108]. There are a number of agro-residues including wheat straw, rice straw, cotton stalks, sugarcane bagasse, cassava bagasse, banana pseudostems, wheat bran, sawdust, wood chips, peanut shells, coffee pulp and husk, sunflower seed, cottonseed hulls, and corn cobs which possess some potential chemical properties that make them suitable substrates for SSF [107, 109]. According to Uthandi et al. [110], ample amounts of agro-residues are generated upon processing of agricultural crops including wheat, paddy, maize, and sugarcane. About 0.75 tons of straw is generated per one ton of paddy, 300 kg of bagasse is generated per one ton of sugarcane, and an equal proportion of stover is generated upon corn processing.

However, the types and composition of the substrate utilized for mushroom production directly or indirectly impose its impact on the growth of mycelia, mushroom yield as well as nutritional and medicinal properties of produced mushrooms. Mushrooms are cultivated around the world for many years. Commercial worldwide mushroom production data are incorporated in Fig. 19.3.

Different edible mushrooms have been consumed for long for their nutritional values, flavor, and aroma. These mushrooms are nothing but the fruiting bodies of the white-rot or sometimes brown-rot fungi.

Mushrooms are a good source of carbohydrates, lipids, proteins along with fibers and minerals; thus they provide substantial health benefits to the consumers. The nutritional properties of edible mushrooms are summarized in Table 19.4.

Such nutritionally rich mushrooms are produced upon solid-state fermentation of various residue-based substrates by white-rot/brown-rot mushroom fungi. For the

Table 19.4 Nutritional values of edible mushrooms

Mushroom	Nutritional value Protein (g/100 g)	Carbohydrate (g/100 g)	Lipid (g/100 g)	Fibers (g/100 g)	References
Pleurotus	17–42	37–48	0.5–5	24–31	[112]
Ganoderma	13.3	82.3	3.0	–	[113]
Agaricus	56.3	37.5	2.7	–	[88]
Tricholoma	18.1–30.5	31.1–52.3	2–6.6	30.1	[114]
Phellinus	6.11–10.9	75.04–83.82	0.96–15.86	–	[115]
Grifola	21.1	58.8	3.1	10.1	[116]
Auricularia	7.2	88.6	1.7	–	[117]
Lentinus	26.3	65.1	2.3	–	[118]
Cordyceps	21.9	24.2	8.2	–	[119]
Flammulina	3.9–17.8	8.6–70.8	1.8–2.9	–	[118]

bio-based production (SSF) of such mushrooms, availability of the lignocellulosic biomass substrate is the primary element. In the field, large amounts of residues are generated, but in contrast very small amounts are utilized for different purposes. The total availability of agro-residues for biological processing is dependent on various parameters, including total production, moisture content, leftover residues on soil to maintain soil organic content, animal feed in terms of grazing, and other agro-activities [120].

As fungal growth is influenced by nutrient availability, the production of mushrooms is influenced by the chemical composition of the lignocellulosic substrate used. Moreover, some other macro- and micro-elements including potassium, calcium, phosphorus, magnesium, manganese, sulfur, iron, zinc, boron, and molybdenum occur in agro-residues which help the growth of fungi at lower concentrations.

Fungi efficiently utilize these complex agro-industrial residues with the help of an array of enzyme system. These enzyme systems possess various enzymes that catabolize the degradation of cellulose (cellulase), hemicellulose (hemicellulase), lignin (laccase, lignin peroxidase, manganese peroxidase) as well as other accessory enzymes such as xylanase, hydrolase, endo- and exoglucanase, cellobiohydrolase, and glucosidase. These enzymes convert complex substrates into utilizable nutrients which favors the growth of fungi. In addition to the nutrients, there are certain factors such as moisture, water activity, temperature, and light that regulate the growth of fungal mycelia as well as fruiting [121].

Thus, agro-industrial wastes are extensively used for the cultivation of mushrooms around the world.

19.4.3 Agro-industrial Residues in Animal Feedstock Preparation

Animal nutrition is one of the rising concerns worldwide. Agricultural, dairy, and food industry waste products including lignocellulosic waste, vegetables, fruits, whey as well as waste from sugar processing industries have the great potential solution toward animal nutrition issues.

Agricultural residues such as bagasse, straw, husk, cobs, and stovers are argued to be the most abundant agricultural waste [122]. Although being abundantly generated, their availability as animal feed is limited. Animals may get good amounts of cellulose and hemicellulose from these agricultural wastes, but their application as an animal feed is constrained due to lack of proteins, oils, vitamins, and minerals. Thus in order to use these residues as an animal feed, they must be enriched to increase the nutrients, especially protein content. However, nutrient enrichment can be done with the help of microbes like bacteria and fungi.

Solid-state fermentation (SSF) is one of the most preferred biotechnological processes that can be employed for the nutritional enrichment of agricultural wastes to be used as animal feed. SSF provides convenient environment and conditions which are similar to that of the natural conditions and thus stimulates the growth of filamentous fungi. Various fungi that have already been used in preparing enriched animal feeds are listed in Table 19.5.

Many researchers have also worked on protein enrichment of various fruit and vegetable wastes. Kot et al. [140] reprocessed the potato pulp and wastewater for the enrichment of protein content. Villas-Boas et al. [141] have reported about 500% enrichment of protein using *Pleurotus ostreatus* in apple pomace and furthermore employed in food preparation. Moreover, to increase the nutritional value and digestibility, various food grade enzymes have also been employed as supplements or additives during animal feed preparation [142].

Although agro-industrial raw materials are available and feed production is cheaper, the logistic costs constrain faster development of such production technologies, further making the product costly. Moreover, this technology is somewhat labor intensive and time consuming. There is thus a challenge in improving and developing economically feasible, less time-consuming, on-site applicable and scalable technologies for enrichment and production of animal feed.

19.4.4 Agro-industrial Residues in Production of Bioactive Secondary Metabolites

Secondary metabolites are synthesized by microorganisms during the late log or stationary phase of their life cycle, which are not essential for reproduction and normal growth of an organism. These secondary metabolites may be antibiotics, polysaccharides, alkaloids, terpenes, and steroids, which are economically significant industrial products [143].

The most commonly used technology for production of secondary metabolites is microbial fermentation. Among different fermentation methods, submerged

Table 19.5 Preparation of protein-enriched agro-industrial residues using fungi

Fungal species	Agro-industrial substrate	Improvement in feed product	References
Microsphaeropsis spp., Coprinus fimetarius, Phanerochaete chrysosporium, Pleurotus ostreatus, Neurospora sitophila, Trametes spp., Ganoderma spp., Trichoderma spp.	Wheat bran/straw/corn stover/buckwheat/millet, sugar beet pulp, citrus waste, mustard straw, bean straw, agave bagasse Perennial grass	Protein-enriched straw/feed Edible and medicinal mushrooms	[123–129]
Pleurotus spp.	Coffee pulp; coffee husk	Protein-enriched biomass	[130, 131]
Rhizopus oligosporus, Penicillium funiculosum, Myrothecium verrucaria	Apple pomace, apple waste, apple pulp, grape	Protein-rich fungi and feed	[132–134]
Rhizopus oryzae, Cephalosporium eichhorniae, Lentinus spp.	Cassava wastes (peels; slurry; bagasse; wastewater), cassava Tubers, & starch	Animal feed and food, protein-enriched biomass, edible mushroom; protein-enriched flour	[135–137]
Aspergillus niger	Lupin meal	Improvement of fish growth, feed performance, and gut morphology	[138]
Pleurotus eryngii	Wheat bran	Increase in lignocellulolytic enzymes activity	[29]
Beauveria bassiana, Fusarium flocciferum	Olive cake	Increase in protein content and decrease in phenolic and flavonoids content	[139]

fermentation (SmF) is widely used because the scale-up procedures are quite easier and production parameters are easy to manipulate. Moreover, the control over various parameters such as pH, temperature, and nutritional requirements is better under SmF. However, to use agro-industrial residues for the production of secondary metabolites, SSF must be opted. SSF is comparatively a labor-intensive process, but on the other hand it provides natural environment to the organisms for biological processes.

Fungi are quite ideal for SSF system than bacteria, as they have capability to grow and flourish under lower water activities. There are a large number of fungi capable of producing such biologically active secondary metabolites using agro-industrial residues (Table 19.6).

Table 19.6 Preparation of fungal secondary metabolites from agro-industrial residues

Agro-industrial substrate	Fungal species	Secondary metabolite	References
Barley	*Cephalosporium acremonium*	Cephalosporin	[144, 145]
Corn	*Fusarium moniliforme*	Zearalenone	[146]
Rice, rice bran, rice husk	*Metarhizium anisopliae*	Destruxins A and B	[147]
Sugarcane bagasse	*Claviceps purpurea, C. fusiformis*	Ergot alkaloids	[148, 149]
Sugarcane bagasse	*Penicillium chrysogenum*	Penicillin	[150]
Wheat bran	*Tolypocladium inflatum*	Cyclosporin A	[148]
Wheat bran	*P. brevicompactum*	Mycophenolic	[151]
Wheat bran, corn cob, cassava flour, grains	*Gibberella fujikuroi, Fusarium moniliforme*	Gibberellic acid	[152, 153]
Wheat, oat, rice, maize, peanuts	*Aspergillus oryzae, A. parasiticus*	Aflatoxin	[154, 155]
Wheat, oat, rice, maize, peanuts	*A. oryzae*	Ochratoxin	[156]

There are several factors that influence the production of bioactive secondary metabolites under submerged fermentation. These factors include type of agro-industrial residue, particle size, moisture content, temperature as well as aeration and agitation of substrate.

Although being greatly available, the agro-industrial wastes are underutilized for the commercial production of industrially significant secondary metabolites. However, the use of agricultural waste must be prioritized by the industries for large-scale production of such metabolites as it is evident that higher concentration of the products can be achieved through SSF. Moreover, the substrate is even cheaper than that of media components used in SmF.

19.4.5 Agro-industrial Residues in Production of Biofuels

Finite fuel resources, increasing demand for fuels around the globe, and emission of toxic greenhouse gases upon combustion lead researchers to find some alternative sources; and biofuels are one of those. Biofuels are also known as bio-based fuels; they are made from a combination of biomass and chemicals, considered as the most economical transportation fuel. There are two major types of biofuels: gaseous and liquid biofuels. Biofuels are fast processing fuels, unlike the fossil fuels which are created through slow geological processes. Agro-industrial waste biomass is used as raw material for the production of biofuels. It can be made from different sources, such as plants, industrial wastes, domestic and commercial crops. The carbon content of the fuel varies depending on the environment and the emission levels

[157]. The global annual biofuel production reached 161 billion liters in 2019, which is about 6% higher than that of 2018 [158]. In 2000 the global biofuel production was about 187 thousand barrels of oil equivalent per day, which rise to 1677 thousand barrels of oil equivalent per day in 2020. Salidini et al. [159] classified biofuels into four classes (first-, second-, third-, and fourth-generation biofuels), based on their feedstocks and production methods.

First-generation biofuels are made from edible biomass like starch (from potatoes, wheat, barley, and corn) or sugars (from sugarcane and sugar beet). They initially showed promise in reducing fossil fuel combustion and lowering atmospheric CO_2 levels as crops grow using edible crops as feedstocks, as well as the impacts on croplands, biodiversity, and food supply [160]. Biodiesel (bio-esters), bioethanol, and bio-gas are examples of first-generation biofuels.

Diesel fuel, with a chemical formula ranging from $C_{10}H_{20}$ to $C_{15}H_{28}$ with an average molecular weight of 168 (amu), is a popular liquid petroleum fuel for transportation [161]. Biodiesel is made by transesterifying oils or fats and can be used as a vehicle fuel in its pure form (B100), but it is most commonly employed as a diesel additive to reduce particulates, carbon monoxide, and hydrocarbon emissions from diesel-powered vehicles. It is generally made up of fatty acid methyl (or ethyl) esters chemically (FAMEs) [162]. Biodiesel is also safe to handle and transport because it is nontoxic and biodegradable, with a flash point of around 148 °C, compared to 52 °C for petroleum diesel fuel [163]. Bioethers (also known as fuel ethers) are additives to gasoline that increase the octane number. They can be used to replace petro-ethers and increase the performance of engines [164]. Bioethers can also significantly reduce engine wear and hazardous exhaust emissions. They are created when bioethanol reacts with iso-olefins such as isobutylene. Wheat and sugar beet are the most common sources of bioethers [165].

Second-generation biofuels are produced using more sustainable techniques. When second-generation biofuels are burned, the net carbon emitted or consumed is neutral or even negative. Agriculture waste, poplar trees, willow and eucalyptus, sugarcane bagasse, switchgrass, corn cobs, and wood are only a few examples of cheap and plentiful nonedible abandoned materials that can be utilized as biofuel feedstock [166].

Second-generation bioethanol is prepared by hydrolysis and subsequent fermentation of agro-industrial residues. It can also be made by thermochemical methods, such as gasification followed by fermentation or a catalyzed reaction [167]. However, these processes are complicated by the difficulty of biomass breakdown, the release of various types of sugars after the breakdown of hemicellulose and cellulose polymers, the need to ferment these sugars with suitable organisms, which may necessitate genetic engineering, and the cost of collecting and storing low-density lignocellulosic feedstocks [168]. In the lignocellulosic conversion process, there are four main operational steps: pretreatment, hydrolysis, fermentation, and product separation or distillation [169] (Fig. 19.4).

Energy crops, agricultural waste, and wood residual wastage are all examples of second-generation feedstock that can be used to make biodiesel. Jatropha, *Aleurites moluccana*, salmon oil, Rubber tree, *Madhuca longifolia*, tobacco seed, sea mango,

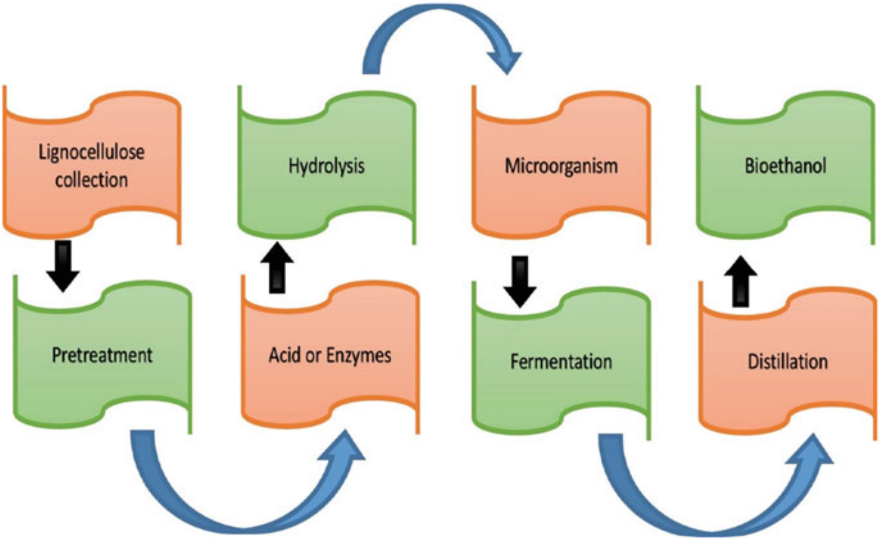


Fig. 19.4 Schematic representation of bioethanol production from LCB

and jojoba oil are the most popular energy crops used for this purpose. The waste from cooking oils, nonedible oil crops, restaurant grease, and animal fats can be included as feedstock for the production of second-generation biodiesel [170].

In the third generation of biofuels, a variety of microorganisms are used as feedstocks [115]. The most frequent form for biofuel production is promising microalgae because of their photosynthetic ability, producing specific chemicals and nutritious items. When compared to fossil-based oil produced by quick pyrolysis of wood, microalgae-based bio-oil has a high heating value, low density, and low viscosity [171]. Genetically engineered microorganisms such as microalgae, yeast, fungus, and cyanobacteria are used as sources in fourth-generation biofuels [172].

19.4.5.1 Biohydrogen from Agro-industrial Residues

Hydrogen is a very high energy (122 kJ/g) yielding fuel as compared to ethanol or methane. When combusted it liberates water in place of greenhouse gases. Using light as a primary source of energy, photoautotrophic growing bacteria and microalgae, the hydrogenase enzyme splits water into hydrogen and oxygen. Various solid agricultural wastes such as black strap molasses, rice straw as well as liquid waste from rice winery and sugar mills have been successfully employed for the production of hydrogen fuel [173]. The application of potato steam peels has also been studied for hydrogen production. The total hydrogen and acetate production using only glucose as a source of carbon and equivalent amount of sugars in potato steam peel hydrolysate (prepared by the action of amylase and glucoamylase) was assessed. The study revealed that higher hydrogen production and maximum hydrogen productivity (218 mM and 11.7 mmol/L.h, respectively) occurred from the peels than that from glucose (130 mM and 10.7 mmol/L.h, respectively) [174].

19.4.5.2 Bioethanol from Agro-industrial Residues

Bioethanol is produced by simple fermentation of cheaper and renewable agricultural carbohydrate feedstock using yeasts as biocatalysts. Various common sugar feedstocks such as sweet sorghum, sugar beet tubers, and sugarcane stalks have been successfully employed for the production of bioethanol. The yeast cell produces two enzymes, namely zymase and invertase, which mediate the fermentation process. Initially, the lignocellulosic biomass is subjected to chemical or enzymatic pretreatment for the conversion of cellulose and hemicellulose into complex sugars. Then invertase enzyme produced by the yeast cell converts these complex sugars into simple fermentable sugars which will be fermented further to produce crude ethanol and carbon dioxide. This crude ethanol contains significant amounts of water and thus it is subjected to fractional distillation (vaporization) to remove water and pure ethanol (95%) is further obtained upon distillation. Bioethanol production from renewable and cheap agro-industrial residues reduces greenhouse gas emissions like CO_X, SO_X, and NO_X as well as eliminates smog. Thippi, corn steep liquor, switchgrass (*Panicum virgatum*), potato waste, oat straw, rice straw, wheat straw as well as Ami-ami solution (Brewer's yeast autolysate and fish soluble waste) have been globally used as raw materials for bioethanol production [175, 176].

19.4.5.3 Biodiesel from Agro-industrial Residues

The use of oil from peanuts was initially demonstrated by Rudolf Diesel in his self-designed engine during the World Exhibition held in Paris in 1900. After that, numerous trials have been made to establish the potential of triglycerides as an alternative to diesel. Anyhow, high viscosity and poor low temperature properties of triglycerides were the limitations to be used directly in diesel engines. These limitations can be overcome by modifying the properties of vegetable oils that resemble that of petrodiesel. Biodiesel is mono alkyl esters produced upon transesterification of triglycerides with alcohol (methanol) in the presence of chemical catalysts like acid/alkali or biological catalysts like enzymes. Biodiesel is generally prepared from vegetable oils like palm oil, rice bran oil, rapeseed oil, sunflower oil, and soybean oil as well as from animal fats. The type of vegetable oil to be used in the biodiesel production mainly depends upon the abundance near the production site. Biodiesel from animal fats has several advantages over biodiesel from vegetable origin. Biodiesel produced from animal fats has a high cetane number due to less amounts of unsaturated fatty acids than as compared to vegetable oils; and a higher cetane number emits lower NOx gases [177]. Moreover, biodiesel from animal fats also has a high calorific value [178]. Researchers have reported that blends of soybean/beef tallow biodiesel presented higher oxidative stabilities as compared to biodiesel from soybean oil only [179].

Increasing prices of crude oils and cost-effectiveness of major biofuel technologies have globally accelerated extensive utilization of agro-industrial residues for the production of alternative biofuels. Gaseous biofuels (biomethane and biohydrogen) as well as liquid biofuels (bioethanol and biodiesel) have evolved as a potential alternative to the diminishing fuel resources. Biotechnologies used for the production of biofuels from agro-industrial wastes have potential in reducing greenhouse gas emissions and release of toxic pollutants, thus saving the environment and partly solving the global fuel crisis. By considering the sustainability and transformative power of biotechnologies in biofuel production, the "second industrial revolution" can be enabled that the society now requires.

19.4.6 Application of Agro-industrial Residues in Pharmaceutical Industry

Pharmaceutical industries are one of the essential industries in the world and are the backbone of many developing nations including India. According to a study carried out by IQVIA, the pharmaceutical sector should experience market growth between 3 and 6% worldwide over the next five years, which amounts to exceeding 1.5 trillion dollars in total value by the year 2023 [180]. India currently ranks third in the world in terms of volume and 14th in terms of value for pharmaceutical compound production. The country has vast domestic pharmaceutical sector with a robust network of 3000 pharmaceuticals businesses and 10,500 production units as of 2022 [181]. With the constant rise in population along emergence and re-emergence of diseases, the demand of pharmaceutical products will increase in near future which puts pressure on supply of raw products to meet the demand. Agricultural residue can provide alternate raw material for many pharmaceutical products and help meeting the demand in future [182].

In recent times there has been an increase in manufacturing antimicrobial compounds to combat respiratory disease, infections, and many other physiological conditions in humans [183]. However the excessive usages of synthetic pharmaceutical products have led to unforeseeable consequences for humans such as resistance in microorganism and side effects of drugs [184]. These limitations have sparked interest among research community to investigate alternate routes for drug preparations and use of bioactive compounds from agricultural residues [185]. Edible fruits are heavily utilized in food industries and their waste is known to possess raw materials that can be used in drug manufacturing. Currently, citrus fruits (Lemon, Orange, limes, etc.) are receiving special attention from researchers for their antiviral, anti-inflammatory, antibacterial, and antifungal properties [186]. Agri-food wastes such as peels, pomace, and seeds can assist in enhancing bioavailability of various drugs as they are a rich source of nutrients as well as phytochemical compounds. They are an excellent source of organic acid, sugars, and polyphenolic compounds such as flavonoids and anthocyanins which have proven antibacterial, antifungal, anti-inflammatory, immunomodulatory, and antioxidant properties [187].

Constant emergence and re-emergence of viral diseases such as hepatitis, Ebola, MERS-CoV (Middle East respiratory syndrome), SARS-CoV (severe acute respiratory syndrome), H7N9 (avian influenza virus), and Crimean-Congo fever have put increasing pressure on the entire health sector and industry to focus research on finding alternative medicine with antiviral properties. In this regard, bioactive compounds present in agro-wastes such as tangeretin, nobiletin, and hesperidin have shown great potential of antiviral properties in terms of infected cell activity reduction and viral multiplication inhibition [188]. In the light of recent disease outbreaks such as Zika virus and COVID-19, many alterative drugs and natural compounds like Arbiol, Remdesivir, and Lopinavir are now being investigated for their direct antiviral activities [189].

19.4.7 Miscellaneous Applications of Agro-industrial Residues

Agricultural residues such as seeds, fruit peels, fruit skins, and cereal husks have the capability to enhance sensory and nutritional characteristics when partially substituted with 10% to 30% of wheat and corn flour in preparation of bread. Furthermore fruit peels are a novel source of colorant which adds in color, flavor, antioxidant and anti-inflammatory properties to bakery products [182]. Natural phytophenolic compounds are valuable products because of their medicinal properties and some of the important sources are peels of lemons, oranges, and grapefruits. Notably peel residues from apples, peaches, pears, and nectarines contains twice the amount of total phytophenolic compounds compared to fruit pulp [190]. Similarly grape seeds and skins which are waste products from the grape juice and wine industry are also sources of several phytophenolic compounds such as mono, oligo, and polymeric proanthocyanidins [191]. Dietary fibers are an essential component of diet as they have a role in the prevention of diabetes, obesity, atherosclerosis, heart diseases, colon cancer, and colorectal cancer. Among the LCB components, hemicellulose and pectin possess significant metal binding capability, which has a positive role in metabolism. The utilization of by-products or wastes from industrial processing of fruit and vegetables, i.e., apple, currant, citrus fruit, carrot, tomato, melon, or spinach pomace, is convenient and cost-effective and enables rational management of troublesome wastes.

Agricultural wastes and residues are biodegradable in nature and although most common use of it is as the feedstock, huge amount of it goes straight to landfills and dumps. This waste can be used to obtain composite materials which can be used in manufacturing many products and as a building material [192–194]. The raw agricultural residues can be used to produce nano-composite materials for a wide range of applications. The common ingredients of nanocomposites (NCs) are nanocellulose, nanoscale carbon-based materials, and nanosilica. They are currently utilized in industrial sector, agriculture, pharmaceutical, and remediation of pollutants. The most potent agro-residues for preparation of nanocomposites are banana peels, orange peels, wheat whiskers, straw, cotton stalks, corn stalks, coconut shells, almond shells, corn silk, rice husks, oil palm empty fruit bunches, bagasse, peanut hulls, and ginger rhizome [192, 194, 195]. NCs can be fabricated using hydrothermal carbonization, sol-gel method, co-precipitation, polymer solution casting, phase inversion technique, ball milling, and direct compounding methods (Fig. 19.5) [196].

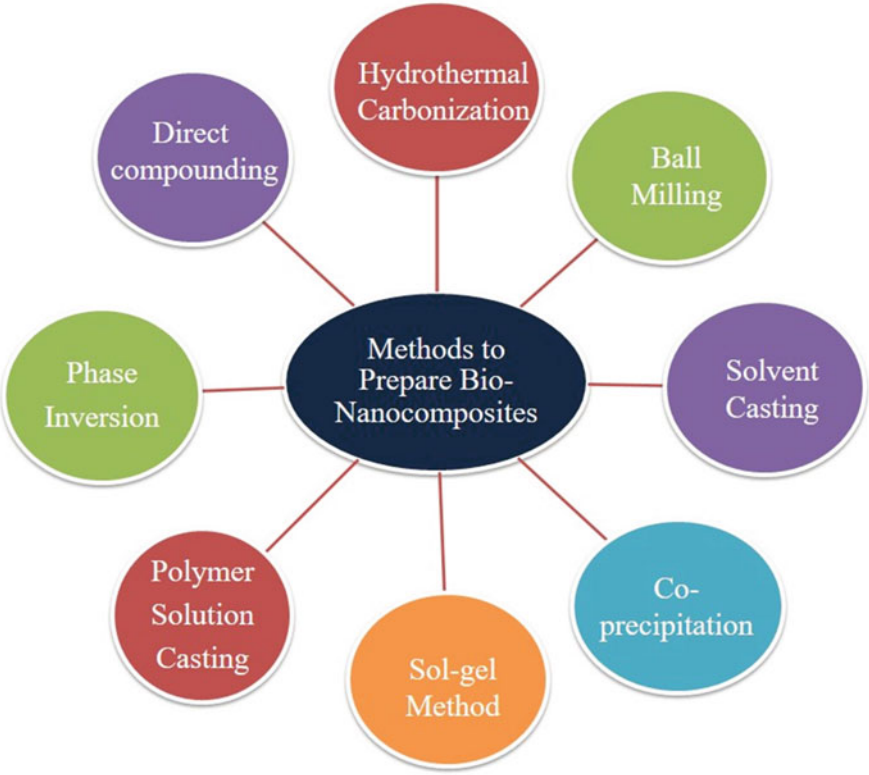


Fig. 19.5 Different methods for the preparation of bio-nanocomposites from LCB

19.5 Conclusion and Future Prospects

Agro-industrial residues are abundantly found in nature and have been widely distributed all over the world through trading, import-export, and direct industrial applications. However the major portion of these residues is not utilized efficiently, and it ends up in landfills and waste dumps. While common agro-residues like cereal straws and cobs are used in animal fodders, other residues like oil cakes, pseudostem, bagasse, and fruit shells and peels are not suitable as fodder; thus most of it ends up as a solid waste. In the present scenario regarding economy and environmental changes in the world, it is important that not only these agro-residues be recycled and treated but also be utilized for the production of renewable energy and value-added products. In recent times, fungi have been the most suitable organism for the production of many value-added products from agro-residue due to their robustness and ability to survive in adverse environmental conditions and different ecological niches. Furthermore, fungi can produce a wide array of enzymes which can break down complex LCB residues and generate value-added products.

This chapter summarizes all types of agro-residues and their potential industrial applications by using bio-based refinery approach. One of the important components of the biorefinery concept is the fractionation of complex lignocellulosic biomass residues which help in the separation of major components of LCB residue such as cellulose, hemicellulose, and lignin with minor phytochemicals. While cellulose and hemicellulose can be used for the production of animal feed, industrially significant enzyme, and organic fertilizers, lignin component is used for the production of laccase class of enzymes and phytophenolic compounds. The direct implementation of LCB residues as a substrate has also been used for the production of industrially significant enzymes, secondary metabolites, and mushroom production. Phytochemicals from LCB residues have vast potential to generate many bioactive compounds which have antimicrobial, nutraceutical, antioxidant, and many other pharmaceutically significant properties. Currently the energy and food demand has sharply increased due to population rise, exploitation of natural resources, and environmental changes. Thus it is the need of the hour to switch to renewable resources and switch to green technologies with low carbon emission and high recyclability.

Agro-industrial residues are the most prominent resource which are easily available in nature. The limitations of bioactive compounds and emerging drug resistance of pathogens have also put the industry in dire need of looking for alternative medicinal compounds. Agro-residues can be used to generate many novel bioactive compounds which can be used for the purpose of alternative medicine. Current trends in research suggest that in the coming years, utilization of agro-residues will play a major role in renewable energy and product industries.

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