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Multi-Faceted Exploration of Lignocellulosic Biomass: From Physicochemical Fundamental to Advanced Bioconversion and Waste Valorization Techniques

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Abstract

One of the world's most abundant and renewable resources, lignocellulosic biomass has vast potential for the development of sustainable material and energy. This review will take a multi-faceted approach to the exploration of lignocellulosic biomass, starting with the physicochemical fundamentals, including its complex structural components: cellulose, lignin and hemicellulose. These components pose significant challenges to its efficient utilization, demanding advanced pretreatment and bioconversion technologies. Advanced bioconversion processes are addressed, such as using microbial and chemical processes to utilize biomass to form useful products like chemicals, biofuels, and bio-based materials. Additionally, waste valorization techniques are looked at, recovering high-value compounds from lignocellulosic residues to reduce waste and enhance economic viability. By combining physicochemical insights with advanced bioprocessing and valorization strategies, this paper outlines a holistic approach toward the transformation of lignocellulosic biomass into sustainable solutions, addressing both environmental and economic concerns.

Keywords- Lignocellulose, valorization, agricultural waste management, pre-treatment, value added products.

1. Introduction

Wastes from forests and agriculture are substantial and abundant sources for lignocellulosic materials. Sustainable conversion of lignocellulosic waste from agriculture and industry into biomaterials and bioenergy is achieved through a range of integrated processes. Agricultural waste biomass is a particularly attractive source of lignocellulosic materials, as it is often generated in large quantities and is typically considered a low-value by-product. The three main components that make up lignocellulosic biomass are hemicellulose, lignin and cellulose. Cellulose, the primary component of lignocellulosic materials, can be hydrolyzed into glucose and other soluble sugars using cellulase enzymes, which can then be fermented or converted into various value-added products. The amount of lignocellulosic biomass waste created in the world is greater than 20 billion tonnes annually. Sawdust, corn stalks and wheat straws, and are among the agricultural and forest wastes that make up the majority of this waste materials. There are social and economic advantages to using lignocellulosic biomass feedstock as a raw material to produce bioenergy and biobased resources. It is thought that biomass derived from lignocellulose and aquatic material is an intriguing raw material source for producing biochemicals, bio-fuels, and biomaterials. Efficient exploitation of all components is required in the biorefinery, which integrates processes and technologies for the conversion of biomass. In terms of efficient waste management, such a solution promotes the circular economy as an example of a successful strategy. An estimated 11.2 billion tonnes of solid waste are produced every year, the UN

Environment Program says. Over 90% of waste is incinerated or dumped in the open in poor countries, and hence this is one of the largest causes of environmental degradation and harmful health impacts. Several types of technologies such as chemical, biological, and physical ones are employed to remove lignocellulosic content from agricultural residue. The extraction of lignocellulosic components from agricultural wastes can be proceeded through chemical, biological and physical processes. The final product in question and the type of waste biomass used will determine this.

2. Lignocellulosic biomass

Lignocellulosic biomass (LCB) is a widely occurring biorenewable compound in the universe. It is a product of photosynthesis from water and CO2. An essential cell wall component of woody plants, LCB is a compound consisting of proteins, polysaccharides, and phenolic polymers. Cellulose, a polymer of carbohydrates, is accompanied by hemicellulose and lignin, an aromatic polymer, to constitute the complex spatial structure of LCB (Yousuf, Pirozzi and Sannino, 2020). Global plant biomass output is around 200×10^9 tonnes per year, with lignocellulose accounting for over 90% (Kuhad and Singh, 1993).

However, only $8\text{-}20\times10^9$ tonnes of primary biomass are theoretically accessible. Maize, wheat, rice, and sugarcane are the most productive and widely cultivated agricultural crops. The majority of lignocellulosic biomass harvested from agriculture is produced by four crops, while the rest agro wastes represent a really small fraction of the total agricultural wastes generated globally. Corn by-products include stalks, leaves, cobs and husks that remain in the field after gathering the kernel. The yearly production rate is around 1 kg/kg maize grain, or 4 tons/acre (Cheng and Timilsina, 2011). Under harsh agricultural circumstances, wheat grain harvest generates 1-3 tonnes of straw per acre yearly. Rice straw consists of remaining rice production materials such as stems, leaf blades, leaf sheaths, and panicle remnants after threshing. This is the common lignocellulosic waste product worldwide.

In Asia alone it produces 667.6 million tons of rice straw each year, and at the global level, 731 million tons is annually produced. During the processing of sugarcane, enormous amounts of bagasse are generated. According to, it is a cost-effective and renewable agricultural resource for producing ethanol. Whereas wheat straw contains proteins and pectin, rice straw has higher silica (Sarkar *et al.*, 2012). Most agricultural leftovers have comparable cellulose, hemicelluloses, and lignin concentrations (Fig. 1). Although this substance forms a significant proportion of lignocellulosic agricultural waste, the chemical composition of cellulose varies extremely (Table 1). Table 2 displays the global output of primary agricultural waste and their potential for bioethanol generation.

Urban grasses are widely recognised as the primary cellulosic biomass sources. Miscanthus, Switchgrass, canary grass, lucerne, giant reed and Napier grass are key herbaceous energy crops that provide LCB. In addition to avoiding the "food versus fuel" debate, they provide energy, environmental and economic benefits over food crops for production of ethanol. Forest trees contribute significantly to cellulosic biomass due to their rapid growth and short rotation intervals. Forests serve an important role in minimising landslides, lowering CO2 levels in the atmosphere, and maintaining a balance between humans and wildlife, despite their unequal distribution.

In the United States, woods yield more than 370 million tonnes of LCB annually. Among other nations, China, Russia, Canada and Brazil have abundant forests. The LCB collected from the aforementioned nations accounts for half of the total amount worldwide. There are diverse sources of woody biomass; these include natural forest leftovers like sawdust and wood chips, dead tree branches, tree bark, shavings, sawdust, poor-quality timber, pulp,

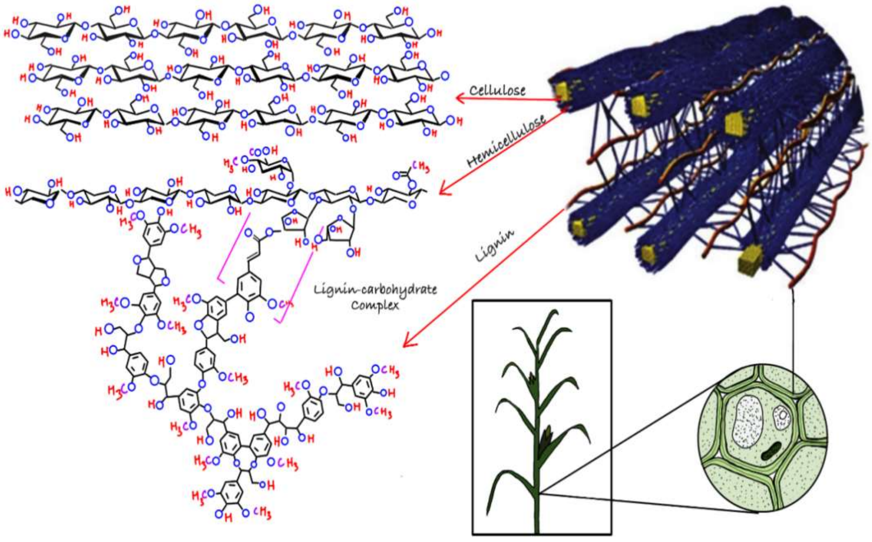

Fig. 1: Composition of agricultural feedstock (Yousuf, Pirozzi and Sannino, 2020)

Table 1: Diverse sources of agricultural and lignocellulosic biomass residues (Saini, Saini and Tewari, 2015)

S. No	Agricultural Feedstock	Cellulose	Hemicellulose	Lignin
1	Cotton	80-95	5-20%	nil
2	Hardwood	45±2	30±5	20±4
3	Softwood	42±2	27±2	28±3
4	Cornstalk	39-47	26-31	3-5%
5	Wheat stalk	37-41	27-32	13-15
6	Corn fodder	38-40	28	7-21%
7	Sugarcane/Bagasse	32-48	19-24	23-32
8	Rice husk	28-36	23-28	12-14%
9	Barley husk	31-45	27-38	14-19
10	Sorghum straw	32	24	13
11	Newspaper	40-55	25-40	18-30

plywood, and sawmills leftovers. Non-woody biomass has low lignin concentration. They have comparably low energy and are large in size. Liquid fuels abounded in readily available and relatively inexpensive sources of lignocellulosic biomass; these include wastes generated from agricultural fields, processing wastes like palm oil, sugarcane bagasse, animal manure, and cotton gin waste. Rice husks are the hard, protective rice seed pod that contribute 20-22% of overall rice output. The rice mill business today processes a substantial volume of rice husk, which contains hemicellulose 12.0-29.3%, cellulose 28.7-35.6%, and lignin 15.4-20.0%.

The most commonly used lignocellulosic sources of various available bioactive compounds include prunes/ brans, bagasses, straws, leaves, peels, barks, and cuticles/shells (like those on hazelnuts). These comprise fatty acids, steroids, eventually alkaloids, terpenes, terpenoids, and phenolic compounds; other pertinent

Table 2. Availability and bioethanol production potential of major agricultural residues (Saini, Saini and Tewari, 2015)

S. No	Agricultural waste	Availability	Bioethanol potential estimated
1	Rice Straw	731.3	205
2	Sugarcane Bagasse	180.73	51.3
3	Wheat Husk	354.34	104
4	Corn Husk	128.02	56.6

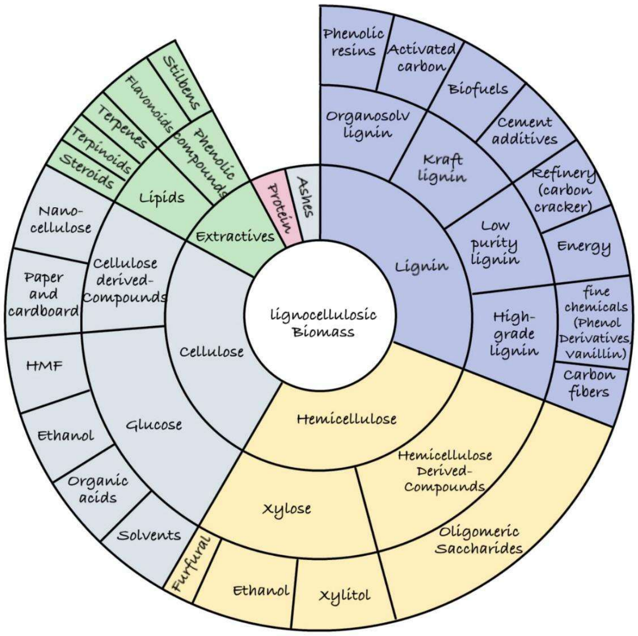

Fig. 2: Processing of lignocellulosic biomass: primary fraction and product spectrum (Romaní *et al.*, 2020)

portions of carbohydrates, proteins, and lipids might also be of relevance (Romaní *et al.*, 2020). The most frequently mentioned class of extractives from lignocellulosic biomass is phenolic compounds (Fig. 2). These matrices commonly contain phenylpropanoids, phenolic acids, lignans, tannins, flavonoids, and stilbenes, a class of secondary plant metabolites renowned for their strong antioxidant qualities (Anderson, 1967).

3. Lignocellulose composition

3.1. Cellulose

About 1.5×1012 tonnes of cellulose are produced (and degraded) globally each year, making it the most common natural polymer found in the environment. Cellulose is an unbranched chain, homo-biopolymer with a higher molecular weight that is connected by beta 1→ 4 glycosidic linkage and repeating D-glucose units. The cellulose chain only has hemiacetal functionality at one end (Heinze and Liebert, 2012). Each glucose residue in cellulose has three hydroxyl groups. The cellulose chains are strongly bound together by intra/intermolecular hydrogen bonds (-H) and by strong forces of van der Waals, thus being densely aggregated with a lateral dimension ranging from 3-5 nm (Seddiqi Erfan Oliaei Hengameh

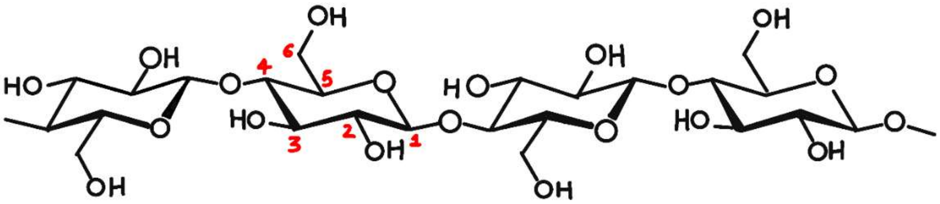

Fig. 3: Cellulose molecule representation (Heinze, 2015)

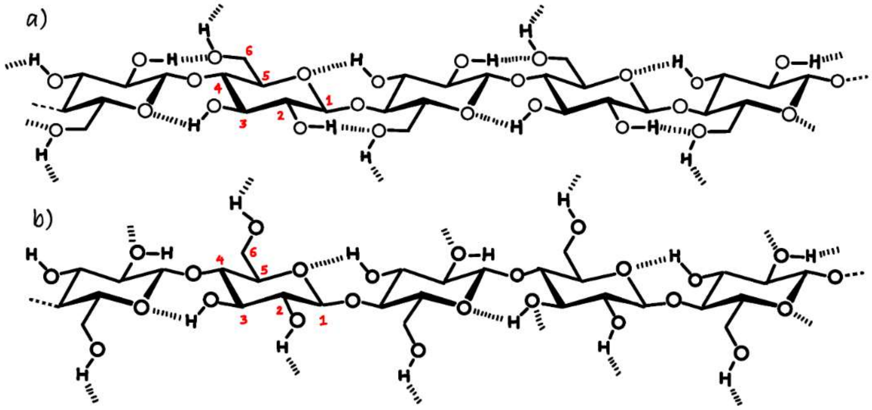

Fig. 4: Comparative analysis of Hydrogen bonding a) Cellulose I and b) Cellulose II based on (Heinze, 2015)

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The lowest energy conformation, the $^4C_1$-chair structure, is made up of D-glucopyranose ring units that make up cellulose, regardless of the source (RAO *et al.*, 1967). There are β-1,4-glycosidic bonds linking these units together and the cellulose chain axis rotates alternatively 180 degrees because of this. In the anhydroglucose unit (AGU), each cellulose chain possesses three reactive hydroxyl (OH) groups: one major one at C6, and two subsidiary groups in the ring plane at C2 and C3. (Fig. 3).

Different hydrogen bonding systems are present in cellulose, and these systems significantly affect its characteristics. Combined with intramolecular hydrogen bonding to the β-glycosidic covalent bond, the cellulose polymer achieves its stiffness or rigidity. The H-bonding system in cellulose (I) and (II) is schematically depicted in Figure 4. The extraction method, processing, and place of origin all affect the degree of crystallinity in cellulose. Cellulose originating from bacteria and tunicin has 80–100% crystallinity, whereas normally, for the cellulose extracted from wood and plants, the crystallinity is about 40–60%. (Klemm *et al.*, 2011). There are many uses, such as fillers, construction materials, viscosity modifiers, optical films, sorption materials, laminates, sheets, textiles, and high-performance functional substances, that can be enhanced by the chemical and physical modification of cellulose (Heinze and Liebert, 2012). Because of their less cytotoxicity, biodegradability, and biocompatibility, cellulosic substances hold considerable potential as future-proof and worthwhile materials for biomedical applications. Furthermore, cellulosic materials can be easily changed to produce value added products because of their chemical functionality. Algae, fungi, minerals, plants, and mammals all naturally contain cellulose.

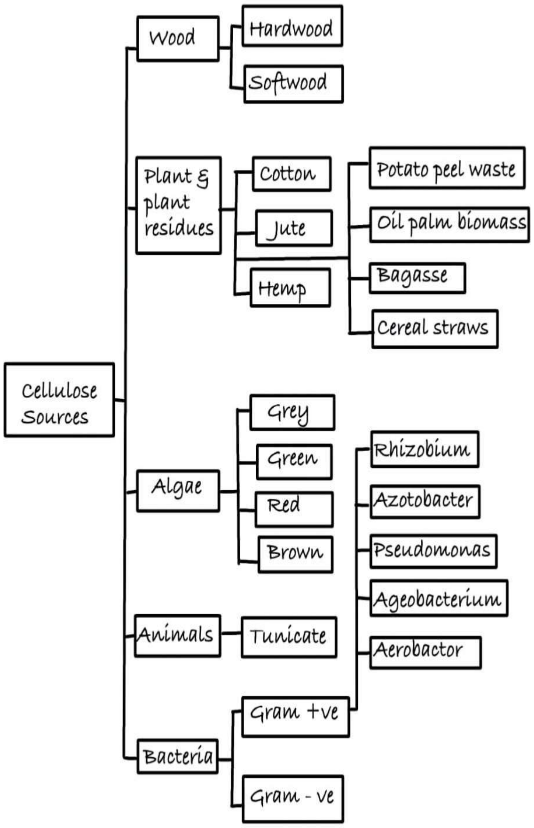

Fig 5: Cellulose classification according to their sources (wood, algae, animals, plant and bacteria) (Seddiqi *et al.*, 2021)

Depending on its origin, cellulose is classified into five types: bacteria-based cellulose (BC), wood-based cellulose (WC), algal-derived cellulose, plant-derived cellulose (PC), and tunicate-derived cellulose (Fig. 5). In contrast to BC, tunicate-derived cellulose, and algae-derived cellulose, WC and PC have become the most widely recognized forms of cellulose over the lengthy history of its use due to its abundance and affordability (Klemm *et al.*, 2005). Softwoods from gymnosperms as well as hardwoods from angiosperms have all been used to extract cellulose (Nam, Hillyer and Condon, 2020). Wood and plant-derived fibres have comparable constitution and configuration, with carbohydrate polymers (biodegradable) such lignin, hemicellulose, and cellulose. (Table 3).

3.2. Hemicellulose

Hemicelluloses are the second most prevalent biopolymer in plants, behind cellulose. Unlike cellulose, these cells have a homogeneous 1→4-β-linked polyglucan as their principal cell wall ingredient. Hemicelluloses are complex polysaccharides that comprise arabinose, galacturonic acid, glucose, glucuronic acid, mannose, galactose, xylose and fucose in varying proportions according to the source. Sustainable lignocellulosic biomass, including cereals, herbs, straws etc. may be used to produce hemicelluloses and derivatives (STEPHEN, 1983). Previously, research on hemicelluloses concentrated on converting plant biomass into sugar, chemicals, and fuel to generate heat.

Table 3: Major component in chemical composition of plant fibers and wood as content of hemicellulose, cellulose and lignin (Seddiqi *et al.*, 2021).

S.No.	Sources	Type	Cellulose (wt.%)	Hemicellulose (wt.%)	Lignin (wt.%)
1	Biomass Fibers		30-75	10-35%	0-20
2	Wood Fibers	Deciduous wood (Hardwood)	40-50	24-40	18-25
		Coniferous wood (softwood)	45-50	18-35	23-35

Hemicellulosic components in plant cells, tissues, and organs can vary greatly based on species and cell wall composition (Schindler, 1998). Examples include wheat straw (32%), barley straw (27%), oat straw (31%), rye straw (25%), rice straw (25%), sunflower husk (23%), sugarcane rind (22%), and maize cobs (37%) (Sun *et al.*, 2003). Straw hemicelluloses are a valuable source of raw material for several sectors, including papermaking, baking, food, and non-food industries. Hemicelluloses, a prevalent natural polysaccharide, account for roughly one-third to one-fourth of plant components. Hemicelluloses generally have a 1,4-β-D-xylopyranosyl main chain with side chains containing L-arabinofuranosyl, L-galactopyranosyl, 4-O-methyl-D-glucuronopyranosyl, or D-glucuronopyranosyl units. Hemicelluloses are usually produced in hardwood or annual plants, although differences exist between the hemicelluloses produced in harwood and annual plants (Laluce *et al.*, 2012).

Hemicelluloses may be classified into four types based on their structural differences: xyloglycans (xylans), mannoglycans (mannans), xyloglucans (XG), and mixed-linkage β-glucans (Fig. 7.) (Ebringerová, Hromádková and Heinze, 2005). Xylans typically have a beta (1→4)-D-xylopyranose core with chains of carbohydrates on the 2- or 3-position, including D-glucuronic acid or its 4-O-methyl ether, L-arabinose, and/or oligosaccharides like D-galactose, L-arabinose, D-glucose and D-xylose. (Fig. 6). GX (glucuronoxylan) with a side chain on the 2-position of either α-D-glucuronic acid or its 4-O-methyl derivative (Fig.7. a, b) occurs in date seed fibres, sugar beet pulp, hardwood, grape skin, luffa fruits fibres, fruits, and storage tissues such as the pericarp seed of the pear, and hulls of Jojoba, and various dicotyls.

3.3. Lignin

The most prevalent substance in plants, lignin plays a crucial role in the cellular wall. It is incredibly insoluble and hydrophobic in both alcohol and water. Made up of monolignol units, lignin is a complex organic polymer. Since lignin waste is burned or disposed of as low-grade fuel, it also poses a threat to the environment because it wastes natural resources.There are many uses, such as fillers, construction materials, viscosity modifiers, optical films, sorption materials, laminates, sheets, textiles, and high-performance functional substances, that can be enhanced by the chemical and physical modification of cellulose.Therefore, to achieve sustainable resource management, it is essential that lignin valorization be upgraded through technical advancements. Many value-added compounds, such as ethylbenzene (a crucial precursor for organic synthesis), can be synthesised thanks to technical advancements like thermochemical customisation technologies of lignin. guaiacol (phenolic resin making). As a byproduct of the lignocellulosic biorefinery and the paper industry, more than 80 million tonnes of lignin are currently generated.

However, very little of this lignin is utilised by the industry as a fuel or energy source. To enhance the sustainability of the biorefinery process, researchers want to synthesise different fine compounds with higher economic value from lignin. The derivatives of lignin can also be utilised in the production of foams, polyols, polyurethane resins, antifungal agents, and other industrial goods (Regmi *et al.*, 2018). The creation of char as a byproduct, the difficulty of purifying and separating the products, and the low selectivity of product synthesis are the main obstacles in the lignin conversion process that must be taken into account when operating a lignin-based biorefinery. The main reason lignin was studied was because it was important for the pulp and paper industries, which generated cellulose-rich fibrous products by removing lignin from wood. Thus, the main research was done on the structure and makeup of lignin. Some lignin research also targets herbaceous plants, partly due to issues in the nutritional conversion and digestion of animal feed. However, these days, the biorefinery may produce energy, green chemicals, and

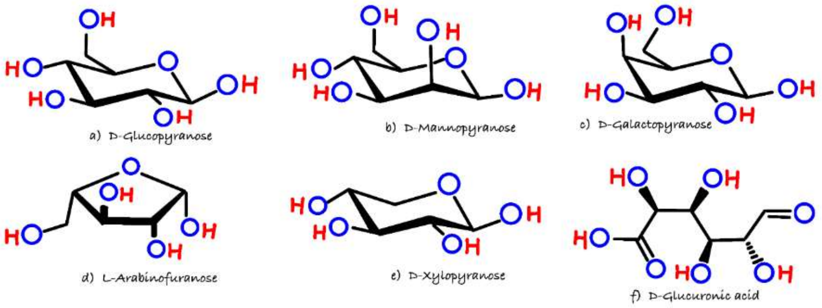

Fig 6: Hemicellulose main constituents (Peng *et al.*, 2011)

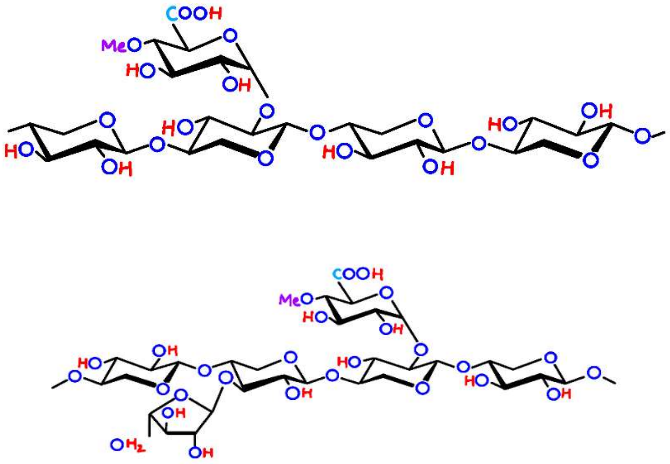

Fig. 7: a) Structural framework of 4-O-methyl-D-glucorono-D-xylan (MGX); and b) AGX (L-arabino-4-O-D-glucorono-D-xylan) primary structure (Peng *et al.*, 2011)

bioproducts from these lignocellulosic wood species and wastes. Lignin is primarily bound in plants to polysaccharides which are closely associated with cellulose and hemicelluloses. Nevertheless, lignin, cellulose, and hemicellulose are not evenly distributed throughout the plant's body. Lignin, the second most prevalent natural polymer after cellulose, is mostly found in the spaces between vascular plant cells. In a biorefinery, lignin is known to be the main source of complex organic polymers used in the chemical industry. More precisely, the lignin concentration in woody plants ranges from 15% to 40%.

Understanding the properties of lignin and proposing a lignin-based approach require a full understanding of its structural features. The three monoolignol primary precursors of lignin are sinapyl alcohol (syringyl), p-coumaryl alcohol (hydroxyphenyl), and coniferyl alcohol (guaiacyl). The cytosol uses the shikimate pathway to synthesise lignin polymers. Lignin may be an essential precursor in the synthesis of aromatic compounds because of

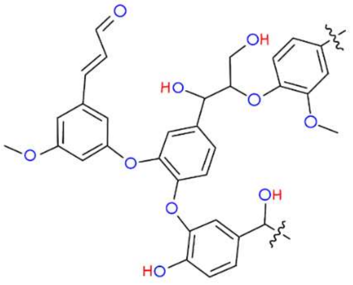

Fig. 8: Lignin structure (*Lignin: Biosynthesis and Transformation for Industrial Applications - Google Books*, no date)

the chemical sites that are present in its structure. There are also a few additional uncommon monolignol precursors found in trace concentrations. Furthermore, in aquatic settings, these polyphenolic rings confer hydrophobicity, which in turn confers resistance against the chemical and biological destruction of plants (Fig.8).

4. Valorization of Waste Based on Lignocellulosic Materials

The most significant renewable resource on Earth is lignocellulosic biomass. A significant amount of lignocellulose-based trash is produced during agroindustrial operations (Anwar, Gulfraz and Irshad, 2014). The current drives for an eco-friendly society with maximum valorization of biomass are biorefinery and circular economy principles, even if fuels and energy were the primary motivations for the exploitation of lignocellulosic-based waste (Bauer *et al.*, 2017). Therefore, a biorefinery could be a collection of facilities that transform biomass into a variety of energy and economic products. Typical lignocellulose-based wastes include woody debris, grasses, forestry residues, and agricultural wastes (Sánchez and Cardona, 2008). For example, the earliest sources of bioethanol were forestry leftovers, including wastes from the pulp, paper, and wood industries, tertiary wastes, short rotation crops, specialized crops, and wastes from the agrofood sector (Adekunle, Orsat and Raghavan, 2016).

The primary barries in this subject is the utilisation of lignocellulosic biomass through several methods of valorisation. Furthermore, the lignocellulosic biomass source has a significant impact on these pathways. Nevertheless, a significant number of nonstructural components (phenolic compounds, essential oils) with intriguing biological properties can be found in peels, seeds, hulls, and shells, among other food industry leftovers (Lin *et al.*, 2014). The current focus of research is on the integral value-adding of these agroindustrial residues, which may include the synthesis of biomaterials, chemicals, and fuels as well as the extraction of value-added products such as antioxidants from lignin, cellulose, and/or hemicellulose. The structural (lignin, cellulose, and hemicellulose) and nonstructural (extractives, ash, and protein) components of lignocellulosic-based wastes vary depends on the raw material. These parts work together to create a three-dimensional structure that is difficult to use industrially since it is inflexible and complex.

In order to convert lignocellulose into value-added products, a multistep processing method is needed. This involves using biological, physical, or chemical pretreatments to obtain the desired fraction, and then occasionally using chemical or enzymatic depolymerisation for monomer liberation that will subsequently be transformed into the desired product. Conventional biomass technologies have been divided into four categories: physical (such as extrusion and milling), chemical (such as organosolv, acid, alkali, steam explosion, ammonia fibre explosion [AFEX], etc.), and biological (such as white-rot fungi) treatments (Romaní *et al.*, 2020). In certain instances, the development of sustainable processes is impeded by the use of conventional heating systems and harsh chemicals, which have significant requirements for energy. Emerging technologies have emerged as more environmentally friendly and promising methods of valuing lignocellulosic biomass. These include ultrasounds, enzymatic processes, electric fields, green solvents, and microwaves. The aim of the pretreatment is to decompose the lignocellulose biomass in order to produce fermentable sugars that may be utilised in biotechnological production processes.

5. Pre-teatment strategies for lignocellulosic waste

The lignocellulosic biomass undergoes pretreatment, which increases its susceptibility to enzymatic hydrolysis and produces high sugar yields in contrast to high costs and low yields (Wyman *et al.*, 2013). The refractory nature of lignocellulosic biomass should be addressed by an optimal pretreatment technique. Another significant barrier to the practical manufacture of biofuels from lignocellulosic biomass is the high cost of the necessary enzymes, such as cellulase and other auxiliary enzymes (Hong *et al.*, 2013). By separating 108 hemicellulose and lignin and reducing cellulose crystallinity, pretreatment increases the porosity of 107 lignocellulosic biomass. Effective pretreatment needs to be 1) increase the formation of sugar, 2) decrease the rate at which carbohydrates degrade, 3) Prevent the production of inhibitory compounds and 4) be viable from an economic perspective (Yat, Berger and Shonnard, 2008). To start with, a suitable pretreatment technique is needed to reduce the polysaccharide's recalcitrance and improve its accessibility to enzymatic hydrolysis (Wang *et al.*, 2016).

Thus, pretreatment ought to be an advantageous and inexpensive method of turning lignocellulosic biomass into ethanol (Kim, Lee and Kim, 2016). Dissociating the hydrogen bonds in crystalline cellulose, which breaks the hemicellulose and lignin interlinkage matrix, is an appropriate pretreatment technique. After the pretreatment stage, simple sugars are fermented and saccharified enzymatically to produce biofuels and other products (Patel *et al.*, 2005). The kind of lignocellulosic feedstock determines the optimal pretreatment technique, as well as its parameters and process (Wang *et al.*, 2016). For lignocellulosic biomass processing, a variety of chemical, physical, biological, and physiochemical techniques have been studied (Fig. 9). To fractionate, hydrolyse, or solubilise the lignocellulosic constituents-lignin, hemicellulose, and I cellulose- is the

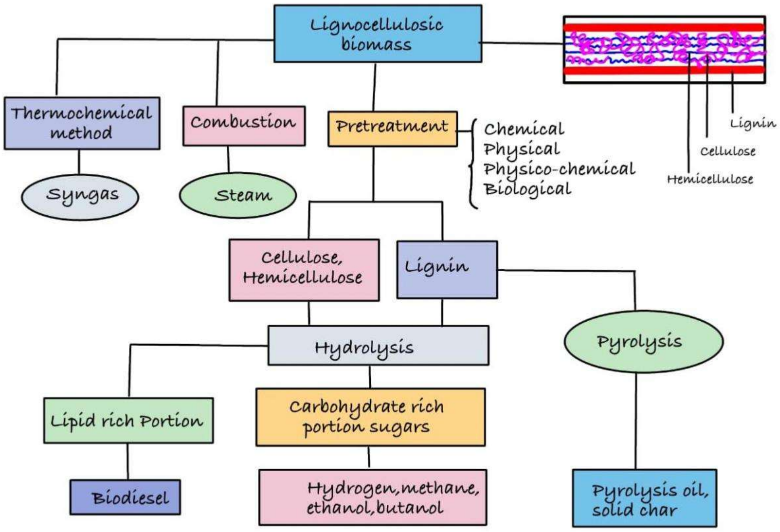

Fig. 9: Technologies for energetic valorization of lignocellulosic biomass (Blasi *et al.*, 2023)

main aim of all pretreatment techniques. By lowering particle size or destroying structural regularity, mechanical pretreatment speeds up the hydrolysis of lignocellulosic biomass (Madadi, Tu and Abbas, 2017). Chemical processes break down the cellulose, which lowers its crystallinity index and increases its disintegration and overall productivity. They also eliminate the lignin and hemicellulose, respectively (Anu *et al.*, 2020). Physico-chemical techniques often require extremely regulated operating conditions and high temperatures and pressures. The purpose of biological pretreatment is to extract the lignin from lignocellulose biomass (Bala and Singh, 2019).

5.1. Physical Techniques

The physical pre-treatment of biomass wastes (seed cakes and energy crop stalks) left over from the liquid biofuels manufacturing industry frequently entails mechanical or manually handled processing. Here, there is a possibility to reduce the cellulose structure's crystallinity (Yoshida *et al.*, 2008). As a result, both the available surface area and the waste to be improved as feedstock material's particle size vary [41]. Technologies of this kind need a lot of energy. The resultant fine powder can be divided into smaller sections using sieve techniques. A significant portion of the total cost of industrial operations is frequently attributed to the pre-treatment of biomass waste (Baruah *et al.*, 2018). This indicates that in order to fully benefit from the waste material upgraded using this technology, the proper procedure must be followed (Fang, 2013).

5.1.1 Drying

Waste lignocellulosic biomass usually has a high intrinsic moisture content. Consequently, before utilising other methods for pre-treatment, drying processes are a bare minimum required for preparation of feedstock. There are several techniques for drying lignocellulosic biomass, including freeze drying (vacuum sublimation), convection oven drying (fan assisted), direct oven drying, and air drying (ambient atmosphere) (Karimi and Taherzadeh, 2016). For some feedstock materials, drying has been shown to deduct pore size; drying processes are employed to deduct the waste material's overall content of moisture to < 20 weight % (Nunes, Matias and Catalão, 2014). Due to their naturally occurring hygroscopic character, lignocellulosic waste products typically have a moisture content of 15 to 60 weight percent (Chen *et al.*, 2017). Removing water content is essential to increasing overall calorific value and combustion efficiency. This indicates that depending on the moisture content, the necessary temperature will be lowered, and oven drying can take place between 45°C-105 °C (Esteghlalian *et al.*, 2001). The amount of drying also depends on, either the feedstock is herbaceous or woody, which causes the inherent moisture content to vary. Grass, straw, and crop stubble are a few examples of herbaceous or non-woody biomass (Widjaya *et al.*, 2018).

5.1.2 Reduction of particle size Technique

Identifying the ideal particle size for the feedstock can be challenging since lignocellulosic biomass waste has fibrous characteristics (Nunes, Matias and Catalão, 2014). Reduced particle size of residues improves efficiency of releasing maximum calorific content as useful energy, because high size leads to lower conversion efficiency for generating heat energy in a boiler owing to the reduction in the heat and mass transfer rates (Barakat *et al.*, 2014). In addition, the synthesis of bioethanol is affected by the specific porosity and surface area of feedstocks undergoing enzyme hydrolysis of biomass wastes (Che Kamarludin *et al.*, 2014). Cellulose can be reduced in its crystallinity by using any number of physical and mechanical means. This increases the available surface area to be heated or cooled, thus speeding the transfer of heat and mass and the porosity and size of the particles in the feedstock material (Barakat *et al.*, 2014). The first technique to be investigated is milling, which is often the main technique

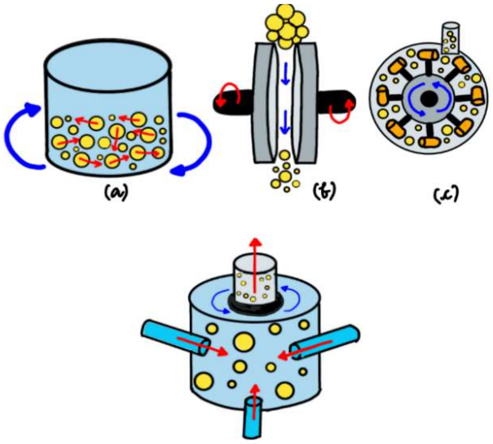

Fig. 10: Jet milling (yellow ball represents lignocellulosic waste) (Taylor, Alabdrabalameer and Skoulou, 2019). a) Ball milling; b) Disc milling; c) Hammer milling

utilized for large-scale valorization of lignocellulose biomass waste (Kumari and Singh, 2018).

5.1.3 Wet and Dry Ball Milling

The material undergoes a reduction in net crystallinity due to shearing force from the centripetal forces of the metallic balls during this high-intensity milling process (Fig. 10.) (Zakaria *et al.*, 2014). Batch and continuous scale versions of this process are eligible to provide the first treatment available for second generation wastes or be part of a feedstock source that generates supplementary energy production that is yielded as a consequence of first-generation feedstocks in liquid biofuel synthesis. Both the grinding jar size and the quantity of metallic spheres employed are adjustable (Zakaria *et al.*, 2014).

Ball milling is observed as an eco-friendly pre-treatment technique with low energy usage that works well under a variety of circumstances. The cellulose superstructure's hydrogen-bonded networks are disrupted under such circumstances by utilising solvent and solvent-free (dry) environments in comparison (Nuruddin *et al.*, 2016). With this type of milling, the gap between physicochemical and physical pre-treatment operations is filled in. Several research groups are now looking into the combination of ball milling with acid treatment to break down lignin in the substrate (Qu *et al.*, 2015). When ball milling is combined with a acid of low concentration at room temperature, the porous material swells, which leads to more destructive action. Compared to traditional acid hydrolysis, which requires a higher acid concentration, this method technique has been seen as less harsh. The lignocellulosic material is treated with less energy than with a traditional milling procedure since the swelling and milling temperature operations are performed at room temperature (Kim, Dien and Singh, 2016).

5.1.4 Extrusion

Because of mixing and shear stress on the sample, extrusion typically occurs at high temperatures, which modifies the cellulose physically. Biomasses with a moisture content of 15-20% are heated and sheared by extruders (Zheng and Rehmann, 2014). Remaining char and gaseous products have been produced via extrusion. The composition of lignocellulosic biomass is altered by extrusion, increasing the accessibility of carbohydrates to enzymes. Shearing, mixing, and heating are some of the methods that produce various alterations, such as chemical and physical ones. Extrusion causes lignocellulosic biomass (cellulose, hemicellulose, and lignin) to be depolymerised utilising affordable chemicals in straightforward, low-cost machinery (Capolupo and Faraco, 2016).

Various parameters, such as barrel temperature and screw speed, cause the lignocellulosic biomass's structure to be disrupted, resulting in the fibres' defibrillation or shortening, which raises the carbohydrates' enzymatic accessibility, improve the glucose yield of soybean hulls by 132.2%, 128.7%, and 69.6%, respectively, by using extrusion, alkali, and diluted acid pretreatment (Karunanithy, Muthukumarappan and Julson, 2008). Enzymes and the extrusion process have recently been used as a unique technique for the synthesis of ethanol. Several compounds, including Na_2S, H_2O_2, NaOH (Vandenbossche *et al.*, 2014), and diluted acid, have been processed using the extrusion procedure. Extrusion pretreatment's flexibility to different process adjustments is a significant benefit. whereas some drawbacks include the inadequate breakdown of hemicellulose and the lignin-carbohydrate matrix (Yoo *et al.*, 2011).

5.2 Physicochemical Methods

Physicochemical approaches are pre-treatment methods that alter the physical characteristics (previously described) as well as their chemical bonding (bond cleavage) and intermolecular interactions in a hybrid manner.

5.2.1 Steam (H2O) Explosion

Steam explosion, often referred to as auto-hydrolysis, is the first pre-treatment method discussed in this class and frequently considered to be the most prevalent (Brodeur *et al.*, 2011). High temperatures (160–260 C) and pressures (0.7–48 bar) are applied to the substrate during this hydrothermal process (Agbor *et al.*, 2011). The system quickly depressurises and repressurises after a while. This implies that steam is pushed into the fibrous waste's porous network and will quickly expand upon decompression, resulting in an explosion (Fig. 11). (Taylor, Alabdrabalameer and Skoulou, 2019). By intermolecular interactions, including hydrogen bonding in the matrix, being disrupted, this leads to hydrolysis of the physical bonds and upgrades the waste's chemical structure. It also applies a mechanical shearing force of high-intensity to the particle structure, a kin to the grinding techniques previously discussed.

Thus, blast-based treatments reduce the bulk density overall while increasing the lignocellulosic biomass waste particle's surface area and drastically changing its pore size and volume. The aforementioned attribute holds significant importance as it affects the logistics of the bioenergy/biofuels industry's waste materials storage, handling, and transportation for their conversion into solid biofuels (pellets), which are then used in the residential heating sector (Michopoulos *et al.*, 2014). Since the process is time-resolved, this technique might be controlled by changing the decompression rate to alter the intensity of the explosion. Using this pre-treatment technique, (Datar *et al.*, 2007). were able to produce biogas from hemicellulose with a high yield of hydrogen without requiring further acid pre-treatment (Datar *et al.*, 2007). The other way around, steam explosion is considered low energy compared to many other pre-treatment processes that have been mentioned up to this point by considering this approach compared to motor-driven mechanical shearing procedures.

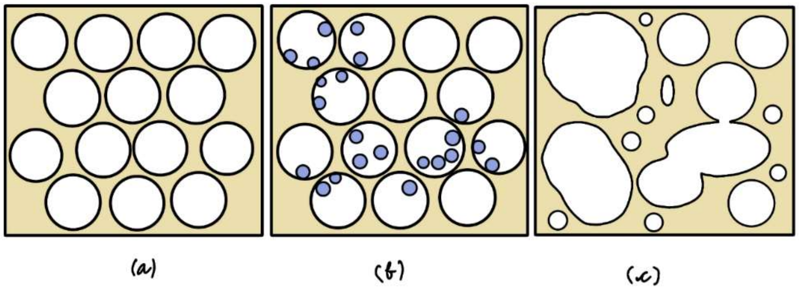

Fig. 11: Lignocellulosic waste’s porous network (Taylor, Alabdrabalameer and Skoulou, 2019). a) Untreated material; b) Adsorbent addition; c) Post explosion

5.2.2 Ammonia Fibre Explosion (AFE)

Heated liquid ammonia (NH_3) has been investigated as a potential fibrous explosion method. It has been discovered that this pre-treatment method increases the waste material's surface area, reduces the cellulose component's crystallinity, and breaks down or modifies the structure of lignin (Taylor, Alabdrabalameer and Skoulou, 2019). Compared to stream/CO_2 explosions, this pre-treatment method, which is solvent dependent, operates at a lower temperature (60–120 °C). Furthermore, pressure requirements of 17.2-20.6 bar have been shown to be lower for this pre-treatment than for CO_2 explosions at low temperatures (Haghighi Mood *et al.*, 2013). In contrast to the previous pressure-based techniques discussed, residence time prior to fast decompression determines how efficient this waste pre-treatment is. Another advantage of this technique is the pre-treatment of waste feedstock, having a moisture content similar to that of a CO_2 explosion. This process of explosion also cleaves ester bonds through hydrolysis and ammonolysis processes, producing a number of other byproducts. Using ammonia fibre explosion has also been discovered to enhance the porosity of the lignocellulosic biomass waste. This is due to the lignin's partial solubilisation that occurs during the pre-treatment (A. K. Mathew *et al.*, 2016). The process, therefore, tends to be more efficient on herbaceous wastes like straws than on woody biomass wastes like hardwood (Hatfield, Rancour and Marita, 2017).

5.2.3 The Microwave Irradiation Method for Pre-treating Biomass Waste

Molecule-level heating of lignocellulosic biomass waste can be achieved through dipole rotation by applying microwave irradiation which is a form of electromagnetic radiation. The depolymerization of the lignin component and a reduction in the crystallinity of cellulose are caused by the swelling effect that results from raising the moisture level inside the substrate (Kostas, Beneroso and Robinson, 2017). When opposed to traditional heating, the microwave irritant heating method is entirely different. In contrast to microwaves, which heat objects from the inside out, this is where heating happens from the outside in. A “explosion’’-like phenomenon, similar to steam/CO_2/ammonia fibre explosions, may result from the creation of hot patches within the polymeric structure (Fig. 12). This can be a point for inhomogeneous heating to take place in a sample of waste, whereby the process differs from the majority material. According to assumptions, the "microwave effect" can also cause waste materials crystalline structures to become unstable, but this is unrelated to thermal effects (Zhu *et al.*, 2015). To upgrade the dielectric qualities of the waste, however, are what determine whether microwave irradiation is a suitable heating technique. This type of biomass waste undergoes pre-treatment in a manner akin to the previously discussed hydrothermal procedure.

The waste biomass is combined with an aqueous medium and heated to a particular temperature, duration of residence, and ratio of medium to substrate. This implies that the material can be heated "selectively," which means that while the

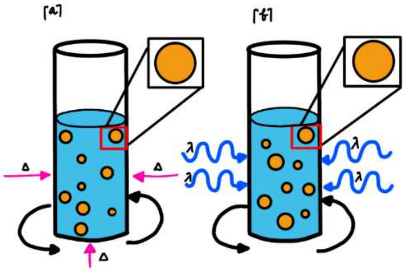

Fig. 12: Comparison of heat transfer profiles a) Conventional heating versus vs. b) Microwave-assisted biomass heating in solvent medium where bigger ball represents warmer area; ball inside the solvent medium represents particles of waste biomass (Taylor, Alabdrabalameer and Skoulou, 2019)

temperature of the specific solvent can be elevated, the waste cannot overheat. Because of their polarity, the available solvents employed in the particular process varied greatly from one another. Because they can absorb the radiation, polar solvents like water, alcohols, acetone, or acetonitrile will be more able to be heated. Non-polar solvents, on the other hand, have substantially higher dipole moments than alkanes, toluene, and dichloromethane, which allows for less absorption of radiation and thus less heating. (Kostas, Beneroso and Robinson, 2017). As a whole, this procedure appears to be significantly higher energy-optimization than using a traditional heating technique. Not only does the revolving dipole convert energy, but it also releases heat energy into the solid's colder areas by conduction. Almost instantaneous heating can create hotspots much more effectively, able to trigger an "explosion" within the porous network of biomass waste. A short dwell period combined with this suggests the pre-treatment could be energy.

5.3 Chemical Pre-Treatment Methods

Chemical pre-treatment methods do not mill the physical structure; instead, they are typically carried out under pressure, at a range of temperatures, and in an environment that is either alkaline or acidic, which can alter the chemical configuration of the waste and usually facilitate reactions such as hydrolysis or delignification. Weaker covalent interactions and hydrogen bonding between the molecules weaken the polymeric structure (Li *et al.*, 2010).This leads to the hemicellulose and lignin components of the cellulosic superstructure breaking apart.

5.3.1 Ozonolysis

Over the past 20 years, ozone has received a lot of attention as a potent oxidising agent that can be used to enhance lignin degradation (Travaini *et al.*, 2016). Ozone's electron deficit causes it to target high electron density regions, such as phenolic and aromatic compounds, first. It has been discovered that hemicellulose can also experience slight changes, despite the fact that lignin degradation is more selective as compared to other parts of the lignocellulosic waste matrix (University, 2001). This pre-treatment has also been used to decrease lignin, which is often acid insoluble, in conjunction with acid treatments. Ozonolysis is recognised for not creating any hazardous materials that need to be processed further on its own. The surface structure and fibrous character of the feedstock material have changed due to ozone-induced delignification, according to the results of microscopy techniques (Ahmad Rizal *et al.*, 2018).

Structural changes caused by swelling in the form of pore opening from the intrinsic moisture content discussed above increase the surface area that can interact with ozone (Fig. 13). Ozone instability in water leads to the easy formation of hydroxyl radicals, which independently function as potent oxidisers, hastening the breakdown of lignin (Den *et al.*, 2018). But producing ozone for the purpose is expensive (in terms of energy and equipment needed), which lessens its appeal as the main pre-treatment method. Having stated that, the process can operate effectively on the substrate at any temperature. This pre-treatment process can be done at room temperature in a variety of reactor setups. Fixed bed reactors in particular have been shown to be the most

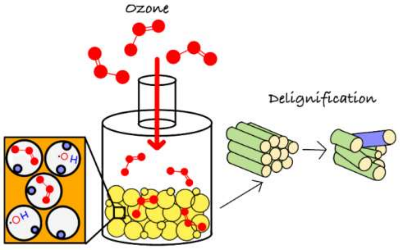

Fig. 13: The ozonolysis process and how it affects the delignification and hydroxyl radical production in the biomass waste particles' porous network (where yellow ball represents waste biomass; blue balls represent H_2O) (Taylor, Alabdrabalameer and Skoulou, 2019)

efficient and readily built up to an industrial size (Travaini *et al.*, 2016). I.e. The lignin decomposition rate of this kind of reactor has been observed to range from 34% to 78% depending on the biomass waste feedstock that is used, necessitating a 1-3 hour operation period (Den *et al.*, 2018).

5.3.2 Acidic Pre-Treatment

Even though acids are generally considered to be hazardous chemicals that corrode, they are in fact chemical instruments that facilitate the dissolution of the solid parts of the waste matrix of lignocellulosic biomass.There are two primary methods of employing acid as a pre-treatment. The first approach applies high temperature (160–220 ◦C) and low acid concentration in order to promote the hydrolysis of hemicellulose (Badiei *et al.*, 2014). The second variation entails a higher acid content and lower temperature, i.e., ambient -160 °C. High temperatures are suggested to degrade the hydrolysed products by ring-opening reactions with sugar-derived aromatic compounds.Although these molecules inhibit enzymatic fermentation though they are a platform molecule for directed chemical catalytic upgrading and have the ability to convert hemicellulose to xylose-based compounds such as furfural in high acid concentrations, even greater acetic acid concentrations may not be optimal.

Hydroxyl-methyl-furfural, acetic acid, and many other phenolic compounds were also detected as degradation products. Even though it is an acid treatment byproduct, acetic acid is frequently used in the pre-treatment phase (Wang *et al.*, 2019). Concentrated acid use has a significant drawback in that cellulose can degrade severely. This suggests that diluted acids are a more cost-effective long-term solution because they should cause less corrosion and are also a more selective pre-treatment method (Sun *et al.*, 2016). While this chemical pre-treatment of a feedstock material is extremely effective, recycling inorganic acids like H2SO4, HCl, H3PO4, and HNO3 is extremely costly, employs corrosion-resistant equipment, and ultimately demands downstream neutralisation processing, which is amplified with the use of concentrated acid (Romaní *et al.*, 2020).

5.3.3 Basic Pre-Treatment

It has been established that alkaline pretreatments of biomass waste favor solubilization of lignin and hemicellulose as do wet oxidation and ozonolysis (Sahoo *et al.*, 2018). The process involves the breaking of alkaline saponification of acetyl bonds and esters, which releases acetate when high working temperatures are not present. Indeed, alkaline-based pre-treatments that have been claimed to be effective in the very large temperature range of -15 to 210 ◦C (Sun *et al.*, 2016). This is very desired in using a base as a pre-treatment tool, given its wide temperature range because it uses less energy to accomplish the operation and is less caustic than alternatives that are highly concentrated in acid (Kim, Lee and Kim, 2016). In all cases, the residence time gets reduced because a successful treatment takes days or weeks to achieve completion, although this class of pre-treatment treatment usually undergoes at room temperature. Besides promoting saponification-type reactions, alkaline type-based treatments have been proven capable of improving features of the textural behavior within the biomass waste material that now has alterations in the form cellulose crystallinity, pores of several sizes, and inner surfaces area. (Agbor *et al.*, 2011). This is compounded by the swelling effect from the addition of alkaline substances. Examples of such alkaline chemicals used include aqueous solutions of Urea, $Ca(OH)_2$, NH_4OH, LiOH, NaOH, Na_2CO_3 and KOH, among others, to anhydrous ammonia and hydrazine.

6. Bioconversion of lignocellulose into value added products

Cellulose and hemicellulose, the carbohydrate components of lignocellulose, are degraded into low-molecular organic molecules such as methanol, ethanol, acetic acid, formic acid, 5-hydroxymethyl furfural, and others, and bioenergy. The fundamental raw material employed to produce resins, composite films, polyimide, and other synthetic aromatic polymers is refractory lignin macromolecular component. Hence, the cascade utilisation of biomass comprises several pretreatment steps followed by a process of separation of the individual biomass component, which is an effective greener technology methodology for systematically producing various bioproducts compared to other ineffective processes of thermochemical and biochemical processes. It was found that the best pretreatment processes to hydrolyse and dissolve the biomass components are advanced ones. These include ionic liquid (IL) pretreatment processes, hydrodynamic cavitation, electromagnetic field perturbation, ultrasonic irradiation, and supercritical fluids (CO2, H2O, and ethanol).

Table 4 illustrates high-value bioproducts that can be produced from lignocellulosic biomass. Bioproducts like vanillin, guaiacol, bioethanol, nanomaterials of carbon nature, bioplastics, dispersants of dye, and aerogels can be produced using the lignin content. As compared to standard silica and polymer-based aerogels, cellulose-based aerogels possess a greater degree of hydrophilicity, specific surface area, are biodegradable in nature, and biocompatible as well. They exhibit low sonic velocity, refractive index, and thermal conductivity too. Hemicellulose biofilms can be used for wound dressings, drug capsules, biodegradable packaging, and the production of conductive sheets using carbon nanotubes (CNTs) for metal-insulator transitions in electronics (Ashokkumar *et al.*, 2022a).

6.1. Biosorbents

Biological remediation tools are cheaper, safer, and more environmentally friendly, which promotes development. According to some reports, using biochar to purify the environment, create microbial communities from industrial effluents, or modify organic waste is also a great technique to obtain high fertility and quality (B. B. Mathew *et al.*, 2016). A developing method for erradicating pollutants from soil and water is the use of microbial biomass. A biological technique known as "biosorption" uses various biological elements, most notably bacteria, fungi, yeast, algae, etc., to remove contaminants from the environment in an effective manner (Antonino *et al.*, 2017). Due to their potential for eliminating environmental pollutants, bioabsorbents—also known as biosorbents—have drawn a lot of interest. An adsorbent (biological substance) and a sorbent (biosorbent) are used in the procedure.

One possible low-cost method for extracting or recovering contaminants from aqueous solutions is biosorption. Pollutants and adsorbent materials interact physicochemically to facilitate pollutant uptake. In order to effectively remove environmental pollutants, a variety of materials have been utilised as adsorbents in conjunction with biological materials in recent years (Pranay Samarth, Jangluji Chandekar and Kaustubh Bhadekar, 2012). Adsorption technology has been recognised as the most efficient and successful method for a few decades now. In recent times, diverse information regarding the application of different adsorbents from different sources has been gathered and investigated with the aim of purifying wastewater. Materials originating from various biological sources, such as agricultural by-products, are known as bioadsorbents.

The most prevalent kinds are microorganisms, which include algae, fungi, bacteria, and yeasts. There are variuos types of biological biosorbents such as chitosan, biochar, chitin, peat etc. The second most used polymer after cellulose in the world is chitin and a remarkable natural biopolymer. This rigid, white, inelastic nitrogenous polysaccharide serves as the supporting structure for a variety of organisms, including insects and crustaceans. Chitin and chitosan are isolated from crustaceans (Dutta *et al.*, 2021). Crustaceans exoskeleton is available in large amounts and also available as a metabolite of food processing. N-acetyl-and

Table 4: High-value bioproducts obtained from lignocellulosic biomass (Ashokkumar *et al.*, 2022b)

Lignocellulosic biomass components	Category	Applications/Uses
Cellulose	Ionic Liquids	Adsorbents for CO, sequestration, gold recovery
	Composites	Multi-functional materials: catalysts, energy storage, drug carriers
	Adsorbents	Sorption of water, oll, organic solvents, removal of heavy metal ions, dyes, drugs
	Carbon Nanoparticles	Bioimaging, biomedicines, biosensors, photocatalysts, optoelectronics, solar cells
	Aerogels	Separation of water/old/dye, thermal insulators, metal removal, electrode materials
Hemicellulose	Thin Films	Conductive films, drug capsules, food packaging, wound dressing materials
	Pharmaceutical Carriers	pH- and temperature-sensitive hydrogen, site-specific drug delivery, metal-ion recovery
Lignin	Carbon Materials	CNTs, graphene, GQDs, activated carbon, hard porous carbon; supercapacitors, lithium-ion batteries, catalysts
	Dye Dispersants	Lignosulfonate, alkali lignin, paper, plastic, leather, textile, rubber
	Bioplastics	Cheap additives, recyclable thermoplastics, eco-friendly plastic bags, solvent resistant, bio-based polyphenols
	Aerogels	Monolith, composite blankets, thin films, particles, powder, electromagnetic shielding, thermal insulators, sound-adsorbents, scaffolds, super capacitors

N-glucosamine units co-polymerise to form chitin. Numerous investigations have shown that chitosan and chitin-based biosorbents are effective adsorption materials.

Peat is essentially the surface layer of organic material that has formed in a soil due to nutrient deficiencies, low levels of oxygen, high acidity, and saturation with water. It is primarily composed of partly decomposed organic matter from plants. It is a widely available, reasonably priced, and plentiful biosorbent. Humic acid, cellulose, lignin, and fulvic make up raw peat. It is a porous composite soil material that is rich in humic compounds, or organic matter, at different phases of decomposition (Kinoshita *et al.*, 2013). Along with having polar functional groups, carboxylic acids, aldehydes, phenolic hydroxides, alcohols, ketones, and ether, lignin and humic acid can also create chemical interactions. Peat is divided into four categories based on the type of source material: sedimentary peat, moss peat, woody peat, and herbaceous peat. Numerous studies have clearly shown that peat is effective in removing color from a solution (Sanghi and Verma, 2013).

6.2. Bioethanol

The most widely produced biofuel worldwide, bioethanol is being eyed for substitution in the transport sector in place of petrol. Ethanol is also a useful organic solvent and intermediate in the manufacture of many significant chemicals and composites (Ashokkumar *et al.*, 2022b). Indeed, bioethanol warrants more study because it is a valuable historic product synthesized from lignocellulosic biomass. Several carbohydrate-rich renewable resources can be hydrolyzed into fermentable sugars that can be converted to ethanol as a source of bioethanol. Due to the base raw material and manufacturing process, bioethanol can be segmented into three generations. Directly for human or animal consumption, sucrose crops such as sugarcane (juice, molasses), cereals like wheat and corn (maize), or tuber crops such as sugar beet and potato, which are fermented by yeast, generate first-generation (1-G) bioethanol (Hans *et al.*, 2023). Non-food plants such as switchgrass and trees are used in second-generation or 2-G bioethanol, as well as other residual materials such as solid waste, municipal rubbish, wood processing waste, and agricultural waste. Algal biomass is used to produce third-generation (3G) bioethanol (Robak and Balcerek, 2018).

With increasing food production, agro-industrial waste is usually discarded raw and thrown away, burned, or simply dumped in an unorganized landfill, which pollutes the environment, affects public health, and depletes soil organic matter. By 2015, the market for bioethanol is expected to rise to $10×10^{10}$ l. China, Brazil, and the United States are the world's top producers of bioethanol. Brazil produced about 30×109 litres of ethanol from sugarcane in 2009, while the US produced 39.5×109 litres from corn (Ivanova, Petrova and Hristov, 2011). Cellulose is a glycosidically linked insoluble homopolysaccharide of fermentable sugars.Agro-industrial residues contain 40–50% cellulose. Hemicellulose, which is made up of pentoses, hexoses, and uronic acids, is thought to account for around 40% of agro-industrial residue. The three components that constitute the complex natural polymer known as lignin are sinapyl alcohols, coniferyl and P-coumaric. Three stages are necessary in converting lignocellulosic material into 2 g of bioethanol: fermentation, saccharification (hydrolysis), and pretreatment. Pretreatment is needed for lignocellulose biomass to minimize size, solubilize, hydrolyze, and separate its constituents-the constituent components, which are lignin, hemicellulose and cellulose. There are several pretreatment techniques accessible, comprising physiochemical, physical, electrical, chemical, biological, and combinations (Ravindranath *et al.*, 2011).

6.3. Biogas

Biogas is a clean energy resource used for heating and electricity rather than fuel. Biogas is a blend of gases produced by anaerobic digestion or biomethanation of organic waste. It predominantly comprises carbon dioxide and methane (CO2 and CH4), with traces of hydrogen sulphides and siloxanes. Anaerobic organisms use fermentation to digest biodegradable elements such as green waste, agricultural waste, municipal waste, food materials, plant waste, sewage, and compost in a closed system. A closed fermentation system is called a bioreactor, biodigester, or anaerobic digester. The production of biogas can boost rural economies and job creation through waste management and valorisation of biomass technologies. Parameters that influence the efficiency of biogas production are pH, temperature, mixing, retention time, C/N ratio, and organic loading rate. Microorganisms employed in bioreactors are sorted into three categories based on temperature sensitivity: mesophilic (35-40◦C), psychrophilic (15-25◦C), and thermophilic (55-60◦C) (Okolie et al., 2021). However, its use in anaerobic digestion is limited by the resistant internal components of lignocellulose, which in turn causes poor digestion and biodegradation. Future development will focus on optimizing and enhancing the productions of biogas through co-digestion processes and pretreatment methods with the addition of microbial inoculum, chemical additives (NaOH and CaO), and biological additives (white-rot and brown-rot fungi) (Ashokkumar *et al.*, 2022c).

6.4. Biosilica from Rice Husk

Lignocellulosic biomass is a type of agricultural waste that is widely produced on Earth in significant amounts. Rice husk is a significant byproduct of milling rice and a form of lignocellulosic biomass. The rice plant is notable for its ability to extract silica from the soil and store it inside of its cellulose micro-compartments as silicic acid. As a result, the RH produced by milling rice contains a sizable amount of amorphous silica, which has other uses. Moreover, RH, rich in silica, can be utilized as a raw material for thermochemical processes like gasification and pyrolysis to produce biofuels and biochars instantly. Among the most effective materials are nanoparticles, which are utilised extensively in a variety of industries including chromatography, anticorrosion treatment, medicine delivery, ceramic manufacture, and catalysis. RH comprises 13.6%–34.8% of lignin and cellulose and hemicellulose in varying amounts (56%–75%).

When produced from lignocellulosic biomass, advanced biofuels and bioproducts have the potential to significantly reduce emission of greenhouse gas and increase indigenous energy production in countries that have sufficient renewable energy sources. Because it produces a large amount of rice husk (RH) ash and contain plenty of organic materials including hemicellulose, celluloses and lignin, rice husk (RH) is the world's most useful agricultural waste. Therefore, rice husk (RH) is processed thermochemically to produce adsorbents (activated carbon and biochar) for environmental protection by the removal of pollutants, biofuels, and building materials (natural fibres) from the highly organic components in RH. It has also been seen that rice husk (RH) ash is a very good source for the production of biosilica because it contains trace levels of transition metals (like Al, Fe, Cu, and Zn), alkali metals (like Na and K), alkaline metals (such as Ca and Mg), and non-metals (such as Cl, S, and P). Specifically, biosilica is used as a precursor during the synthesis of silica derivatives, which are used in a wide range of applications, from additives for epoxy resins and refractory ceramics, to catalysts, composite material components, and pollutant adsorbents.

Because of this, the majority of researchers are now concentrating their efforts on creating ecologically acceptable rice husk (RH) pretreatment methods that are employed prior to the rice husk (RH) being used to produce biosilica. The utilization of rice husk (RH) as a source of biosilica as well as energy is extremely desirable because it is low-cost and highly available. Amorphous biosilica is generated as a possible raw material for different industries. In addition, numerous researchers have evaluated RH on a single basis for its combustion and extraction processes.RH was used mainly for energy production or as biosilica, considering the high concentration of silica and the heating value. Future research is focused on industrial-scale RH extraction for energy and biosilica generation. This option goes in line with the concept of sustainable development, which focuses on zero waste disposal (Nawaz *et al.*, 2022).

7. Difficulties and Approaches for Upcycling Lignocellulose

Despite its potential, upcycling lignocellulosic biomass is correlated with a number of technical and economic challenges. The inherent complexity and recalcitrance of the lignocellulosic structure make its efficient breakdown difficult, requiring energy-intensive pretreatment processes to expose fermentable sugars. Lignin is the major barrier due to its resistance to degradation and its tendency to inhibit enzymatic and microbial activity. To overcome these issues, researchers explore innovative approaches for developing genetically modified microorganisms and engineered enzymes that will be able to more effectively break down lignocellulose. Optimizing the pretreatment process, such as steam explosion, alkaline hydrolysis, or ionic liquid treatments, reduces the cost and increases yield for the process. Efforts are also being made to improve the integration of waste valorization strategies, such as lignin conversion into high-value chemicals, which may make the overall process more economically viable. Addressing these difficulties through a combination of biological, chemical, and engineering approaches makes the path toward efficient lignocellulose upcycling more attainable. The future of lignocellulosic biomass upcycling promises a lot for tackling global challenges related to energy, waste management, and sustainable material production. Newer innovations in biotechnological tools, such as metabolic engineering and synthetic biology, hold exciting promises for the improvement of microbial strains and enzymes that degrade lignocellulose into valuable biofuels, chemicals, and bioplastics more effectively. Advances in nanotechnology and catalytic systems will improve pretreatment process efficiencies, providing better hemicellulose, cellulose, and lignin separation. The complete valorization of biomass through biorefineries aligned with circular economy principles will further revolutionize this space by minimizing waste and maximizing economic returns from lignocellulosic feedstocks. As these technologies continue to mature, they will also be contributing toward the development of more sustainable industrial processes that could reduce dependence on fossil fuels and mitigate environmental impacts.

8. Conclusion

Lignocellulosic biomass is one of the most crucial resources in this transition towards a more sustainable and circular bioeconomy, since it can produce biofuels, biochemicals, and biomaterials from renewable feedstocks. However, its effective use is currently prevented by several major challenges. Lignocellulose, due to its complex, recalcitrant structure, and particularly the inability to break down lignin and effectively access fermentable sugars, calls for significant technological advances in pretreatment, bioconversion, and downstream processes. This will require the continuous research effort on advanced microbial strains, engineered enzymes, and innovative catalytic systems to improve efficiency and reduce the costs of degrading and valorizing lignocellulose. The economic feasibility of lignocellulosic upcycling is another critical hurdle, especially since many of the current processes are energy-intensive. The integration of waste valorization strategies, such as the conversion of lignin into valuable products, presents a major opportunity to enhance the economic viability of these technologies. Future developments in biorefinery design, which adopt circular economy concepts and minimize waste, are expected to be central to the wider application of lignocellulosic biomass. Ultimately, the effective upcycling of lignocellulosic biomass will only be achieved with interdisciplinary collaboration, involving fields from biotechnology, chemical engineering to materials science, and environmental economics. Such a collaboration will foster innovation in developing solutions to the current technical challenges while addressing environmental and economic sustainability. As the field continues to evolve, the advances in lignocellulosic bioconversion and waste valorization will make important contributions toward reducing dependence on fossil resources, mitigating climate change, and supporting the development of greener, more resilient industries.

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Authors Contribution

All authors have made substantial contributions to the concept, design and development of this review paper. Dr. Mahjabin: Provided critical revisions, ensuring clarity, coherence and academic rigor. Megha: Conducted the literature review, analysed key findings, structured the manuscript and ensured a logical flow of information and coherence in the discussion. Ananya Mathpal: Analysed key findings, conducted the literature review, structured the manuscript and ensured a logical flow of information and coherence in the discussion. Dr. Yuvraj Yadav: Coherence and academic rigor.

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