



## Lignocellulosic biomass feedstock: A benchmarking green resource for sustainable production of bioplastics

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### ABSTRACT

Presence of plastics in the surroundings is ubiquitous, as generation of plastics is booming globally and it gets accumulated in oceans leading to deleterious impacts on marine life, public health and the surrounding environment. Owing to its non-degradable nature, plastic particles remain in surroundings for extended periods which automatically facilitate its out spreading. Therefore, there is a need to shift to bio-based plastics, as bio-based green economy hinges on sustainable employment of bioresources for generating a broad spectrum of products, biofuels, chemicals and bioplastics. Typically bioplastics are synthesized from bio-based resources considered to contribute more to sustainable production of plastic as a part of the circular economy. Bioplastics are luring attention and growing as counterfeit material for petroleum-derived plastics owing to their biodegradability. Recently an engrossed interest has been burgeoning in producing drop-in polymers and new-fangled bioplastics by utilizing lignocellulosic feedstock. This paper reviews the enormous potential of lignocellulosic feedstock as a significant inedible substrate for bioplastic synthesis. Polyhydroxyalkanoates, polyurethanes, polylactic acid and starch-bioplastic are prevailing bio-based plastic comparably derived from lignocellulosic biomass. In forthcoming years bioplastic derived years' bioplastic derived from lignocellulose will loom as valuable material in numerous fields for an extensive range of cutting-edge applications.

### Introduction

Plastics have circumvented other polymers and conquered human lives owing to their inexpensiveness, flexibility, versatility and exceptional thermal properties. Plastic is an indispensable artificial polymer that has surmounted contemporary societies. Accumulating plastic wrecks in marine areas dates back half a century, with progress piling up on the ocean's surface in the past 60 years. But even in one of the

most promising scenarios of the ultimate reduction of plastic waste in forthcoming years, plastic is aggregating and building up regularly in the environment. The projected global emanation of plastics in ocean lakes and rivers ranges from 9 to 23 million tons yearly, comparably 13 to 25 million metric tons annually into the terrestrial environment as of 2016 (Rhodes, 2018). Plastic has numerous applications for multifarious utilizations and is a

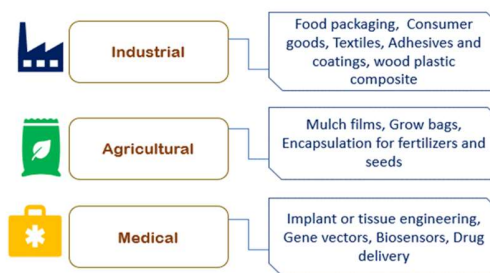
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distinguished counterfeit for diverse materials. Proclaimed global reports show that relatively 187 million tonnes of synthetic polymers based on petroleum are profusely generated annually and consequentially result in an enormous accumulation of plastic material, which induces environmental deterioration (Li *et al.*, 2021). Plastic garbage makes up around 8% of the entire weight of municipal solid waste, which is 25% (Lau *et al.*, 2020). Degradation of conventional plastics takes about 20-100 years in nature. It creates perilous problems, for instance, water pollution, air pollution and environmental contamination, which are further infuriated by the incineration of petroleum-based plastics as it discharges noxious gases into the atmosphere. Plastic pollution is extensively perceived as a principal environmental burden, peculiarly in aquatic ecosystems due to prolonged biophysical breakdown. Additionally, the presence of plastics in oceans manifests an alarming situation for marine organisms and affects them gigantically. Plastics consist of pernicious components such as phthalates, antimony trioxide, bisphenol A (BPA), and polyfluorinated compounds; they generally leach and cause adverse impacts on health and the environment. Plastics customarily end up in landfills with municipal solid waste due to inadequate waste management practices. There are elucidations required to solve the menacing problem of plastic waste, which has triggered the need to generate environment-friendly materials such as bioplastics. Bioplastics are innovative materials of this century and would be of immense relevance to the materials world. Bioplastic generation and usage will advance more in the forthcoming years; owing to this; these materials require careful evaluation for waste management and sustainability. Bioplastics are approaching imminent substitutes for petroleum-based plastics to diminish the detrimental environmental impacts and perilous health issues (Okolie *et al.*, 2020). Several applications of bioplastics have been depicted in figure 1. Bioplastic fabrication by exploiting renewable feedstocks has been endorsed in former years for the generation of advanced bio-sourced plastics. Using renewable resources for bioplastic production has distinguished research interest in the past years as an expedient to mitigate and alleviate greenhouse gas emissions that are principally

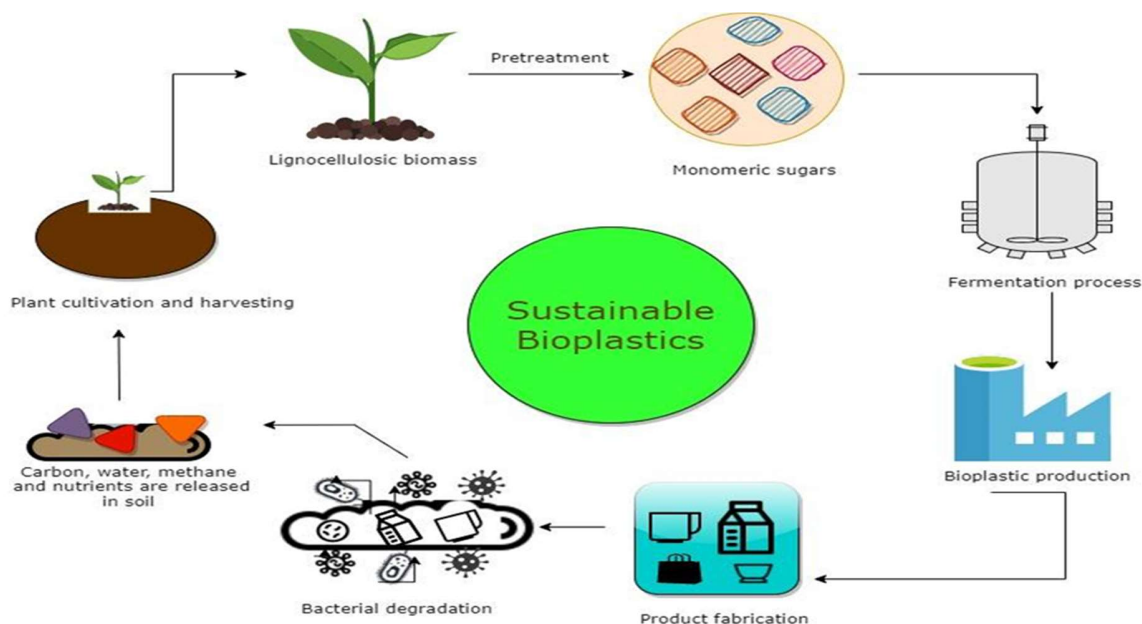


**Figure 1: Plethora of applications of bioplastics**

generated by fossil fuel burning, production and fabrication of petrochemical-based plastics. Because such materials might be used for the preservation of resources which automatically renders sustainability (Ahmad *et al.*, 2018) among them, lignocellulosic feedstocks are an appealing alternative. Lignocellulosic feedstocks are specified non-edible plant components primarily composed of three building blocks (i.e. lignin, cellulose and hemicellulose) (Nanda *et al.*, 2014). On average, lignin is (10-40%), cellulose (25-55%) and hemicellulose (11-50%) (Zhang *et al.*, 2020). Lignocellulosic biomass (LCB) is principally categorized into forestry biomass (e.g. wood logs, sawdust bark etc.), energy crops (e.g. poplar, switchgrass, willow, elephant grass etc.) and crop residues (e.g. wheat straw, corn stover, rice straw, oat hull etc.) (Singh *et al.*, 2020). LCB is a propitious feedstock for the feasible production of bioplastics owing to its non-seasonal opportunistic availability and socioeconomic advantages. Additionally, lignocellulosic feedstock being non-edible does not mien any competition to food crops, being contemplated as next-generation feedstocks (Nanda *et al.*, 2018). Recently, numerous inedible resources such as bagasse, kraft pulp, corn stover, and switchgrass are being employed as lignocellulosic feedstock for a significant circular economy (Sherwood, 2020). This review highlights recent bioplastic overtures and bio-based polymer synthesis from lignocellulosic feedstocks. Fig. 2 depicts sustainable bioplastic production using LCB.

#### **Present scenario of bioplastic production from lignocellulose**

The aim of developing bio-based and eco-friendly polymers has tremendously increased in current years. LCB has enormous capability to produce bioplastics, and it is compelling because the



**Figure 2: Sustainable production of bioplastics from LCB**

generation of high-performing renewable materials is an indispensable factor for bio-based industries (Deepa *et al.*, 2015). The usage of LCB for bioplastic generation faces confrontations, such as the high cost of production routes, and it signifies the necessity for technical advances and improvement in the field. In reported studies, it has been investigated that bioplastic production from organic waste and corn stover can typically cut down expenses (Kim *et al.*, 2020). This interdisciplinary section of research is a remarkable amalgam of engineering and life science. It can offer and endeavour novel methodologies to redesign routes of biosynthesis for conversion of biomass; it will eventually lead to supreme economic and effective strategies to transform biomass into valuable commodities such as biopolymers (Galbe and Walberg, 2019). The recalcitrant nature of LCB is a primary heed in biorefinery industrial processes for bioplastic production and chemical transformation. In order to accomplish environmental and economic feasibility, it is necessary to use an adequate pre-treatment method, which typically increments cellulose digestibility through disruption of the complex lignin-carbohydrate matrix; it also helps in increasing specific surface area and in reducing particle size ultimately, resulting in an extensive

recovery of sugar after the process of enzymatic hydrolysis. Pre-treated biomass could be saccharified using acid hydrolysis, by simultaneous saccharification and co-fermentation (SSCF) or by simultaneous saccharification and fermentation (SSF). Released monomeric sugars are directly fermented into biopolymers after the process of enzymatic hydrolysis. Required components are fermented by utilizing a broad range of microbes to produce several fragments that can be used for biopolymer production.

#### **Pre-treatment of LCB for bioplastic production**

LCB has a complex and heterogeneous composition, ultimately making it demanding for bioplastic production. In order to make LCB technically, environmentally, and economically feasible, there is a need to assimilate their production with different components. In the sector of bio-refineries, this includes techniques and several processes for the conversion and extraction of numerous products. Multifarious pre-treatment methods will be discussed in the next section.

#### **Physical pre-treatment methods**

Size reduction is a powerful method to escalate the receptibility of enzymes for hydrolysis. Hammer milling, chipping, cutting and grinding are the physical methods to curtail the particle size of biomass (Raj *et al.*, 2022), thereby immensely

increasing pore size, surface area and decrystallizing biomass for high enzymatic digestibility. Meanwhile, the final particle size totally depends on the kind of method used; chipping gives a particle size of 10-30mm, while milling and grinding provide a particle size of 0.2-2mm (Veluchamy *et al.*, 2019). But the primary drawback of ball milling is that it consumes high energy and sometimes does not remove lignin content efficiently (Mankar *et al.*, 2021). In a study to attempt the minimum energy consumption, wet desk milling (WDM) was used for the pre-treatment of rice straw, Hiden *et al.*, (2009) found the energy requirement for 30 minutes (10 cycles of 3 min each) was 5.4 MJ/Kg. In contrast, the energy requirement during the dry ball milling method for the pre-treatment of rice straw under the same conditions was found to be 54 MJ/kg of biomass. The energy required for pre-treatment in the WDM process also depends on the kind of biomass feedstock (Da silva *et al.*, 2010).

Another promising and encouraging thermo-mechanical method is extrusion; biomass is exposed to shear and heat with continuous mixing (Duque *et al.*, 2017). High temperature and pressure during the process modify the substrate's physical (defibrillation) and chemical structure; it boosts the availability of surface area and augments enzyme accessibility for expediting hydrolysis (Kumar *et al.*, 2020). Extrusion has been established as a comparable method for accustomed

methods, such as alkaline and acid treatments relating to hydrolysis efficiency. In a demonstrated study, a comparison of saccharification yields was established between extruded soybeans hulls with material pre-treated with alkali-acid and being extruded. Extrusion was found to be as competent as alkali, effectively superior to acidic pre-treatments, and improved saccharification by 132% (Yoo *et al.*, 2011).

Microwaves are nonionizing electromagnetic radiations having a wavelength range between 1mm to 1m, and these radiations selectively transfer energy to different substances (Huang *et al.*, 2016). Microwave radiation disrupts recalcitrant units by triggering an explosion within the particles in the given material (Mankar *et al.*, 2021). Microwaves have captured comprehensive attention in diligent biorefinery applications for the treatment of LCB, being a thermal process. And in the last three decades, the utilization of microwaves in the pre-treatment processes of LCB has deliberately moved from the laboratory to pilot scale studies (Li *et al.*, 2016). Heating by microwave distinguishably enhances the enzymatic saccharification process by fibre fragmentation and swelling (Diaz *et al.*, 2015) by virtue of accelerated hasty and uniform heating of LCB particles. Plant fibres remain intact, and approximately no effect can be seen in plant fibres when pre-treated with microwaves under a temperature equivalent to 100 °C (Chen *et al.*, 2017).

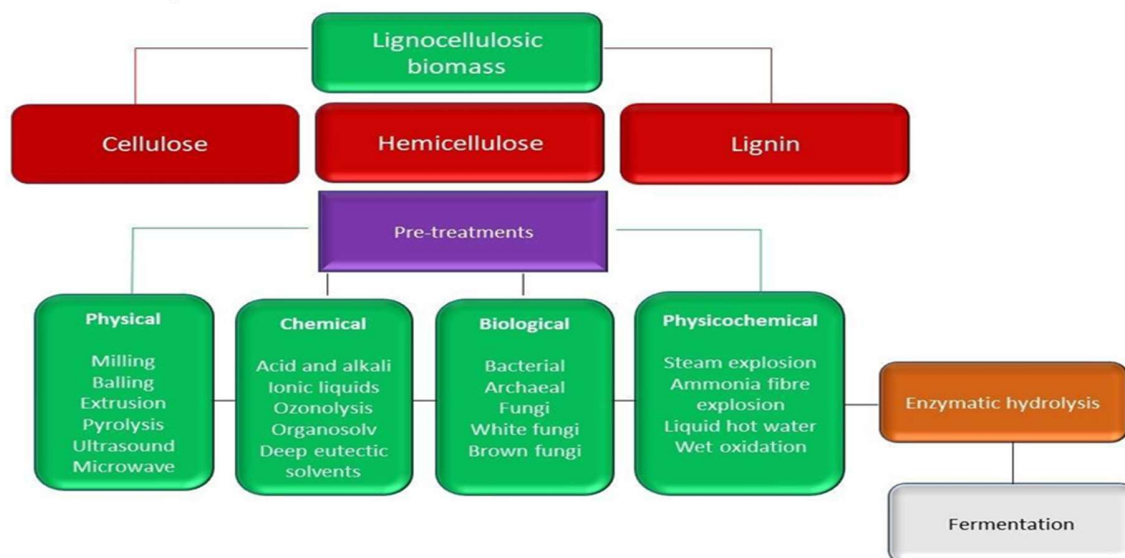


Figure 3: Different pretreatment approaches for LCB

Alternatively, LCB is grounded into minuscule particles in traditional heating pre-treatment methods to avoid a temperature gradient. Then high-pressure steam injection and heat conduction are used for heating; it might degrade the hemicellulose in humic acid or furfural and therefore afflicts the sugar recovery (Li *et al.*, 2016). Fig. 3 shows several pre-treatment approaches.

#### Chemical pre-treatment methods

An array of distinct chemical methods are used for the pre-treatment of LCB, including organosolv, kraft pulping, ionic liquid and dilute acid etc. Mentioned pre-treatment methods have compellingly proven as an adequate and effective method for a broad range of lignocellulosic feedstocks (Tu and Hallett, 2019). LCB acid treatment is primarily accustomed to eliminate hemicellulose. Acid pre-treatment results in enhanced receptivity of enzymes towards cellulose; generally, phosphoric acid, acetic acid, and sulphuric acid are used for improved pre-treatment (Rezania *et al.*, 2020). In dilute acid pre-treatment, LCB is treated through the action of hydrolysis and solubilization of hemicellulose and acid-catalyzed depolymerization of the lignin. Moreover, the type of acid used and its concentration can affect solubilized lignin's condensation (Hendricks and Zeeman, 2009). Two different ways could achieve acid pre-treatment – concentrated acid (30-70%) treatment at approximately lower temperatures and dilute acid treatment at relatively higher temperatures (Den *et al.*, 2018). Both the mentioned approaches have their own leverage and impediments, In dilute acid treatment minimum amount of acid is used, but the needful energy requirement for the process is ultimately higher. On the contrary, meagre energy is consumed in treatment with concentrated acid, but it relatively results in higher acidity, which brings about the generation of fermentation inhibitor (5-hydroxymethylfurfural). These inhibitors severely affect fermenter microorganisms by breaking down DNA and reducing RNA synthesis, which automatically hinders enzymatic activity (Woiciechowski *et al.*, 2020). On the other hand, alkali pre-treatment includes hydroxides of calcium, sodium, ammonium, and potassium, amid pre-treatment bond cleavage (ester, alkyl-aryl, aryl-

ether) occurs, and uronic acid and acetyl groups are subsequently removed from hemicellulose and lignin (Kumar *et al.*, 2020), and it results in improved access of enzymes towards cellulose thus helps in efficient fermentation of sugars (Cheah *et al.*, 2020). In an investigated study, alkali-catalyzed hot water pre-treatment was performed at 170 °C, and it resulted in the alteration of present recalcitrants in bamboo biomass and produced 30.9% reducing sugars. In a reported study, pine poplar wood treated with sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>) and NaOH (sodium hydroxide) at a temperature of 93°C, it adeptly dissolved hemicellulose and lignin content and generated 69.3% glucose (Bay *et al.*, 2020). Furthermore, ammonia or CO<sub>2</sub> explosions and ozonolysis are effective alternative pre-treatment methods. Biological pre-treatments are usually innocuous and require low energy, and do not generally generate inhibitors for the downstreaming processes (Tu and Hallett, 2019). Microorganisms such as bacteria and fungi are utilized in degrading LCB to macromonomers by hydrolyzing cellulose or depolymerizing lignin (Chen *et al.*, 2017)

#### Cellulose conversion routes for bioplastics production

Cellulose is extracted from LCB and practised for bioplastic production (Govil *et al.*, 2020). The ultimate amount of cellulose content relies on the source from which it has come. Conversion of cellulose into bioplastic composites includes lignin and hemicellulose removal, cellulose extraction and surface modifications (Reshmy *et al.*, 2021).

#### Hemicellulose removal and delignification

Generally, the removal of lignin includes high pressure and temperature, the occurrence of developmental processes at lower temperatures promptly removes the lignin, and simple recovery of chemicals becomes difficult (Yang *et al.*, 2019). In the delignification process, lignin is isolated from biomass, and some part of hemicellulose also gets removed. Delignification is imposed using hydrogen peroxide, sodium chlorite and oxygen. Delignification results in the degradation of lignin content, transfer of it into a liquid medium and consequentially, elimination of lignin by proper washing. Delignification does not selectively remove lignin; therefore, some quantity of cellulose and hemicellulose is eliminated altogether (Reshmy *et al.*, 2021).

**Cellulose extraction and surface modification**

Highly purified cellulose in different forms has been extracted by utilizing several processes relatively depending on the source and type of pre-treatments (Mondal, 2017). Various methods such as pulping ball milling, microfluidization and homogenization are practised for cellulose extraction from LCB. Extracted pulp through these techniques can be further chemically and mechanically treated for liberating cellulose. High-pressure homogenizing techniques are used for refining to get the defibrillated cellulose in the nano range (Kargarzadeh *et al.*, 2017). Combined force in high-pressure technique aids immense defibrillation and results in the generation of nanocellulose. The kraft process is a supreme chemical pulping method, in this method, lignin is dissolved using  $\text{HO}_3\text{S}^-$  and  $\text{H}_2\text{SO}_4$  (Khalil *et al.*, 2012). Another cellulose extraction method is steam explosion; this LCB is treated with several chemicals at high-pressure steam for a precise interval of time, followed by abrupt steam discharge. Due to the abrupt release of pressure, the extracted cellulose will be having high aspect ratio and size of particles in the nano range (De Moraes *et al.*, 2013).

Cellulose has hydrophilic nature to boost its solubility and processibility; some surface modifications are needed, and various methods are being used for this purpose (Yoo and youngblood, 2016). Surface modification methods include surfactants and graft copolymerization (Rahman and Putra, 2019) and surface derivatization (Kargarzadeh *et al.*, 2017). A graft polymer primarily consists of branches of a particular polymer being attached to the backbone of other polymers; typically, graft polymerization is of specific interest because of its adaptability in creating an extensive range of functional groups on the surface since it allows the combination of required properties of two or more polymers into an individual unit Acetylation was found to improve transparency, and thermal degradation contrastingly decreases the hygroscopicity of biocomposites of cellulose without even intruding the microfibrillar morphology (Ahmad *et al.*, 2015). Owing to its defined structure, modifications can be made in cellulose in numerous ways; presence of hydroxyl groups in the chain offers many potential capabilities and the way in which cellulose will be

affected ultimately depends on the conditions and chemicals applied (Rol *et al.*, 2019). Carboxymethylation of cellulose generates extensively pure water-soluble cellulose derivatives being applicable primarily as ophthalmic solutions. Various novel enzymes have been substantially tested, such as laccases, hemicellulases and lytic polysaccharide monooxygenases (LPMO); these enzymes promote and improve fibrillation by improving access to cellulose to cellulase (Rodríguez-Zúñiga *et al.*, 2015). In a study, an epoxy modification was done by surface modification of fibrils of cellulose through the process of oxidation using cerium (IV) consequential follow-up by grafting with glycidyl methacrylate (Oliveira *et al.*, 2017). Bioplastics incorporated with cellulose have exceptional mechanical strength. They can be produced from the suspension of nanocellulose by practising several film-forming methods such as extrusion or blow molding.

**LCB bioconversion to biodegradable and recyclable biopolymers****Polyhydroxyalkanoates (PHAs)**

PHAs are polyesters and both biocompatible and biodegradable in nature, consisting of hydroxyalkanoic acids. Numerous bacterial species extensively synthesize them as a reserve material for carbon and energy. Synthesis of PHAs in bacterial cells occurs in unfavourable conditions like surplus carbon with environmental stress of essential growth nutrients such as phosphate, nitrogen or oxygen limitations (Annamalai and Sivakumar, 2016). PHAs have loomed and emerged as an excellent polymer for the corrective solution to the problem of plastic waste. PHAs are biodegradable in the marine environment and soil, forming methane, carbon dioxide, biomass and water as by-products after efficient decomposition (Chalermthai *et al.*, 2021; Jadaun *et al.*, 2022).

Additionally, PHAs classically represent those value-added products which are generated from renewable feedstocks such as LCB by utilizing microorganisms and pose comparable properties to petroleum-based polymers (Mannina *et al.*, 2019). Numerous strategies to produce PHAs from LCB have been developed and demonstrated based on the bacteria used or which LCB should be used (hemicellulose-rich or cellulose-rich) (Moorkoth and Nampoothiri, 2016). Various *Bacillus* sp. has



the potential to produce poly(3-hydroxybutyrate) [P(3HB)], a class of PHAs, from LCB without pre-treatment, i.e. mango peels (Gowda and Shivkumar, 2014) and oil palm trunk sap (Lokesh *et al.*, 2012) were utilized as a primary carbon source to produce [P(3HB)] in *B. thuringiensis* and *B. megaterium* with a concentration of 4.03 g/L and 3.28 g/L respectively. However, detoxification and pre-treatment are required in most cases. Over time, several methods have been advanced and developed for the pre-treatment of LCBs and to depose the inhibiting compounds for the efficient and adequate usage of lignocellulosic feedstock. Sugarcane bagasse, a cellulose-rich biomass, was effectively detoxified and pre-treated with acid to form sugarcane bagasse hydrolysate, it was utilized as a substrate to produce P(3HB) with an achieved concentration of 4.4 g/L and 2.73 g/L in *Burkholderia cepacia* and *Burkholderia sacchari* strains. (Silva *et al.*, 2007). Another reported study demonstrated and established an integrated pre-treatment process, AFEX (Ammonia fibre expansion), followed by enzymatic hydrolysis of hemicellulose and cellulose fractions to prepare wheat straw hydrolysate, *B.sacchari* potentially produced P(3HB) with a final titer of 105g/L by utilizing a feedstock that primarily consisted

xylose, arabinose and glucose in fed-batch fermentation (Cesário *et al.*, 2014).PHA copolymers production, counting natural and non-natural PHAs, in addition to P(3HB), is another compelling research area. At first, numerous LCBs, such as sugarcane bagasse, rubber wood, cassava stalk and sorghum stalk, were investigated and tested for mixed microbial fermentation as a feedstock for the production of PHA after being given pressurized hot water treatment. Physical treatments given to feedstocks efficiently increase saccharification with the distinguished recovery of sugar yields of 178.0 mg/g of xylose and 438.7 mg/g of glucose in rubber wood. Microbial fermentation, principally including Alphaproteobacteria and Bacteroidia classes, culminated in the production of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) [P(3HB-co-3HV)] (Yan *et al.*, 2021). Using the same microbial classes to produce P(3HB-co-3HV.), rubber wood hydrolysates were also investigated. Primary PHA accumulating strains belonging to the Bacteroidia and Alphaproteobacteria classes were successfully screened by adding xylose to rubber wood hydrolysate as a co-substrate with final PHA content of 43.6% of dried cell weight (Li *et al.*, 2022). Table 1 is displaying production of PHA copolymers using LCB

**Table 1: PHA copolymer production from LCB (Govil *et al.*, 2020)**

Lignocellulosic feedstock	PHA Conc. (g/L)	% PHA accumulation (w/w)	Microbe used	PHA copolymer	References
Barley biomass hydrolysate	1.8	54	<i>Ralstonia eutropha</i> 5119	PHBV	Bhatia <i>et al.</i> , 2018
Grass biomass hydrolysates	0.3	33	<i>Pseudomonas</i> strains	MCL-PHA	Davis <i>et al.</i> , 2013
Liquefied wood hydrolysates	60.5	NA	<i>Cupriavidus necator</i>	PHBV	Koller <i>et al.</i> , 2015
Sawdust hydrolysates	0.3	78	<i>Brevundimonas vesicularis</i> and <i>Sphingopyxis macrogoltabida</i>	MCL-PHA	Silva <i>et al.</i> , 2007
Miscanthus biomass hydrolysate	2.0	44	<i>Ralstonia eutropha</i> 5119	PHBV	Bhatia <i>et al.</i> , 2018
Pine biomass hydrolysate	1.7	63	<i>Ralstonia eutropha</i> 5119	PHBV	Bhatia <i>et al.</i> , 2018
Rice bran and corn starch hydrolysates	77.8	55.6	<i>Haloferax mediterranei</i>	PHBV	Matsumoto <i>et al.</i> , 2011

PHBV - Poly (3-hydroxybutyric acid-co-3-hydroxyvaleric acid).

MCL-PHA - Medium chain length PHA.

NA - Not available.

**Polylactic acid (PLA)**

Lactic acid (LA) is a polymerized chemical that could be utilized to produce biodegradable LA polymers using biotechnology on waste and agricultural residues (Djukić-Vuković *et al.*, 2019). It has extensive usage in food, pharmaceutical and cosmetic industries as a preservative as it retards the growth of pathogens (Komesu *et al.*, 2017). Still, the crucial application of LA is its usage in the processing and synthesis of polylactic acid (PLA), a significant biocompatible plastic currently in use. Biotechnological practices predominantly prevailed production and synthesis of LA to possibly obtain optically pure LA enantiomers by selecting a suitable strain which can be efficiently grown on renewable feedstocks, resulting in high productivity and purity (Lunelli *et al.*, 2010). Commercially available PLA is generated by ring-opening polymerization and polycondensation (Garlotta *et al.*, 2001), PLAs chirality is controlled by tuning the optical activity and dissemination of LA units in the polymer backbone; it enhances final polymer performance. Currently, sugar beet, sugarcane and corn starch are used as raw materials for the production of LA on a global scale. Profound research is going on PLA resin production on a lab scale using second-generation feedstock such as wheat straw bagasse, wood chips and corn stovers, striving to accomplish comparable qualities, challenges and solutions relevant to increase sustainability and competitiveness of LA production on agricultural residues and wastes. The fermentation of monomeric sugar generates bio-based lactic acid, and hydrolysis of LCB is a luring way to the production of lactic acid. PLA being thermoplastic, can be easily transformed into different end products using numerous industrial techniques such as blow molding, fibre extrusion, film extrusion and injection molding; PLA's processing temperature is low in contrast to conventional thermoplastics. Numerous strains, such as *Bacillus coagulans*, can metabolize hexose and pentose to LA in an effective way. In a study, LA was synthesized from Beachwood and pine being organosolv pretreated, cellulose-rich solids were subsequently fractionated and simultaneously employed saccharification and fermentation using *Lactobacillus delbrueckii* subsp. in batch mode, and the final yield reported was 62g/L<sup>-1</sup> (Karnaouri *et al.*, 2020). The polymerization of LA could be

carried out through either ring-opening polymerization or direct condensation polymerization (Lopes *et al.*, 2014). Reactions in direct condensation require probably high temperature, an extended reaction time and low pressure for producing PLA of high molecular weight. On the contrary, ring-opening polymerization could be carried out at relatively low temperatures and requires a meagre reaction time. PLA being made from direct condensation generally has low molecular weight with indigent mechanical properties, while ring-opening-produced PLA has high molecular weight through heating in the presence of the catalyst, stannous octoate under Vacuum (Singla *et al.*, 2012). In recent times several PLA-based technologies are imminently emerging expeditiously for the advances in developing green material procured by making blends with polymers and reinforced fibres like starch and cellulose with enhanced mechanical, chemical, and biological properties in accordance with the required application. List of various lignocellulosic feedstocks is given in Table 2 that could be used for producing bioplastics.

**Bio-ethylene**

Polyethylene (PE) is an aliphatic polyolefin generated by the polymerization of ethylene and conjointly impersonates more than 30% of the plastic market on a global scale (Hutley and Ouederni, 2016). And presently produced from natural gas or crude petroleum by employing steam cracking using numerous metal catalysts at a temperature of 750–850 °C. In spite of that, bio-based-polyethylene can be produced from second-generation ethanol generated in cellulosic biorefineries (Raj *et al.*, 2022). Bioethylene is a chemically indistinguishable substitute for ethylene we get from petrochemicals. Bioethanol is produced from well-developed routes such as fermentation and hydrolysis of sugarcane and corn feedstocks. The ultimate production cost of bio-ethylene depends on bioethanol production, which shows the importance of the origin of bioethanol in the process. The technology used to convert ethanol to ethylene is well-established and commercially available; bio-polyethylene (bio PE) is a newly developed bioplastic being prepared and produced from ethanol extracted through solid-state fermentation of LCB (Reshmy *et al.*, 2021).



**Table 2: Production of PHA and PLA using LCB (Kawaguchi *et al.*, 2022)**

Bioplastic	Lignocellulosic feedstock	Specified condition	Microorganism used	Titer (g/l)	Reference
PHAs	Rice husk	Alkali pre-treatment given; Batch fermentation with supplementary urea	<i>Burkholderia cepacia</i> USM	2.35	Heng <i>et al.</i> , 2017
	Corn stover	Combined acid and alkali pre-treatment; fed-batch fermentation using lignin	<i>Pseudomonas putida</i> KT2440	1.0	Sindhu <i>et al.</i> , 2013
	Lignin	Fed-batch using lignin-abundant black liquor; obtained from alkaline pretreated sugarcane bagasse	<i>Pseudomonas monteilii</i>	0.24	Unrean <i>et al.</i> , 2021
PLA	Sugarcane bagasse	Acid pre-treatment; furfural-supplemented pre-culture	<i>Bacillus coagulans</i>	75.9	Van der Pol <i>et al.</i> , 2016
	Pulp residues	Fed batch SSF; pH neutralized with CaCO <sub>3</sub>	<i>Bacillus coagulans</i>	110	Zhou <i>et al.</i> , 2016
	Sugarcane bagasse	Acid and steam explosion treatment; pH adjustment using NaOH	<i>Lactobacillus pentosus</i>	72.8	Unrean, 2018

Numerous commercial stakeholders, like SABIC (Netherlands), Braskem (Brazil) and Ineos (bi-naphtha from UPM Biofuels) are currently producing bio HDPE, bio-PE and bio-LDPE from bioethanol, being derived from sugarcane (Raj *et al.*, 2022). Moreover, advances in bioethanol-producing technologies are highly alluring, as they are a drop-in equivalent to petroleum-based polyethylene, bio-PE also displayed effective applications as being used as epoxy resins as a substitute to petroleum-based processes (Delgado-aguliar *et al.*, 2017). In a study bio-PE from sugarcane ethanol was synthesized for the purpose of biocomposite reinforcement application; it improved tensile and mechanical strength (Castro *et al.*, 2017). Consequentially unified synthesis of C2 molecules from relatively bountiful renewable feedstock has acquired a massive interest in substituting synthetic plastics in biorefineries.

#### **Polyglycolic acid (PGA)**

It is an integral biopolymer owing to its biodegradable nature and mechanical properties which offers numerous applications of this biopolymer in the medical and renewable industries (Budak *et al.*, 2020). Glycolic acid (monomer of PGA) is relatively small alpha-hydroxy acid which consists of alcohol and carboxyl groups. PGA is produced petrochemically from formaldehyde and CO by utilizing several acid catalysts; it is an aliphatic ester of glycolic acid. Although it can also be obtained from renewable resources (sugarcane, sugar beets etc.), the worldwide market of glycolic acid will exceed from \$160 million in 2015 to an

estimated \$415 million by 2030 (Jem and Tan, 2020). Generally, PGA could be synthesized via two methods, first one is Poly-Condensation of glycolic acid and the one is Ring-Opening Polymerization of glycolide. Precursors of glycolic acid can be generated from renewable resources (grapes, cantaloupe, sugar beets and sugar cane) via biotechnological approaches by using genetically modified strains like *E. coli* and *Corynebacterium glutamicum* (Salusajarvi *et al.*, 2019). Gokturk *et al.*, (2015) optimized copolymerization conditions for the conversion of C1 feedstocks into formaldehyde and CO into PGA through cationic alternating copolymerization and ultimate results gave 92% yield of PGA with extensive crystallinity and high melting point (192°C), triflic acid was being used as catalyst. The presented method constituted a simple, effective and economical approach for the purpose of synthesizing PGA directly from C1 feedstocks, which are derived potentially from biomass. VTT research centre demonstrated the formation of glycolic acid using natural feedstocks i.e., sugar hydrolysate by the fermentation of sugars using constructed engineered yeast strains (Gadda *et al.*, 2014). A number of blends can be prepared using PGA, PLA, PHAs and cellulose, in a study PGA-PLA polymer blend was prepared for particular uses in drug delivery and tissue scaffolds applications (Salusajarvi *et al.*, 2019).

#### **Polyurethanes (PUs)**

PUs are generated from condensation polymerizations between polyols and isocyanates,

which are one of the most versatile and flexible polymer families. Presently, isocyanates and polyols together are extensively petroleum-derived; in recent years, comprehensive research interest has developed in generating polyols and PUs from renewable bioresources (Tenorio-alfonso *et al.*, 2020). Being the most plentiful biomass in the world, LCB has enormous potential to be used as feedstock for the production of polyols and PUs as it contains hydroxyl groups (Malani, 2021). LCB acts as an economical substitute for the development of PUs. Conversion of LCB into liquid polyols for PU applications includes acid- or base-catalyzed atmospheric liquefaction processes using polyhydric alcohols as liquefaction solvents, and derived polyols could be further used to prepare several PU products like film, foams and adhesives. And eventual properties of these biomass-derived polyols extensively depend on the characteristics of the biomass being used and liquefaction conditions. Various diverse LCBs, including crop residues, wood and biorefinery by-products examined for PUs and polyols production. LCB has solid nature; hence its chemical modification is essential to change LCB into liquid polyols for the generation of PUs. For optimized mechanical properties of PUs, it is necessary to incorporate versatile aliphatic polyols with tough and rigid lignin polyols (Kuranska *et al.*, 2013). The ultimate mechanical properties of PUs largely depend on the relative content of lignin and its nature. Organosolv lignin (15–25 W%) in non-modified forms generates quality PUs on the other hand, large quantities of lignin accompany brittle PUs. Lignin fragments having low molecular weight amalgamated with flexible polyols such as glycerol and polyethylene glycol via enzymatic hydrolysis with consequentially following mechanical treatments. In a study conducted by Araujo and Pasa (2003), they used guaiacyl-syringyl-based lignin having residual polysaccharides obtained from Eucalyptus tar distillation, and prepared PUs using different amount of hydroxyl-terminated polybutadiene.

#### **Challenges and future prospects**

The abundant availability of LCB composed it an economical source for fabricating biobased polymers using innovative biotechnological avenues. Nonetheless, commercial feasibility is still defined by virtue of the huge cost of transportation,

curtailed pre-treatment efficiency, extensive chemical input and enzyme requirement demand. (Hassan *et al.*, 2019). In the world's bioplastic market, the contribution and participation of LCB-derived bioplastic are flat due to lower prices of crude oil. The approach of circular bioeconomy should be contemplated for the valorization of a variety of by-products from a specific biorefinery process. For instance, a pilot plant in cellulose biorefinery might be used for the production of the biodegradable polymer such as PLA and PHA from monomeric sugars. In the same way, ethanol being generated in the cellulosic biorefinery may be integrated with catalytic conversion techniques for the production of biological origin Bio-PE and PET (Rosales-Calderon, and Arantes 2019). However, recyclable bioplastic has comparable attributes to petroleum-based plastics, but worldwide acquiescence of these biobased plastics is still restricted. Presently, maximum bioplastics are being derived from monomeric sugars generated from starch-based feedstocks; the apparent complexity of LCB is its recalcitrant nature and inaccessibility to combined LCB to recyclable plastic process are primary limitations in its commercial evolution. Additionally, the maximum quantity of sugar titer after enzymatic hydrolysis and the requirement of well-fermenting microbial strains to produce bioplastic monomers are the prime tailbacks in LCB-based plastic manufacturing industries. The cost of feedstock plays an important factor, which significantly depends on harvesting methods, land use, and supply chain; therefore, a careful, perceptive understanding of all the factors would enormously contribute to bioprocess economics. However, numerous parameters like hydrolysis, pre-treatment and fermentation have been well investigated and documented in the literature though cost reduction of unified units at the commercial level requires evaluation.

Out of the total overall operational cost, 25-30% only accounts for processes of sugar extraction for bioplastic generation from LCB. Therefore a cocktail of development of in-situ, economic enzymes would be significant for the bioplastic industry. And on a general basis, the government must strengthen the effective implementation of policies related to biobased resources and should promote the usage of bioplastics instead of

synthetic plastic for daily routine applications. Although recycling compostable and biodegradable plastics is technically possible, however presently, <1% of bioplastics is being recycled due to non-availability of adequate labelling European standards of bioplastics. Furthermore, automation, skilled manpower, and proper collection management system should be steadfast through responsible government agencies. Significant R&D technology ramifications for anaerobic digestion, impurity eradication and waste recycling should be recommended through private and public agencies.

### Conclusion

Polymeric sugars enmeshed in LCB can be obtained using the required pre-treatment method to transform them into biopolymers. Conversion of renewable chemicals generated from LCBs into biodegradable and recyclable plastic is an entrancing option to supersede conventional petroleum-based plastics. Utilization of LCB for

bioplastic production renders sustainability and promotes a circular economy, although variable structure, heterogenous nature and complexity of LCB are eloquent critical sides that need to be remediated through technological advancements and development of strategies for effective substrate conversion, which would directly enhance commercial viability. Bioplastic production from LCB is at an inchoate phase, but the future outlooks are promising and luring. Significant advancements in fermentation techniques with this inexpensive LCB have to potential to completely transform the shape of the biopolymer industry, allowing production costs to permit to an extent. It will compete with conventional plastic and will offer valuable biodegradable and biocompatible properties with environmental sustainability.

### Conflict of interest

The authors declare that they have no conflict of interest.

### References

- Ahmad, A., Waheed, S., Khan, S. M., Shafiq, M., Farooq, M., Sanaullah, K., & Jamil, T. (2015). Effect of silica on the properties of cellulose acetate/polyethylene glycol membranes for reverse osmosis. *Desalination*, 355, 1-10.
- Ahmad, E., & Pant, K. K. (2018). Lignin conversion: a key to the concept of lignocellulosic biomass-based integrated biorefinery. In *Waste biorefinery* (pp. 409-444). Elsevier.
- Annamalai, N., & Sivakumar, N. (2016). Production of polyhydroxybutyrate from wheat bran hydrolysate using *Ralstonia eutropha* through microbial fermentation. *Journal of Biotechnology*, 237, 13-17.
- Araujo, R. C. S., & Pasa, V. M. D. (2003). Mechanical and thermal properties of polyurethane elastomers based on hydroxyl-terminated polybutadienes and biopitch. *Journal of applied polymer science*, 88(3), 759-766.
- Bay, M. S., Karimi, K., Esfahany, M. N., & Kumar, R. (2020). Structural modification of pine and poplar wood by alkali pretreatment to improve ethanol production. *Industrial crops and products*, 152, 112506.
- Bhatia, S.K., Gurav, R., Choi, T.R., Jung, H.R., Yang, S.Y., Moon, Y.M., 2018. Bioconversion of plant biomass hydrolysate into bioplastic (polyhydroxyalkanoates) using *Ralstonia eutropha* 5119. *Bioresour. Technol.* 271, 306e315. <https://doi.org/10.1016/j.biortech.2018.09.122>.
- Budak, K., Sogut, O., & Aydemir Sezer, U. (2020). A review on synthesis and biomedical applications of polyglycolic acid. *Journal of polymer research*, 27(8), 1-19.
- Castro, D. O., Passador, F., Ruvolo-Filho, A., & Frollini, E. (2017). Use of castor and canola oils in "biopolyethylene" curauá fiber composites. *Composites Part A: Applied Science and Manufacturing*, 95, 22-30.
- Chalermthai, B., Giwa, A., Schmidt, J. E., & Taher, H. (2021). Life cycle assessment of bioplastic production from whey protein obtained from dairy residues. *Bioresource Technology Reports*, 15, 100695.
- Cheah, W. Y., Sankaran, R., Show, P. L., Ibrahim, T. N. B. T., Chew, K. W., Culaba, A., & Jo-Shu, C. (2020). Pretreatment methods for lignocellulosic biofuels production: current advances, challenges and future prospects. *Biofuel Research Journal*, 7(1), 1115.
- Chen, H., Liu, J., Chang, X., Chen, D., Xue, Y., Liu, P., & Han, S. (2017). A review on the pretreatment of lignocellulose for high-value chemicals. *Fuel Processing Technology*, 160, 196-206.
- Chen, W., Chen, Y., Yang, H., Xia, M., Li, K., Chen, X., & Chen, H. (2017). Co-pyrolysis of lignocellulosic biomass and microalgae: Products characteristics and interaction effect. *Bioresource technology*, 245, 860-868.
- Da Silva, A. S. A., Inoue, H., Endo, T., Yano, S., & Bon, E. P. (2010). Milling pretreatment of sugarcane bagasse and

- straw for enzymatic hydrolysis and ethanol fermentation. *Bioresource technology*, 101(19), 7402-7409.
- Davis, R., Kataria, R., Cerrone, F., Woods, T., Kenny, S., O'Donovan, A., (2013). Conversion of grass biomass into fermentable sugars and its utilization for medium chain length polyhydroxyalkanoate (mcl-PHA) production by *Pseudomonas* strains. *Bioresour. Technol.* 150, 202e209. <https://doi.org/10.1016/j.biortech.2013.10.001>
- De Moraes, J. O., Scheibe, A. S., Sereno, A., & Laurindo, J. B. (2013). Scale-up of the production of cassava starch based films using tape-casting. *Journal of Food Engineering*, 119(4), 800-808.
- Deepa, B., Abraham, E., Cordeiro, N., Mozetic, M., Mathew, A. P., Oksman, K., ... & Pothan, L. A. (2015). Utilization of various lignocellulosic biomass for the production of nanocellulose: a comparative study. *Cellulose*, 22(2), 1075-1090.
- Den, W., Sharma, V. K., Lee, M., Nadadur, G., & Varma, R. S. (2018). Lignocellulosic biomass transformations via greener oxidative pretreatment processes: access to energy and value-added chemicals. *Frontiers in chemistry*, 6, 141.
- Diaz, A. B., de Souza Moretti, M. M., Bezerra-Bussoli, C., Nunes, C. D. C. C., Blandino, A., da Silva, R., & Gomes, E. (2015). Evaluation of microwave-assisted pretreatment of lignocellulosic biomass immersed in alkaline glycerol for fermentable sugars production. *Bioresource technology*, 185, 316-323.
- Djukić-Vuković, A., Mladenović, D., Ivanović, J., Pejin, J., & Mojović, L. (2019). Towards sustainability of lactic acid and poly-lactic acid polymers production. *Renewable and Sustainable Energy Reviews*, 108, 238-252.
- Duque, A., Manzanares, P., & Ballesteros, M. (2017). Extrusion as a pretreatment for lignocellulosic biomass: Fundamentals and applications. *Renewable energy*, 114, 1427-1441.
- Gadda, T. M., Pirttimaa, M. M., Koivistoinen, O., Richard, P., Penttila, M., & Harlin, A. (2014). The industrial potential of bio-based glycolic acid and polyglycolic acid. *Appita: Technology, Innovation, Manufacturing, Environment*, 67(1), 12.
- Galbe, M., & Wallberg, O. (2019). Pretreatment for biorefineries: a review of common methods for efficient utilisation of lignocellulosic materials. *Biotechnology for biofuels*, 12(1), 1-26.
- Garlotta, D. (2001). A literature review of poly (lactic acid). *Journal of Polymers and the Environment*, 9(2), 63-84.
- Govil, T., Wang, J., Samanta, D., David, A., Tripathi, A., Rauniyar, S., ... & Sani, R. K. (2020). Lignocellulosic feedstock: A review of a sustainable platform for cleaner production of nature's plastics. *Journal of cleaner production*, 270, 122521.
- Hassan, S. S., Williams, G. A., & Jaiswal, A. K. (2019). Moving towards the second generation of lignocellulosic biorefineries in the EU: Drivers, challenges, and opportunities. *Renewable and Sustainable Energy Reviews*, 101, 590-599.
- Hendriks, A. T. W. M., & Zeeman, G. (2009). Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresource technology*, 100(1), 10-18.
- Heng, K. S., Hatti-Kaul, R., Adam, F., Fukui, T., & Sudesh, K. (2017). Conversion of rice husks to polyhydroxyalkanoates (PHA) via a three-step process: optimized alkaline pretreatment, enzymatic hydrolysis, and biosynthesis by *Burkholderia cepacia* USM (JCM 15050). *Journal of Chemical Technology & Biotechnology*, 92(1), 100-108.
- Hideno, A., Inoue, H., Tsukahara, K., Fujimoto, S., Minowa, T., Inoue, S., ... & Sawayama, S. (2009). Wet disk milling pretreatment without sulfuric acid for enzymatic hydrolysis of rice straw. *Bioresource Technology*, 100(10), 2706-2711.
- Huang, Y. F., Chiueh, P. T., Kuan, W. H., & Lo, S. L. (2016). Microwave pyrolysis of lignocellulosic biomass: Heating performance and reaction kinetics. *Energy*, 100, 137-144.
- Hutley, T. J., & Ouederni, M. (2016). Polyolefins—the history and economic impact. In *Polyolefin Compounds and materials* (pp. 13-50). Springer, Cham.
- Jadaun, J. S., Bansal, S., Sonthalia, A., Rai, A. K., & Singh, S. P. (2022). Biodegradation of plastics for sustainable environment. *Bioresource Technology*, 126697.
- Jem, K. J., & Tan, B. (2020). The development and challenges of poly (lactic acid) and poly (glycolic acid). *Advanced Industrial and Engineering Polymer Research*, 3(2), 60-70.
- Kargarzadeh, H., Ioelovich, M., Ahmad, I., Thomas, S., & Dufresne, A. (2017). Methods for extraction of nanocellulose from various sources. *Handbook of nanocellulose and cellulose nanocomposites*, 1, 1-51.
- Karnaouri, A., Asimakopoulou, G., Kalogiannis, K. G., Lappas, A., & Topakas, E. (2020). Efficient d-lactic acid production by *Lactobacillus delbrueckii* subsp. *bulgaricus* through conversion of organosolv pretreated lignocellulosic biomass. *Biomass and Bioenergy*, 140, 105672.
- Kawaguchi, H., Takada, K., Elkasaby, T., Pangestu, R., Toyoshima, M., Kahar, P., ... & Kondo, A. (2022). Recent advances in lignocellulosic biomass white biotechnology for bioplastics. *Bioresource Technology*, 344, 126165.
- Khalil, H. A., Bhat, A. H., & Yusra, A. I. (2012). Green composites from sustainable cellulose nanofibrils: A review. *Carbohydrate polymers*, 87(2), 963-979.

- Kim, H., Lee, S., Ahn, Y., Lee, J., & Won, W. (2020). Sustainable production of bioplastics from lignocellulosic biomass: technoeconomic analysis and life-cycle assessment. *ACS Sustainable Chemistry & Engineering*, 8(33), 12419-12429.
- Koller, M., Miranda de Sousa Dias, M., Rodríguez-Contreras, A., Kunaver, M., Zagar, E., Krzan, A., Braunegg, G., (2015). Liquefied wood as inexpensive precursor-feedstock for bio-mediated incorporation of (R)-3-Hydroxyvalerate into polyhydroxyalkanoates. *Materials* 8 (9), 6543e6557. <https://doi.org/10.3390/ma8095321>.
- Komesu, A., de Oliveira, J. A. R., da Silva Martins, L. H., Maciel, M. R. W., & Maciel Filho, R. (2017). Lactic acid production to purification: a review. *BioResources*, 12(2), 4364-4383.
- Kumar, B., Bhardwaj, N., Agrawal, K., Chaturvedi, V., & Verma, P. (2020). Current perspective on pretreatment technologies using lignocellulosic biomass: An emerging biorefinery concept. *Fuel Processing Technology*, 199, 106244.
- Kurańska, M., Aleksander, P., Mikelis, K., & Ugis, C. (2013). Porous polyurethane composites based on bio-components. *Composites Science and Technology*, 75, 70-76.
- Lau, W. W., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., ... & Palardy, J. E. (2020). Evaluating scenarios toward zero plastic pollution. *Science*, 369(6510), 1455-1461.
- Li, H., Qu, Y., Yang, Y., Chang, S., & Xu, J. (2016). Microwave irradiation—A green and efficient way to pretreat biomass. *Bioresource technology*, 199, 34-41.
- Li, J., Li, D., Su, Y., Yan, X., Wang, F., Yu, L., & Ma, X. (2022). Efficient and economical production of polyhydroxyalkanoate from sustainable rubber wood hydrolysate and xylose as co-substrate by mixed microbial cultures. *Bioresource Technology*, 355, 127238.
- Li, P., Wang, X., Su, M., Zou, X., Duan, L., & Zhang, H. (2021). Characteristics of plastic pollution in the environment: a review. *Bulletin of environmental contamination and toxicology*, 107(4), 577-584.
- Lokesh, B. E., Hamid, Z. A. A., Arai, T., Kosugi, A., Murata, Y., Hashim, R., ... & Sudesh, K. (2012). Potential of oil palm trunk sap as a novel inexpensive renewable carbon feedstock for polyhydroxyalkanoate biosynthesis and as a bacterial growth medium. *Clean-Soil, Air, Water*, 40(3), 310-317.
- Lopes, M. S., Jardini, A., & Maciel Filho, R. (2014). Synthesis and characterizations of poly (lactic acid) by ring-opening polymerization for biomedical applications. *Chemical engineering transactions*, 38, 331-336.
- Lunelli, B. H., Andrade, R. R., Atala, D. I., Wolf Maciel, M. R., Maugeri Filho, F., & Maciel Filho, R. (2010). Production of lactic acid from sucrose: strain selection, fermentation, and kinetic modeling. *Applied biochemistry and Biotechnology*, 161(1), 227-237.
- Malani, R. S., Malshe, V. C., & Thorat, B. N. (2021). Polyols and polyurethanes from renewable sources: past, present and future—part 1: vegetable oils and lignocellulosic biomass. *Journal of Coatings Technology and Research*, 1-22.
- Mankar, A. R., Pandey, A., Modak, A., & Pant, K. K. (2021). Pretreatment of lignocellulosic biomass: A review on recent advances. *Bioresource Technology*, 334, 125235.
- Mannina, G., Presti, D., Montiel-Jarillo, G., & Suárez-Ojeda, M. E. (2019). Bioplastic recovery from wastewater: A new protocol for polyhydroxyalkanoates (PHA) extraction from mixed microbial cultures. *Bioresource technology*, 282, 361-369.
- Matsumoto, K., Kobayashi, H., Ikeda, K., Komanoya, T., Fukuoka, A., Taguchi, S., (2011). Chemo-microbial conversion of cellulose into polyhydroxybutyrate through ruthenium-catalyzed hydrolysis of cellulose into glucose. *Bioresour. Technol.* 102 (3), 3564e3567. <https://doi.org/10.1016/j.biortech.2010.09.098>.
- Mondal, S. (2017). Preparation, properties and applications of nanocellulosic materials. *Carbohydrate polymers*, 163, 301-316.
- Moorkoth, D., & Nampoothiri, K. M. (2016). Production and characterization of poly (3-hydroxy butyrate-co-3 hydroxyvalerate)(PHBV) by a novel halotolerant mangrove isolate. *Bioresource technology*, 201, 253-260.
- Nanda, S., Mohammad, J., Reddy, S.N., Kozinski, J.A., Dalai, A.K.: Pathways of lignocellulosic biomass conversion to renewable fuels. *Biomass Conv. Bioref.* 4, 157–191 (2014)
- Nanda, S., Rana, R., Sarangi, P.K., Dalai, A.K., Kozinski, J.A.: A broad introduction to first, second and third generation biofuels. In: Sarangi, P.K., Nanda, S., Mohanty, P. (eds.) *Recent Advancements in Biofuels and Bioenergy Utilization*, pp. 1–25. Springer Nature, Singapore (2018)
- Okolie JA, Nanda S, Dalai AK, Kozinski JA (2020) Chemistry and specialty industrial applications of lignocellulosic biomass. *Waste Biomass Valoriz* 20:1–25. <https://doi.org/10.1007/s12649-020-01123-0>
- Oliveira, J. A. R. D., Silva Martins, L. H. D., Komesu, A., & Neto, J. M. (2017). Nanotechnology applications on lignocellulosic biomass pretreatment. In *Nanotechnology*

- for bioenergy and biofuel production (pp. 19-37). Springer, Cham.
- Rahman, R., & Putra, S. Z. F. S. (2019). Tensile properties of natural and synthetic fiber-reinforced polymer composites. *Mechanical and physical testing of biocomposites, fibre-reinforced composites and hybrid composites*, 81-102.
- Raj, T., Chandrasekhar, K., Kumar, A. N., & Kim, S. H. (2022). Lignocellulosic biomass as renewable feedstock for biodegradable and recyclable plastics production: A sustainable approach. *Renewable and Sustainable Energy Reviews*, 158, 112130.
- Reshmy, R., Thomas, D., Philip, E., Paul, S. A., Madhavan, A., Sindhu, R., ... & Binod, P. (2021). Bioplastic production from renewable lignocellulosic feedstocks: a review. *Reviews in Environmental Science and Bio/Technology*, 20(1), 167-187.
- Rezania, S., Oryani, B., Cho, J., Talaiekhozani, A., Sabbagh, F., Hashemi, B., ... & Mohammadi, A. A. (2020). Different pretreatment technologies of lignocellulosic biomass for bioethanol production: an overview. *Energy*, 199, 117457.
- Rhodes, C. J. (2018). Plastic pollution and potential solutions. *Science progress*, 101(3), 207-260.
- Rodríguez-Zúñiga, U. F., Cannella, D., de Campos Giordano, R., Giordano, R. D. L. C., Jørgensen, H., & Felby, C. (2015). Lignocellulose pretreatment technologies affect the level of enzymatic cellulose oxidation by LPMO. *Green chemistry*, 17(5), 2896-2903.
- Rol, F., Belgacem, M. N., Gandini, A., & Bras, J. (2019). Recent advances in surface-modified cellulose nanofibrils. *Progress in Polymer Science*, 88, 241-264.
- Rosales-Calderon, O., & Arantes, V. (2019). A review on commercial-scale high-value products that can be produced alongside cellulosic ethanol. *Biotechnology for biofuels*, 12(1), 1-58.
- Rosales-Calderon, O., & Arantes, V. (2019). A review on commercial-scale high-value products that can be produced
- Tu, W. C., & Hallett, J. P. (2019). Recent advances in the pretreatment of lignocellulosic biomass. *Current opinion in green and sustainable chemistry*, 20, 11-17.
- Unrean, P. (2018). Optimized feeding schemes of simultaneous saccharification and fermentation process for high lactic acid titer from sugarcane bagasse. *Industrial Crops and Products*, 111, 660-666.
- Unrean, P., Naphorn, S. C., Tee, K. L., Wong, T. S., & Champreda, V. (2021). Lignin to polyhydroxyalkanoate bioprocessing by novel strain of *Pseudomonas monteilii*. *Biomass Conversion and Biorefinery*, 1-7.
- van der Pol, E. C., Eggink, G., & Weusthuis, R. A. (2016). Production of L (+)-lactic acid from acid pretreated sugarcane bagasse using *Bacillus coagulans* DSM2314 in a alongside cellulosic ethanol. *Biotechnology for biofuels*, 12(1), 1-58.
- Salusjärvi, L., Havukainen, S., Koivistoinen, O., & Toivari, M. (2019). Biotechnological production of glycolic acid and ethylene glycol: current state and perspectives. *Applied microbiology and biotechnology*, 103(6), 2525-2535.
- Sherwood, J. (2020). The significance of biomass in a circular economy. *Bioresource Technology*, 300, 122755. <https://doi.org/10.1016/j.biortech.2020.122755>
- Silva, J. A., Tobella, L. M., Becerra, J., Godoy, F., & Martínez, M. A. (2007). Biosynthesis of poly-β-hydroxyalkanoate by *Brevundimonas vesicularis* LMG P-23615 and *Sphingopyxis macrogoltabida* LMG 17324 using acid-hydrolyzed sawdust as carbon source. *Journal of bioscience and bioengineering*, 103(6), 542-546.
- Sindhu, R., Silviya, N., Binod, P., & Pandey, A. (2013). Pentose-rich hydrolysate from acid pretreated rice straw as a carbon source for the production of poly-3-hydroxybutyrate. *Biochemical engineering journal*, 78, 67-72.
- Singh, A., Nanda, S., Berruti, F.: A review of thermochemical and biochemical conversion of miscanthus to biofuels. In: Nanda, S., Vo, D.V.N., Sarangi, P.K. (eds.) *Biorefinery of Alternative Resources: Targeting Green Fuels and Platform Chemicals*, pp. 195–220. Springer Nature, Singapore (2020)
- Singla, P., Kaur, P., Mehta, R., Berek, D., & Upadhyay, S. N. (2012). Ring-opening polymerization of lactide using microwave and conventional heating. *Procedia Chemistry*, 4, 179-185.
- Tenorio-Alfonso, A., Sánchez, M., & Franco, J. M. (2020). A review of the sustainable approaches in the production of bio-based polyurethanes and their applications in the adhesive field. *Journal of Polymers and the Environment*, 28(3), 749-774.
- simultaneous saccharification and fermentation strategy. *Biotechnology for biofuels*, 9(1), 1-12.
- Veluchamy, C., Kalamdhad, A. S., & Gilroyed, B. H. (2019). Advanced pretreatment strategies for bioenergy production from biomass and biowaste. *Handbook of environmental materials management*, 1507-1524.
- Woiciechowski, A. L., Neto, C. J. D., de Souza Vandenberghe, L. P., de Carvalho Neto, D. P., Sydney, A. C. N., Letti, L. A. J., ... & Soccol, C. R. (2020). Lignocellulosic biomass: Acid and alkaline pretreatments and their effects on biomass recalcitrance—Conventional processing and recent advances. *Bioresource technology*, 304, 122848.
- Yan, X., Li, D., Ma, X., & Li, J. (2021). Bioconversion of renewable lignocellulosic biomass into multicomponent



- substrate via pressurized hot water pretreatment for bioplastic polyhydroxy alcanoate accumulation. *Bioresource Technology*, 339, 125667.
- Yang, J., Ching, Y. C., & Chuah, C. H. (2019). Applications of lignocellulosic fibers and lignin in bioplastics: A review. *Polymers*, 11(5), 751.
- Yoo, J., Alavi, S., Vadlani, P., & Amanor-Boadu, V. (2011). Thermo-mechanical extrusion pretreatment for conversion of soybean hulls to fermentable sugars. *Bioresource technology*, 102(16), 7583-7590.
- Yoo, Y., & Youngblood, J. P. (2016). Green one-pot synthesis of surface hydrophobized cellulose nanocrystals in aqueous medium. *ACS Sustainable Chemistry & Engineering*, 4(7), 3927-3938.
- Zhang, J., Cai, D., Qin, Y., Liu, D., & Zhao, X. (2020). High value-added monomer chemicals and functional bio-based materials derived from polymeric components of lignocellulose by organosolv fractionation. *Biofuels, Bioproducts and Biorefining*, 14(2), 371-401.
- Zhou, J., Ouyang, J., Xu, Q., & Zheng, Z. (2016). Cost-effective simultaneous saccharification and fermentation of l-lactic acid from bagasse sulfite pulp by *Bacillus coagulans* CC17. *Bioresource technology*, 222, 431-438.
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