A paradigm shift towards production of sustainable bioenergy and advanced products from *Cannabis/hemp* biomass in Canada

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Abstract

The global cannabis (*Cannabis sativa*) market was 17.7 billion in 2019 and is expected to reach up to 40.6 billion by 2024. Canada is the 2nd nation to legalize cannabis with a massive sale of $246.9 million in the year 2021. Waste cannabis biomass is managed using disposal strategies (i.e., incineration, aerobic/anaerobic digestion, composting, and shredding) that are not good enough for long-term environmental sustainability. On the other hand, greenhouse gas emissions and the rising demand for petroleum-based fuels pose a severe threat to the environment and the circular economy. Cannabis biomass can be used as a feedstock to produce various biofuels and biochemicals. Various research groups have reported production of ethanol 9.2–20.2 g/L, hydrogen 13.5 mmol/L, lipids 53.3%, biogas 12%, and biochar 34.6% from cannabis biomass. This review summarizes its legal and market status (production and consumption), the recent advancements in the lignocellulosic biomass (LCB) pre-treatment (deep eutectic solvents (DES), and ionic liquids (ILs) known as “green solvents”) followed by enzymatic hydrolysis using glycosyl hydrolases (GHs) for the efficient conversion efficiency of pre-treated biomass. Recent advances in the bioconversion of hemp into oleochemicals, their challenges, and future perspectives are outlined. A comprehensive insight is provided on the trends and developments of metabolic engineering strategies to improve product yield. The thermochemical processing of disposed-off hemp lignin into bio-oil, bio-char, synthesis gas, and phenol is also discussed. Despite some progress, barricades still need to be met to commercialize advanced biofuels and compete with traditional fuels.

Keywords Cannabis · Hemp fiber · Pre-treatment · Enzymatic saccharification · Advanced biofuels · Drop-in oils

1 Introduction

Bioenergy is one of the sustainable resources available to meet the increasing energy demand and reduce the reliance on traditional fossil-based fuels. Owing to the limitations related to conventional feed stocks, the quest for cheaper and abundantly available biomass is at the utmost priority [1]. Therefore, renewable biomass resources such as forest, agriculture residues, and invasive plant species (weeds) are a promising feedstock for the production of bioenergy [2]. Industrial hemp (*Cannabis sativa*) is considered one of the major valuable fibers which has recently been reported for its application in generating biochemicals, biogas, bioethanol, biohydrogen, etc. (Fig. 1). Several salient features highlighting the use of hemp biomass include the low cost of feedstock, high lignocellulosic content, a yield of dry matter (DM), and low nutrient requirement, which eventually enhance soil health. Hemp fiber also has specific properties, including greater absorbency and hygroscopicity, and
possesses excellent thermal and electrostatic properties, making it compatible to use as a bio-adsorbent of pollutants and for developing biocomposites [3]. However, the legal restraints have prevented the production of cannabis by many of the leading countries for over a decade. Interestingly, Canada became the second country after Uruguay to legalize Cannabis sativa sale and production across the nation. But with the increase in the demand and gross, annual production of cannabis in Canada (Fig. 2) had led to considerable adverse effects on the ecosystem, which are often being overlooked. Commercial-scale cultivation practices of hemp such as illegitimate land clearance and logging; stream burying; sediment delivery, contaminated petroleum products, heavy use of pesticides, and fertilizers affect the aquatic and terrestrial habitat [4, 5]. Several waste products generated from hemp, liquid waste such as unused cannabis oils, extracts, drinks; airborne debris in the form of vapor, and smoke generated from hemp; solid waste consisting of cannabis trimmings, capsules, containers, wrappers, dirt, pebbles, sponge used for cultivation, and leftover crop waste need to be addressed. Later, it became the primary cause of global warming, as burning onsite and/or offsite of this waste can result in pollution. It has been reported previously that 1 kg of cannabis waste results in the release of 3000 kg of carbon dioxide adding substantially to the leading cause of global warming [6]. To expand the vision of circular bioeconomy, it is necessary to trace the yearly consumption and production statistics of cannabis after legalization and the steps taken by the government for effective waste management. This study can help in formulating
the planned legal framework for cannabis in order to avoid adverse social and environmental impacts.

The energy yield of 100 GJ/ha/yr is associated with the hemp biomass (HB); however, in 2016, the energy generated by fossil fuels in Canada was 443.5 PJ with higher emission of greenhouse gas (GHG). Moreover, according to the Paris agreement, Canada requires to reduce GHG emissions to limit climate change by 1.5 °C [7]. Hence, it is essential to lower the dependence on fossil-based fuels for the production of energy by the industries. Furthermore, the bioconversion platform used by these biorefineries involves the biomass pre-treatment (physiochemical, biological, and green alternatives such as deep eutectic solvents (DESs) and ionic liquids (ILs)) that allows the deconstruction of cellulosic fibers encased with lignin loosening the hemicellulosic matrix resulting in a slurry rich in cellulose and hemicellulosic fraction followed by enzymatic hydrolysis and microbial fermentations. The enzymatic hydrolysis is a cost-intensive step requiring an array of lignocellulosolytic enzymes (endoglucanase, cellobiohydrolase, β-glucosidase, LPMOs, etc.) from diverse microorganisms to achieve complete hydrolysis into monomeric sugars that can be converted into various useful products such as ethanol, butanol, drop-in-oils, microbial polysaccharides, and biochemicals [8]. This study will serve as a center stage for the hemp producers and processors, policymakers, and researchers by providing a more profound knowledge of current perspectives of hemp consumption and its significance for society along with the future directions.

This review article provides insight into the following vital areas: (1) legal status of industrial hemp/Cannabis sp., (2) its annual production and consumption, (3) environmental pollution and management strategies, (4) its pre-treatment as well as enzymatic hydrolysis strategies to generate edible monomers with maximum efficiency, and (5) biotechnological/thermo-chemical approaches as well as metabolic engineering to develop advanced biofuels and value-added therapeutic biomolecules. Furthermore, processed bottlenecks and their feasible solutions have been addressed for the potential future considerations to scale up the technology.

2 Legal status of cannabis

*Cannabis sativa* has been grown for many ages as a rich source of renewable fuel, fiber, and food [9]. The drug’s colorful history in Canada can be traced back to 1606, when Louis Hebert introduced hemp cultivation in Nova Scotia. However, in the modern epoch, cannabis is known to be venerable on one hand and controversial on the other hand due to which it is not authorized for consumption. But the pot is cautiously being re-admitted into legitimacy that paves the way for the rising demands owing to its medical benefits [10]. The legal status of cannabis throughout the world is in flux. Many countries such as Australia, Canada, Germany, Israel, and eleven states of the USA are heading towards decriminalizing cannabis. In contrast, other countries have more deterring laws that merely authorize the usage of cannabis derivatives, such as Marinol and Sativex [11]. The legalization of hemp involves the endorsement of recreational and medical cannabis that permits scientists and industry to work together and delve into the unknown benefits of this once-forbidden plant [12]. According to which the adults (> 18 years) can legally possess 30 g of dried cannabis, and the users can buy dried cannabis and hemp oil from licensed retailers and can purchase online from the licensed producers. Also, the cultivation of 4 cannabis plants per residence is permitted for personal use. The law regarding the medical use of cannabis has its particular criteria, i.e., a person must show the symptoms that are associated with the specific medical conditions [13]. According to Health Canada’s Marijuana Medical Access Regulations (MMAR) program, the hemp can be obtained by three routes: firstly, dried cannabis as supplied by Health Canada [14]; secondly, production of an individual’s own supply, and thirdly designated person production license (DPL) which entitles another person to produce for the patient [15]. But this became a loophole for the government as a 60-fold rise in the number of individuals from 2001 to 2013 under the MMAR program was observed, which led to unintentional concerns for public health and security. Hence, from April 2014 onwards, the law narrowed the production of domestic cannabis for medicinal purposes and restricted its credentials by the health department [14]. The journey of legalization in Canada can have significant social, economic, and public health impacts. Furthermore, legalizing pot allows the government to collect taxes from the legalized drug that would yield substantial tax returns. The use of hemp has positive as well as negative impacts on health, but still, it is being used for the treatment of various diseases [16, 17].

Unfortunately, COVID-19 (2020–2021) took center stage in international affairs, impacting its utilization patterns [18]. However, Canadian provinces have allowed cannabis supply chains to remain operational despite the regional lockdown. Many innovative measures are being adopted to provide services such as takeaway, delivery, and accommodation of telemedicine to maintain social distance [19]. Recent studies indicate that major cultivators of hemp such as Canopy Growth and Aurora Cannabis are unaffected by the encroaching COVID-19 pandemic; also, the Health Canada authorizes outdoor cultivation that has risen by 25% in the past few months [20]. In the present scenario, the cannabis sale has set an out stage in Canada, and to ensure the appropriate use of cannabis, the Canadian government has focussed on the far-reaching strategies to prevent the abuse of the drug. In order to get better understanding, authorities
should closely watch the developmental program in the adjoining countries to develop an appropriate background that can reduce the crime rate and improve the present laws to legalize cannabis.

### 3 Annual cultivation and utilization of cannabis

The cannabis industry worldwide has flourished in oblivion for almost an era due to the decriminalization of hemp cultivation and sale [21]. Usually articulated in public debates and policies as either an illicit or a medicinal drug, *C. sativa* is rapidly evolving as a quasi-legal agricultural product in many countries [22]. The liberalization of cannabis policies is a boon to agricultural commodities all over the world to create new agricultural frontiers. Several crops are grown in Canada, generating tons of waste products that cause severe environmental impact. Maximum licensed cannabis cultivation in different areas of Canada is observed to be in, Ontario (68%), Quebec (71%), Prince Edward Island (76%), New Brunswick (80%), etc. (Fig. 3) [23].

However, the authorization of recreational hemp according to the Cannabis Act, which addresses offenses related to cannabis trafficking, as well as enhancing impaired-driving inspection and execution measures in 2018, has been the primary driver of the industry surge as consumers started purchasing licensed rather than illegal cannabis which led several industries to grow 68.3% in 2019 alone [24]. Major industries in Canada which are leading producers of pot are Canopy Growth Corp. ($6.969B), Aurora Cannabis ($5.071B), The Hexo Corporation ($656.233 M), Aphria Inc. ($1.807B), and The Cronos Group ($2.844B). Canopy (CGC) is the first unicorn company in Canada’s market that sells its products under the most recognized brand name “Tweed.” However, Aurora Cannabis Inc. (ACB), is the most debuted company for the sale of dry cannabis and possesses a legal license to sell cannabis oil. HEXO Corp. (Quebec) is the first licensed medical hemp company for the sale of recreational cannabis [25].

The annual production of cannabis has increased with the course of time (Fig. 4), leading to a rise in the number of users and an illegal supply of hemp. It has been reported that out of 4,364,163 users of 15 years or above, 621,188 were found to use cannabis daily in 2014, while 718,176 users out of 5,034,949 in 2018 [26]. According to 2019–2020 stats in Canada, the maximum seizure of cannabis products took place, i.e., 1,975,796 g followed by 1,079,281 g cocaine, 122,465 g heroine, 18,977 g hashish, and 372,555 g of other opioids [27].

### 4 Environment pollution caused by waste generation and disposal methods of Cannabis

Although *C. sativa* is a very illicit crop and has several health benefits, its waste or leftover is a major contributor to global warming due to its onsite incineration and offsite disposal [4, 5]. It is a water and nutrient-requiring crop, and its outdoor cultivation significantly affects water diversion, associated with land clearing, chemical pollution, and encroaching threat to wildlife. At the same time, its indoor growth is coupled with increased consumption of energy

![Licensed Cannabis Cultivation In Canada](image)

**Fig. 3** Licensed Cannabis Cultivation in Canada—Industrial hemp licensing statistics for 2018 [23]
[4]. In countries like Canada, pot is regulated under the federal rules and regulations formulated by the cannabis act. For the destruction of waste, licensed cannabis cultivators and processors are required to follow the guidelines issued by narcotic legislation and controlled substances so that they do not expose any smoke or vapor in the surroundings. Several acts have been formulated to save the environment in the district like Ontario, which includes, Pesticides Act, Environmental Protection Act (EPA), Nutrient Management Act (2002), and Ontario Water Resources Act. Alberta, which is known as the runway of cannabis cultivation, has documented proper guidelines for the disposal of all kinds of waste. [28].

5 Cannabis waste management strategies

The legalization of cannabis has ameliorated all the policies associated with the use and possession of pot. Future perspectives to protect the environmental resources should comply with both regulatory and enforcement efforts to help legal producers obey the environmental laws. Before legalization, the endorsement of the Controlled Drugs and Substances Act (1996) and Access to Cannabis for Medical Purposes Regulations (ACMPR) involve the destruction or denaturation of cannabis to the extent that renders it unfit for propagation and consumption. However, the cornerstone for waste management is the licensing of cannabis such that the cannabis industry works parallel with Canada’s Federal Sustainable Development Strategy, proper documentation, and record-keeping relating to the type of facility, energy consumption, water usage, waste production, resource management, and land use. Based on these records, a further license should be given or renewed [29]. The environmental protection act, called umbrella legislation, works to manage all the waste. All hazardous medical waste in Alberta, New Brunswick, and Nova Scotia is disposed of at the central facility. According to Alberta Environmental Protection and Enhancement Act (AEPEA) and Cannabis Control and Licensing Act (CCLA) passed in British Columbia, lethal waste material is processed through the Waste Control Regulation, a transport tracing system, and authorized storage process, treatment, and disposal facilities.

5.1 Waste disposal methods

5.1.1 Waste incineration

Waste incineration is known as a thermal conversion of solid, liquid, or gaseous wastes into ash, flue gas, and
heat [30]. Solid cannabis plant waste such as branches, leaves, and bush are destroyed using incineration. The non-euphoric compound present in cannabis, mainly tetrahydrocannabinol (THC), poses the primary threat to the environment due to its high resistance to several waste treatment methods. Several incinerators employed by the industries render the complete destruction of the toxic compound. But it is necessary to carry out an air quality test after the process as the vapor and smoke generated can be poisonous [28]. The 95% of the waste can be reduced by incineration and is more beneficial than the conventional technologies which involve landflling methods. Most countries such as Canada, France, Germany, and Italy are working on the waste-to-energy project, and countries like Japan and the USA have already administered the method of generation of electricity by the energy derived from waste incineration [31].

5.1.2 Composting Cannabis waste

Ontario’s Food and Organic Waste Framework uses the method of composting for the destruction of solid hemp waste. The technique involves the microbial transformation of waste by mixing the equal parts of cannabis waste with compostable mixed waste that renders the phytocannabinoids in the trash to non-detectable levels and produces nutrient-rich products, which enhances the soil’s nutrient absorption, productivity, and water retention capability. The composting is either done onsite or transported to the authorized composting facilities [28, 32]. This method is cost-intensive as the composting facilities are located far away from the site, including transportation costs. An additional cost is associated by mixing an equal amount of organic waste with cannabis waste [33].

5.1.3 Anaerobic or aerobic digestion

Industries like Micron Waste Technologies Inc. and Aurora Cannabis Inc. work to treat organic waste forged during the production of cannabis products. Several upcoming technologies are employed, one of which is aerobic digestion of organic waste, which nullifies the level of THC and renders the waste unfit for human consumption. The process majorly involves the breakdown of waste by mechanical and biological processes. The aerobic microorganisms process the resultant sludge to reduce the total suspended solids (TSS), biochemical oxygen demand (BOD), fats/oils/grease (FOG), chemical oxygen demand (COD), and THC. The resulting effluent can be discharged in the sewer and meets the requirements of municipal waste discharge standards. This method is more advantageous than other methods as the cost for transportation is not involved [24].

6 Lignocellulose composition, pretreatment, and saccharification of cannabis

LCB biomass plays a vital role in decarbonising our economy as it is the copious renewable feedstock available, with yearly cultivation of 181.5 billion tonnes. Approximately 7 billion tonnes of waste is generated from forest and agricultural activities [25]. The estimated global legal market value of cannabis is USD 17.7 billion in 2019, and a major boom of USD 40.6 billion is expected by 2024. However, Deloitte has estimated the annual revenue of cannabis sales in Canada after legalization to be USD 22.6 billion in 2020 [36, 37]. Globalization has brought a new realm to this world for industrial hemp, and farmers are looking to diversify the hemp waste and reduce their ecological footprint [38].

The glorious aspect of the pot is its potential to form the basis of the revolutionary fuel industry, bioremediation, and novel therapeutic benefits against a number of human disorders [39]. Based on the multiple application aspects of Cannabis, further investigation is encouraged to unwind the new science behind the pot [40]. The significance of research in view of the rapidly expanding cultivation and the bipartite use of hemp in seleniferous areas across Canada has become a core factor for the Canadian economy [17]. Alberta, the province of western Canada, is known to be the land of cannabis cultivation and became Canada’s runaway cannabis with a maximum of 341 provincially licensed stores, followed by British Columbia with 183 stores in 2019 (Fig. 5) [41].

6.1 Structural composition

Structural studies have provided the insight that the stem of cannabis is composed of woody hemp core (WHC) and bast fiber [42, 43]. Bast fibers are made of ~30 phloem cells grouped in bundles consisting of 600 fiber cells on the stem cross section that are connected with the help of middle lamella, primarily rich in pectin. Bast fibers constitute 6–7% of the total cell number and thereof contribute 30% of the stem’s dry mass, which mainly consist of crystalline cellulose, while WHC fibers contain xylem cells infused with a matrix of lignin, ensuring the strength and resistance against the negative sap pressure [43, 44]. Woody core fibers constitute 40–48% of cellulose, 18–24% of hemicellulose, and 21–24% of lignin majorly. However, a high amount of cellulose (57–77%) is present in the bast fibers, 9–14% of hemicellulose, and 5–9% lignin that is lower in comparison to woody core fibers. Furthermore, the bast fiber cell wall consists of pectin (4%), proteins...
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(3%), and phenolic acids (<0.01%) [1]. Cannabis sativa, a versatile weed, is composed of holocellulose (77%), lignin (4–5%), and ash (3%) as compared to Parthenium hysterophorus, another invasive weed species, which is composed of 53.63% holocellulose and 10.44% lignin. Some other varieties of weeds found in Asia are known for the production of bioethanol and biogas which includes Vetiveria zizanioides (Vetiver grass), Pennisetum purpureum (Napier grass), P. polystachyon, Paspalum atratum, and Digitaria decumbens (Fig. 6) [45, 46]. Finola hemp stalks are composed of 62% cellulose content, 17% hemicellulose, and 19% lignin [47]. These LCB rich species are the center stage for research and development industries that are investigating the multiple aspects of these crops.

6.2 Valorisation of LCB biomass

Valorisation of LCB is a prerequisite for the disruption of the supramolecular cellulose–lignin–hemicellulose matrix, which makes the carbohydrate polymers easily accessible to various hydrolases. Pre-treatment technologies reduce the polymerization and crystallinity of lignocellulose.

6.2.1 Conventional pre-treatment methods

Widely used methods for the pre-treatment include physical, chemical, or biological pre-treatment to make biomass suitable for its use as a raw material in microbial fermentation. The commonly used physical pre-treatment methods are milling (i.e., hammer, Vibro energy, and colloidal), steam explosion, and mechanical extrusion. Previous reports on cannabis pre-treatment by steam explosion showed an increase in bioethanol production up to 70% from cannabis fiber [48], owing to the remarkable structural features of surfactants that can enhance biomass solubility and biodegradability, henceforth biofuel production. The mechanical extrusion (>300 °C) is not financially attainable due to high energy demand, poor bioconversion efficiency, gaseous products, and char production from the pre-treated LCB biomass residues. Therefore, a hybrid approach that involves physical, chemical, or other pre-treatment methods

Fig. 5 Number of licensed stores of cannabis in different states of Canada [36, 41]
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is often used to conquer this. Chemical methods include the treatment with acids (H$_2$SO$_4$, HNO$_3$, HCl), alkali (NaOH, CaCO$_3$, NH$_3$), the organosolv process, ozonolysis, SO$_2$ or ammonia (AFEX), and the ammonia recycle percolation (ARP) [49–52]. Abraham and co-workers [45] reported 72% bioconversion efficiency of hemp when treated with NaOH (0.5%, w/v), 35% with H$_2$SO$_4$ (0.5%, v/v), and 30% in case of deionized water. Marcolongo et al. [53] revealed the 90% xylose and 40% glucose yield after alkaline pre-treatment of hemp followed by enzymatic hydrolysis, which was far superior to other methods. But the release of inhibitory by-products such as furfurals (4–8 mM), 5-hydroxymethylfurfural (1-5 mM), acetic acid (8–16 mM), and phenolic compounds (0.5-3 mM) deflates enzymatic hydrolysis and expands the production cost of the biofuel [54]. Biological pre-treatment of hemp biomass includes the use of microorganisms that encode a diverse array of lignocellulolytic enzymes such as cellulases, hemicellulases, peroxidases, and laccases. These enzyme groups play a significant role in feedstock distortion during biological pre-treatment. Filamentous fungi, including Phanerochaete chrysosporium, Talaromyces emersonii, Pleurotus ostreatus, Mycosphaerella thermophilus, and Myceliophthora thermophila, are apt of secreting lignin-deteriorating enzymes for the effective LCB biomass delignification [8, 55–57]. Borah et al. (2016) reported the hydrolysis of Parthenium hysterophorus with H$_2$SO$_4$ followed by NaOH delignification and ultrasound irradiation. The pretreated substrate (4.2% w/v) hydrolysed with cellulase (135 FPU/g of biomass) and cellobiase (75 FPU/g of biomass) yielded 43.8 g/100 g of biomass of which theoretical bioethanol yield was observed to be 27.3 g. Although the biological pre-treatment process is environment-friendly and requires low energy, the process requires the controlled conditions requiring ample space and a prolonged time period to achieve high sugar recovery.

6.2.2 Recently emerged green technologies

The concept of “Green Chemistry” has impetus recently with a plausible solution to negate adverse environmental impacts associated with traditional pre-treatment methods releasing hazardous chemicals. A solution to this problem includes the use of DESs and ILs for the pre-treatments. DESs are greener solvents that contain quaternary ammonium salt and a metal salt or hydrogen bond donor [58, 59]. Pre-treatment of grasses with cholinium-arginate enabled more than 69% lignin digestibility [60]. Choline chloride-lactic acid–assisted pretreatment of rice straw resulted in lignin dissolution of ~68 mg/g [61]. Digestibility of hemicellulose and lignin with cellulose dissolution of > 90% was

Fig. 6 Lignocellulosic composition of different weed species [46]
attained during DESs-assisted pretreatment of corn stover and corncobs [59, 62, 63]. DES is a promising alternative to acid and alkaline solvents due to the low cost, nontoxicity, less sugar loss, and biodegradability.

ILs contain ions with strong electrostatic forces with high stability and low vapor pressure characteristics [64–66]. Moreover, they can be made more efficient by altering the cation (organic) and anion (organic or inorganic) groups [67]. Hemp stem and mugwort biomass when pre-treated with ILs such as 1-ethyl-3-methylimidazolium acetate (EMIM)(OAc), (cyclohexyl)hexyldimethylammonium acetate (CHDMA-C6)(OAc), and 1-Butyl-3-methylimidazolium acetate (BMIM)(OAc) at 120 °C for 2 h followed by saccharification with commercial Cellic CTec2 resulted in 11.32 g/L and 12.27 g/L of sugar recovery from biomass purified with (EMIM)(OAc) and (BMIM)(OAc), respectively [47]. Recently, Fockink et al. [68] showed the effect of IL EMIM-OAc on cotton filter powder (CFP) and dirty cotton residue (DCR) at 140 °C for 2 h. It was observed that DCR yielded 78% glucose and 94.9% xylose while CFP resulted in 75.8% glucose, 95.7% xylose, and 16% of dignified products. The reason behind low sugar recovery is the poor cellulose content that exists in hemp fiber as compared to the cotton. The only limitation associated with the use of ILs is the high cost and, therefore, cannot be employed by several biorefineries [69].

7 Enzymatic saccharification of LCB biomass

The rigid or crystalline lignocellulosic biomass is deconstructed by glycosyl hydrolases (GHs), including cellulas, hemicellulas, carbohydrate esterases (CEs), and auxiliary activity (AA) enzymes [70, 71]. The enzyme costs reported in the literature related to biofuel production vary significantly from USD 0.10/gal to 0.40/gal [72–74]. Such a discrepancy in production cost impedes the robust technoeconomic studies of advanced biofuel fermentation.

Cellulas are the major family of glycosyl hydrolase (GH) enzymes that depolymerise cellulose fraction of LCB biomass to yield glucose monomers [75]. Cellulas include three main hydrolytic enzymes: endoglucanases (EG), exoglucanases (celllobiohydrolases (CBH)), and β-glucosidases (βG) [76]. EGs belonging to GH families (5–9, 12, 44, 45, 48, 51, 74, and 124) break β-1, 4 glycosidic linkage of cellulose randomly to generate long-chain oligomers (varying in degrees of polymerization) which are subsequently converted into cellobiose by the action of exoglucanases (CBHI and CBHII). The cellobiose is later on converted into glucose by the action of βG [70, 77]. Hemicellulas mediate hydrolysis of a hemicellulose polysaccharide fraction [70]. Owing to its heterogeneous nature, depolymerization of hemicellulosic requires a diverse array of enzymes comprising α-glucuronidase, α-arabinofuranosidase, endoxylanase, β-xylosidase, acetyl xylan esterase, and feruloyl xylan esterase [55]. Carbohydrate esterases catalyze the removal of acetyl moieties linked to carbohydrates. This enzymatic action could hasten up the depolymerisation of polysaccharides by enabling target sites to be easily accessible for the function of GH enzymes [78, 79]. However, the literature highlighting the importance of these enzymes is scarce, with special reference to feruloyl esterases (FAEs) and acetyl xylan esterases (AXEs) that are the widely studied enzymes [79, 80]. Another key player in the hydrolysis process includes auxiliary activity (AA) enzymes which are capable of oxidatively cleaving the glycosidic bonds and allow other cellulases to act on the potential sites which were earlier inaccessible [70, 81]. The AA earlier categorized as GH61 is now replaced into families AA1-AA16, of which AA9 is the major candidate known as lytic polysaccharide monooxygenases (LPMO’s) [70, 82].

The enzymatic action majorly depends on the efficiency of pre-treatment approaches. Kuglarz et al. [83] reported 73% cellulose conversion yields of steam pre-treated biomass with commercial cellulase. However, high sugar yields were obtained in the presence of 1% acid during pre-treatment. The use of a high concentration of acids has been earlier reported to generate the inhibitors and may direct the deterioration of released sugars. Other report by Sipos et al. [84] showed that catalyst (SO2)-mediated pre-treatment can lead to high cellulose conversions. Several parameters such as choice of temperature, substrate loading, and type of pre-treatment have a substantial impact on overall sugar yield. Various thermochemical pre-treatments of hemp (0–3% H2SO4, H2O2, or NaOH) at 121–180 °C and subsequent saccharification with commercial preparations such as Novozyme 188 (β-glucosidase) and Celluclast (cellulose) at 15 IU/g and 20 FPU/g of glucan loading rate resulted in the 73.5% of overall sugar release in the case of 3% H2O2 [85].

The hydrolysis of polysaccharides is also dependent on the variety of crops. For instance, the cellulose recovery varied from 62.3 to 85.8% during depolymerization of different hemp varieties such as CBD Hemp, Seward County (SC), Loup County (LC), York County (YC), and 19 m96136 (19 m) that were pre-treated using hot water and disk refining process [86].

8 Bioconversion of cannabis biomass into advanced biofuels and products

The ongoing research practices are mainly focused on the bio-based concept that has great potential to strengthen the efficiency, cost, and yield-related outcomes. Bio-refinery-based products are (i) derived from cellulose and hemicellulose (bioethanol, biobutanol, succinic acid, biohydrogen,
biogas, biodiesel, drop-in oils, bioplastics, and microbial polysaccharides); (ii) derived from lignin (bio-oil, biochar, phenol); and (iii) derived from whole lignocellulosics (bioadsorbent and biocomposite). From the industrial and biotechnological viewpoint, cannabis is available for biotransformation into high-value and industrially relevant products (Fig. 7).

8.1 Bioethanol and biobutanol

LCB-derived ethanol has higher energy content and lower greenhouse effect than sugarcane and corn ethanol. It is a promising substitute to gasoline and other fuels [87]. The lower lignin and higher cellulose content of cannabis make it an attractive feedstock for bioethanol synthesis. A variety of microbes such as *Scheffersomyces stipitis*, *Saccharomyces cerevisiae*, *Zymomonas mobilis*, *Escherichia coli*, *Candida glabrata*, *C. tropicalis*, *C. shehatae*, and *Pichia stipitis* are exploited for biological ethanol production (Fig. 7a; Table 1). These microbes ferment sugars derived from lignocellulosics through a subsequently aerobic and anaerobic process [88–90].

The yeast species *S. cerevisiae* is widely employed for ethanol fermentation at an industrial scale due to its

**Fig. 7**  a Biological and b thermochemical processing of biomass for the biosynthesis of advanced biofuels, and oleochemicals

**Table 1** Pretreatment and enzymatic hydrolysis strategies for cannabis

| Feedstock          | Pretreatment condition | Hydrolysis condition                  | Biofuel yield                  | References |
|--------------------|------------------------|---------------------------------------|--------------------------------|------------|
| Hemp hurds         | Steam                  | *S. cerevisiae*, 10% solid loading rate | 8.5–14.1 g/100 g biomass      | [91]       |
| *C. sativa L*      | Acid-assisted steam pretreatment | *S. cerevisiae*, 7.5% solid loading rate | 15.4–20.3 g/L                  | [84]       |
| *C. sativa L*      | Acid-assisted steam pretreatment | *S. cerevisiae*                       | 4.62–10.0 g/L                  | [83]       |
| Fedora 17 strain   | Acid (H₂SO₄) followed by steam | *S. cerevisiae*, 5% solid loading rate | 14.9–15.5 g/100 g biomass      | [114]      |
| Fedora 17 strain   | alkaline oxidative (H₂O₂) | *S. cerevisiae*, 5% solid loading rate | 16.6–17.5 g/100 g biomass      | [114]      |
| Helena, SS Beta, Tygra, and Eletta Campana | Liquid hot water (LHW) | *S. cerevisiae*, 5% solid loading rate | 9.20–10.9 g/L                  | [48]       |
| Helena, SS Beta, Tygra, and Eletta Campana | H₂SO₄ | *S. cerevisiae*, 5% solid loading rate | 11.94–13.77 g/L                | [48]       |
| Helena, SS Beta, Tygra, and Eletta Campana | (NaOH) | *S. cerevisiae*, 5% solid loading rate | 18.21–20.29 g/L                | [48]       |
| Tygra              | NaOH                   | *S. cerevisiae*, 6–12% solid loading rate | 25.1–65.9 g/L                  | [96]       |
incredible endurance to higher ethanol concentrations, inhibitory components, and high ethanol productivity. The hydrolysate recovered after steam pretreatment of industrial hemp, followed by impregnation of 2% SO2 at 7.5% solid loadings and fermented with S. cerevisiae resulting in 15.4 to 21.3 g/L of ethanol titers in the fermentation broth [84].

Kuglarz and co-workers [83] studied the bioconversion of C6 sugars retrieved from hemp biomass (pretreated) using S. cerevisiae with an ethanol production efficiency of 79 to 92%. The resultant ethanol obtained from pre-treated biomass at 5% solid loadings was obtained to be 9.20 to 20.2 g/L. The ethanol concentration was achieved higher (95.8–96.7%) from dilute alkali pre-treated hemp feedstock compared to hot water pre-treated (67.4–74.7%) and dilute acid-pre-treated (67.2–89.6%) biomass [48] (Table 1). Cannabis biomass has high C5 sugar content, but most of the mentioned research carried out on C6 for ethanol fermentation is indeed wastage of resources. Some of the engineered microbes, such as E. coli, Klebsiella oxytoca, S. cerevisiae, and Z. mobilis, can ferment C5 sugars [23]. Although these microbes can ferment C5 sugars, most are intolerant to high ethanol concentrations and inhibitory components. Hence, co-fermentation of haxose and pentose sugars is not adopted at an industrial scale and is still at the embryonic stage due to such mentioned limitations [91, 92]. Brazdausks et al. [93] proposed a mineral acid (Al2(SO4)3·18H2O) conversion of C5 sugars to furfural and C6 sugars into ethanol or levoglucosan. Furfural is a non-petroleum-based chemical that can catalytically reduce into advanced fuels, polymers, solvents, and further valuable products. Hydrogenation of furfural produces furfuryl alcohol (FA) followed by synthesis of furan resins, which are explored for thermostable adhesives, composites, cement, and coatings. Tetrahydrofurfuryl alcohol (THFA) is used as solvent in agricultural formulations which is produced by hydrogenation of FA [94]. Levoglucosan (LG) is an anhydrous sugar and can be further converted into advanced products such as levoglucosenone, styrene, and 5-hydroxymethylfurfural via catalytic, chemical, and biochemical processes [95]. Industrial scale high hemp ethanol productivity (77 g/L) is achieved by optimizing the ethanol yield/solid loading concentration [96].

Butanol is an essential precursor of plastics, polymers, and paints [23]. Butanol has many advantages over ethanol, such as density, engine safety, and compatibility [98, 99]. The carbohydrate-rich feedstocks such as potato, molasses, corn, whey permeate, and cassavas are used conventionally for the biological fermentation of butanol. These substrates compete with the food supply; therefore, inexpensive LCB feedstock can replace them for sustainable production of butanol [99, 100]. Cannabis can be an effective feedstock for butanol production, which has not been extensively explored yet. The diverse genus of Clostridium such as C. butylicum, C. beijerinckii, C. acetobutylicum, C. saccharoperbutylicum, C. aurantibutyricum, C. pasteurianum C. sporogenes, C. cadaveris, C. perfrigens, C. tetanomorphum, and C. carboxidivorus are executed for the butanol production through acetone-butanol-ethanol (ABE) fermentation process [100, 101]. The Clostridia sp. harbors carbohydrate-degrading secretomes including (α- and β-) glucosidase, (α- and β-) amylose, pullulanase, amylopullulanase, and glucoamylase. These enzymes facilitate the catabolism of complex carbohydrates into monomeric sugars followed by translocation into the microbial cell via membrane transporters. Subsequently, these sugars metabolize via glycolysis or the pentose phosphate pathway. These microbes have high significance to utilize complex/mixed sugars using inexpensive cannabis as ABE fermentation substrate (Fig. 7a), which is a primary process cost determining factor. The UK has developed an improved technology that offers low-cost conversion of ethanol to butanol. The scientific community tries to scale up this technology for commercialization [102]. The butanol market is expected to rise from USD 3890 million, 2016 to USD 5580 million by 2022 [103].

The bottleneck of biological butanol and ethanol production is the product (solvent-stress) feedback inhibition of microbial growth. Product-stimulated response mechanisms involve the energy-dependent efflux pumps and solvent-exclusion systems, which export toxic solvents from microbial cells. These mechanisms can be improved by modifying membrane fatty acids, phospholipid composition, and vesicle formation packed with solvents via metabolic engineering, site-directed mutagenesis, and CRISPR/Cas [104].

8.2 Succinic acid (C4-dicarboxylic acid)

Succinic acid is a precursor of high-value products such as methyl ethyl ketone, adipic acid, 1,4-butanediol, 1,3-butanediene, and ethylene diamine disuccinate [105, 106]. Succinic acid has been derived commercially from petroleum-dependent chemical processes. In recent years, the increased depletion of petroleum reserves and the rising demand for succinic acid have compelled the scientific society to switch to the biological fermentation of low-cost LCB biomass from a conventional petroleum-based chemical method to produce succinic acid [105–107]. Limited research is done on the fermentation process of succinic from hemp hydrolysate and needs to explore more [85]. Microbes that potentially synthesize the C4-dicarboxylic acid are Anaerobiospirillum succiniciproducens, Actinobacillus succinogenes, Mannheimia succiniciproducens, and Klebsiella pneumonia, etc. [85, 109, 110]. Along with these microbes, genetically improved E. coli, S. cerevisiae, and Corynebacterium glutamicum are widely used for the fermentation of succinic acid [106, 108, 111]. A point mutation in the RPOB (β-subunit of DNA-dependent RNA polymerase) gene of E. coli introduced by two-step recombination resulted in
overexpression of succinate [112]. The cloning of mutant genes encoding glucose-specific transporter (ptsG), lactate dehydrogenase A, formate acetyltransferase, and pyruvate carboxylase in *E. coli* resulted in the efficient conversion of corn-stalk hydrolysate to succinic acid [113]. The hemp hydrolysate recovered after H₂SO₄ and H₂O₂ pre-treatment was fermented successfully into succinic acid. Both sugars C5 and C6 were fermented entirely into succinic acid with 78.8–81% yield at 25% hemp hydrolysate and 75% media loading rate. The succinic acid yield attained only 40–43% from pure hemp hydrolysate due to the lack of minerals and nitrogen [85]. The co-fermentation of succinic acid and ethanol during hemp processing can solve the underutilization problem of C5 sugars [114]. The liquid fraction containing mainly C5 sugars fermented with *Actinobacillus succinogenes* 130Z (DSM 22,257) for succinic acid production and the pre-treated (1.5% H₂SO₄) solid fractions subjected to bioethanol fermentation under optimal conditions generated 11.5 and 14.9 g/100 g dry hemp [114].

### 8.3 Biohydrogen (Bio-H₂)

LCB bio-H₂ is gaining momentum as it is a low-impact combustion fuel and has a higher energy yield (120 MJ/kg) than conventional fuels and hydrocarbons [115, 116]. Many researchers have examined various bacterial species such as *Clostridium tyrobutyricum*, *C. beijerinckii*, *C. butyricum*, *Ethanoligenens*, *Enterobacter cloacae*, *E. aerogenes*, *Caldicellulosiruptor saccharolyticus*, *Thermoaerobacterium thermosaccharolyticum*, *Thermotoga elfii*, and *T. neapolitana* for H₂ production [116, 117]. Thermophilic strains, such as *Thermococcus kodakaraensis* KOD1, *Clostridium thermocellum* JN4, and *C. thermolacticum*, are potential producers of bio-H₂. Elevated temperature and partial pressure of bio-H₂ are the crucial factors that determine the H₂ production levels by favoring metabolic reaction and the rate of reaction [118–120].

The hydrolysate derived from untreated hemp stem yielded 13.5 mmol/L of H₂ along with some by-products such as underutilized mono sugars, butyrate, acetate, and ethanol. The dilute acid (0.75% H₂SO₄) as well as base (0.75% NaOH) pre-treated hemp leaves fermented with bacterial strain AK14 (similar to *C. thermobutyricum*) can produce two to three times higher bio-H₂ than the untreated biomass. However, pre-treatment of hemp stems did not affect H₂ productivity. Unutilized C5 and lignin content can be responsible for lower H₂ production from hemp biomass [121]. A single-stage fermentation of hemp fibers, hemp hurds, and purified hemp cellulose by *C. thermocellum* was compared to α-cellulose for H₂ and ethanol production. H₂ fermentation rates were comparable for purified hemp cellulose and α-cellulose during the exponential growth phase. The net H₂ productivity was almost comparable for α-cellulose (12.70 mM), purified hemp cellulose (11.01 mM), hemp fibers (10.91 mM), and hemp hurds (4.72 mM). Final production rates of bioethanol from α-cellulose (8.47 mM) were higher, followed by purified hemp cellulose (6.56 mM), hemp fibers (5.48 mM), and hemp hurds (3.52 mM). The productivity rates of H₂ and ethanol were equivalent in the early-exponential phase and assimilated in the mid-exponential phase. End-product production rates were determined by the presence of cellulosic content and other polymers in LCB biomass which is responsible for metabolic flux distribution [122].

#### 8.4 Biogas and methane (CH₄)

LCB feedstock is a promising source for methane (CH₄) production anaerobically. CH₄-rich biogas fairly produces high energy content (18,630–26,081 kJ/m³) than other biofuels like bioethanol and biodiesel. Biogas can be an excellent alternative to forge electricity by integrating heat and power (CHP) systems with it. This system needs to be upgraded in combustion engines with the perspective to replace conventional fuels with “green” fuel [123]. Cannabis biomass has not been vastly investigated as a potential source of biogas production to replace corn biomass [124]. Cannabis biomass produces higher biogas content (3066 m³/ha) than other feedstock such as jerusalem artichoke (3100–5400 m³/ha) and timothy clover-grass (2900–4000 m³/ha) [125]. However, both cannabis and maize generate the same titres of CH₄, higher C6, and C5 sugar content, and lower lignin content makes it a useful feedstock for biogas synthesis. However, cannabis carbohydrates (C5 and C6 sugars) undergo poor bioconversion into biogas. Hence, the harvesting time of cannabis influences the biogas production levels. Cannabis harvested from September to October yields higher biogas production (14.4 Mg/ha and 296 GJ/ha, respectively) than the cannabis collected in February to April, which yielded 9.9 Mg/ha and 246 GJ/ha [126, 127].

The harvesting period of cannabis ought to be examined to study its impact on biogas production levels [128]. The AD fermentation process involves a complex microbial community for bioconversion of LCB biomass into biogas via sequential hydrolysis, acidogenesis, acetogenesis, and methanation [123]. Cannabis possesses a recalcitrant structure that resists enzymatic accessibility and needs to undergo some physicochemical pre-treatment for efficient AD. Furthermore, cannabis contains higher carbon and nitrogen (C: N-37:1) ratio, which plays a pivotal role in biogas production. The higher carbon content ratio hampers the fermentation of LCBs into biogas due to the poor conversion rate [124]. A biological laccase pre-treatment was successfully detoxified by the cannabis straw; whereas peroxidase was inhibited by phenolic components. Laccase detoxification of hydrolysate considerably lowered the phenolic inhibition.
levels (100 mg/L) to improve biogas fermentation [129]. Green cannabis produced around 190 GJ/ha/year, and other crops such as alfalfa, clover-grass ley mix, sugar beets, and maize-generated comparable biogas production that was 150 GJ/ha/year, 170 GJ/ha/year, 240 GJ/ha/year, and 210 GJ/ha/year, respectively, during growth condition [126].

The only CH4 can be produced via AD process, or co-production of CH4 and ethanol can be carried out by integrating AD and Solid-State Fermentation process (SSF). Where SSF of LCB substrate followed by AD process [130], a grinding of cannabis stems, increased its surface area, which resulted in increased CH4 yields (15%). Still, very fine grinding is not feasible from an energy consumption viewpoint. The steam pre-treated chopped cannabis stems achieved higher CH4 productivity (93–100%) than only chopped and ground stems (80%). The co-fermentation of CH4 and ethanol from steam pre-treated cannabis via an integrated AD-SSF system-generated almost 2-times more energy compared to ethanol production only from hexose sugars [130]. Paka-rinen and workers [124] examined that finely ground c annabis biomass produces 21% more CH4 (290 Ndm3/kg) than only chopped industrial cannabis (239 Ndm3/kg) which is not economical.

The biochemical methane potential (BMP) of the treated and un-treated hemp components such as leaves, stalks, fibbers, hurs, and inflorescence via anaerobic methanogenesis process was analyzed. Hemp hurds (unretted) produced lower BMP (239 ± 10 mL CH4/g VS), and raw fibers generated maximum BMP, i.e., 422 ± 20 mL CH4/g VS. The alkali pre-treated or mechanically ground unretted/retted hurds efficiently improved BMP to 15.9% of both feedstocks. The inflorescences alone (26 ± 5 mL CH4/g VS) and a mix of leaves and inflorescences (118 ± 8 CH4/g VS) produced low BMP values with a prolonged fermentation inhibition. The NaOH pre-treatment of a mix of leaves and inflorescences improved methanogenesis by 28.5% [131].

8.5 Biodiesel/microbial oils

The cannabis seed oil contains carbohydrates (20–30%), protein (20–25%), fiber (10–15%), and minerals such as calcium (Ca), magnesium (Mg), potassium (K), sulfur (S), phosphorus (P), iron (Fe), and zinc (Zn). A research study evaluated that the cannabis B20 blend provides lower fuel consumption, improved thermal efficiency, and lower CO and CO2 discharge than pure diesel and jatropha B20 blends. Still, it has higher NOx emission efficiency, which is unsuitable for the environment [132]. Biological lipid production depends on the potential of oleaginous microbes to metabolize hydrolysate sugars, including C5 and C6 (Fig. 7a). The yeast strain Lipomyces starkey and Rhodosporidium toruloides can metabolize C5 sugar efficiently [133, 134]. Yarrowia lipolytica is inefficient to grow using alone C5 sugar [135]. The insertion and expression of xylose reductase (ssXR), xylulokinase (yXK), and xyitol dehydrogenase (ssXDH) into Y. lipolytica from S. stipitis foster it to metabolize C5 sugar with 20 g/L of lipid yield [136]. Furthermore, the insertion of glyceroldehyde-3-phosphate dehydrogenase (GPD1) and glycerol kinase (GUT1) genes increased lipid titer (2.5-fold) via improved conversion of glycerol into glycerol-3-phosphate. The upregulation of acetyl-CoA carboxylase (ACC) enzyme for fatty acid biosynthesis pathway, diaclyglycerol acyltransferase type-1 and type-2 (DGAT1 and DGAT2) for the Kennedy pathway, and downregulation/blocking β-oxidation, and peroxisome biogenesis improved lipid production [59, 137, 138]. Lipid production mainly relies on the ability of oleaginous microbes to spike up acetyl-CoA flux and a rich stockpile of NADPH to direct lipid production. Recombining of metabolic routes to intensify acetyl-CoA and NADPH supply improved fatty acid biosynthesis in oleaginous microbes [139, 140]. Cannabis sativa feedstock was also subjected to the production of biofuels (biodiesel, biogas, and biochar) via nano-catalytic (Co and Ni) gasification. During downstream processing, 53.3% of lipid, 12% biogas, and 34.6% of biochar were extracted. The electrical conductivity of biochar was observed at 0.4 dS/m [141]. The other facets such as process temperature, catalyst type, free fatty acid (FFA) content, alcohol to oil concentration, and agitation speed also impact biodiesel production [142]. These factors are responsible for high production cost as well as impact biodiesel viscosity. However, the optimal reaction conditions (CH3NaO concentration of 1.0 w/v, reaction temperature of 55 °C, reaction duration of 60 min, and methanol to oil ratio of 6:1) give the lowest kinematic viscosity (3.991 cSt) and the highest biodiesel yield (98.19%) [143, 144]. The optimization of transesterification process (catalyst concentration (0.6–1.2 w/v); methanol to oil ratio (6:1–12:1); reaction temperature (30–60 °C) and process duration (60–120 min) using the Taguchi approach (L9 orthogonal design matrix) for industrial-grade hemp seed oil gave remarkable output. The maximum biodiesel yield was observed 96.87%. The fuel synthesized by the abovementioned optimal process parameters found to be within the range of EN 14,214 global biodiesel specifications [145].

8.6 Drop-in oils (fatty alkanes, biokerosene, bisabolene, fatty alcohols)

Although bioethanol and biodiesel production are well established, these biofuels are not fully compatible with the existing vehicle engines, liquid transportation fuel refining, and distribution infrastructure. Furthermore, the high O2 content in biofuels significantly limits fuel-blending rates. Therefore, O2-free biofuels “Drop-in oil” are in demand to improve fuel quality. Drop-in oils do not contain any polyaromatic
hydrocarbon and sulfur components and consequently emit no CO and particulate matter (PM) on burning; hence, it can be utilized as a straight substitute for petroleum-based fuels such as gasoline, diesel, and jet fuel [146]. It was recently detected that hemp seed oil directly contains drop-in oils, mainly, alkanes and alkenes [147]. The short or medium-chain fatty acids are well-known precursors of alkanes and alkenes [148, 149]. Therefore, the LCB biomass of hemp needs to be explored as a source of short (SCFF) or medium-chain fatty acids (MCFF) for the bioproduction of drop-in oils (Fig. 7a). The microbial process of alkane production involves the fatty acyl-CoA reductase (ACR) which reduce fatty acyl-ACP/CoA into fatty aldehyde (FA) followed by the bioconversion of a FA into fatty alkanes [148] via the action of aldehyde decarbonylase (AD) or aldehyde dehydrogenase (ADO). The overexpression of ACR1, ADO, and CAR in Y. lipolytica improved alkane production to 17 mg/L and 23 mg/L, respectively [62]. The expression of AD into S. cerevisiae from Drosophila melanogaster and Arabidopsis CER1 enables it to convert aldehydes into fatty alkanes [150]. MCFA are valuable precursors for the synthesis of biokerosene. Overexpression of diglyceride acyltransferase (DGAT) in Y. lipolytica from Elaeis guineensis resulted in a 45% MCFA production [151]. Yaegahsi and coworkers [152] investigated that R. toruloides can produce bisabolene from corn stover hydrolysate. The bisabolane production using R. toruloides improved to 1.7-fold during scaling-up from shake flask to 20-L fermenter on sorghum biomass [153]. The genetically improved Chlamydomonas reinhardtii from Drosophila melanogaster and Arabidopsis CER1 can be directly implemented to perform metabolic reactions in oil [150]. A suitable combination of enzyme secretomes can be directly implemented to perform metabolic reactions such as hydrodeoxygenation (HDO), decarboxylation, and decarbonylation to improve the synthesis of selected drop-in oil [160].

### 8.7 Bioplastics—poly-3-hydroxybutyrate P(3HB) and microbial polysaccharides

Poly-3-hydroxybutyrate (P(3HB)) is an eco-friendly thermoplastic and biocompatible for potential applications in the biomedical industry. Various potential microbes such as Corynebacterium glutamicum, Azotobacter sp., Pseudomonas sp., Halomonas sp., Rhodobacter sphaeroides, Wautersia eutropha, Ralstonia eutropha, and E. coli can produce P(3HB) from LCB biomass [161, 162]. Khattab and Dahman in 2019 [163] studied the production of P(3HB) using R. eutropha via fermentation of sugars derived from pre-treated (three methods: hot water, 2% NaOH, and 2% H2SO4) hemp hurs. A high yield of P(3HB) (13.4 g/L) was found in the case of alkali pre-treated hurs biomass. Both sugars (C6 and C5) were consumed during the fermentation. This can be a feasible approach to utilize C5 sugars in cannabis. The pentose sugars-rich hydrolysate derived after pre-treatment can be used for P(3HB) fermentation, and hexasse-rich biomass can be further subjected for bioethanol biosynthesis. Furthermore, both pentose and hexasse sugars can be co-fermented for P(3HB) production (Fig. 7a). Process optimization and metabolic engineering (point/random mutagenesis and protein engineering) strategy targeting which improved higher yields/productivity of P(3HB) can be adopted [164–166]. Microbial polysaccharides such as xanthan, schizophyllan, dextran, pullulan, and curdlan have usages in diverse sectors — petroleum, pharmaceutical, and food industries. The microbial polysaccharides comprise a small proportion of the market due to their higher process cost. A low-cost feedstock is required to drop process costs, and LCB biomass is the potential source for this [167]. Various studies are available on the synthesis of microbial polysaccharides by using likely microbial strains of Xanthomonas campestris, Aureobasidium pullulans, and Schizopyllum commune from wheat bran, coconut kernel, palm kernel rice bran, and rice hull [168–170]. In contrast, no research study is available on the utilization of cannabis to date. Cannabis hydrolysate is rich in monomeric sugars (C5 and C6) and can be applied for the fermentation of microbial polysaccharides inexpensively. Hence, cannabis biomass ought to be examined for the biosynthesis of these useful products.
8.8 Lignin derived bio-oil, synthesis gas, and bio-char

Lignin has a highly aromatic structure and can be used as adsorbents of gases, dyes, organics, and metals. However, only 5% of available lignin is exploited globally. Pyrolysis (450–650 °C) of whole cannabis biomass or lignin followed by rapid quenching of pyrolysis vapor can convert the 75% (w/w) of the feedstock into bio-oil, the rest is solid char and non-condensable gases (Fig. 7b) [171]. Bio-oil has high O2 content, acidity, viscosity, acidity, low volatility, and cold flow issues which make it incompatible for the engine as a fuel. Therefore, an advanced hydrodeoxygenation process is needed to modify the functionality of bio-oil [172]. The use of specific catalysts during pyrolysis of bio-oil is a pragmatic and promising approach [173]. The non-condensable gases CO and CO2 and hydrocarbons such as CH4, C2H4, C2H2, and C3H6 are produced during lignin pyrolysis. The residue solid known as biochar is an aromatic polycyclic benzene structure that can be modified to produce catalyst, biofertilizer, and bioadsorbents [174]. Furthermore, the phenol market is expected to rise by 3.9% in the upcoming 10 years [175]. Lignin, a phenol rich polymer, can replace phenol in the petroleum-based process to fulfill the industrial demand.

8.9 LCBs derived-bioadsorbents and biocomposites

Cannabis fibers or lignin have a high adsorption capacity and have been proposed to be used for the adsorption of gases, dyes, metals, and organics. Pădureanu and co-workers [176] studied interaction among hemp and metal ions (Cr, Cd, Co, Cu, Ag, Pb, and Zn) and removal efficiency in batch and fixed-bed columns [177–180]. Cannabis fiber eliminated metals from 7.5 to 13.5 mg/g of fiber, corresponding to the metal type. A monolayer adsorption capacity of cannabis fiber for Cu2+, Cr3+, Cd2+, and Ag+ was studied 9.07, 4.00, 2.59, and 1.22 mg/g, respectively. The cannabis waste also removed Co2+, Pb2+, and Zn2+ from aqueous solutions. The thermodynamic feasibility of Pb2+ adsorption on cannabis can be calculated from the changes observed in entropy (∆S), enthalpy (∆H), and Gibbs free energy (∆G). These factors provide detailed insight into the mechanism of metal adsorption. It is highly challenging to develop consistent adsorbent materials from lignin due to its heterogenic nature. Therefore, lignin’s carbonization, activation, and modification are carried out to improve its adsorption ability and selectivity. Chemically modified lignin biomass can potentially remove organics and organic dyes (phenols, methylene blue, and Procion Blue MX-R). Integrated co-solvent enhanced LCB fractionation (CELF) pre-treatment and Mannich reaction produce aminated CELF lignin, implemented for recovery of dyes such as Direct Blue (DB)1 and Methylene Blue (MB). The incorporation of amine groups into lignin increases the specific surface area of the aminated CELF lignin which is an efficient dye-adsorbent and decolorant, especially towards Direct Blue (DB)1 with >90% removal efficiency [181]. Lignin doping with N, S, or O is suited for metal adsorption (Au, Pd, Au, and Pt). However, further investigations can associate lignin chemical structure with adsorption characteristics [182].

Cannabis biomass can be combined with other matrices (organic and inorganic) to produce biocomposites for the building industry. For instance, cannabis is a fast renewable feedstock for LCB fibers that can be applied as filler material in composites in European countries due to its high specific strength. Instead of phenol, lignin also composed of various functional groups including methoxyl, aliphatic, carbonyl, hydroxyl, and carboxyl [183]. Lignin can form additional C–C linkages via depolymerization and re-polymerization itself. The C–C linkages reduce the number of hydroxyl groups for further functionalization and increase the molecular weight, which is vital for making lignin compatible with other fibers and thermoplastics. The chemical treatment (propionic, butyric, isobutyric, eronomic, or methacrylic) of lignin introduces new functional groups and makes it more compatible with the matrices. The chemical modifications (esterification, oxalkylation, or hydroxyalkylation) minimize the bonding among lignin molecules and effectively improved their compatibility with the host matrices [183–185]. Lignin is used as a filler (up to 40 wt.%) to develop thermoplastic composites without providing mechanical improvement [186–188]. The sustainable modification of cannabis lignin seems to be an exciting research area that makes it feasible for thermoplastic wood biocomposites.

9 Conclusions

The quest for cheaper technologies required for the bioconversion of lignocellulosic feedstock into sustainable bio-energy and advanced products has placed Cannabis sativa in the limelight. Moreover, hemp is a profitable crop over other energy crops due to its high energy potential (~100 GJ/ha/y) and generates fewer carbon footprints. This review provides the first comprehensive insight into the cannabis annual production, consumption statistics, and dynamics of the legal status in Canada. Interestingly, the high (hexose and xylose) sugar recovery rate from the pre-treated biomass employing a combination of physical, chemical, and biological has been highlighted in this review with a significant focus on the greener technologies (IL’s, DES) that are cost-effective, yields high sugar recovery, and are eco-friendly. Furthermore, the review summarizes the necessity and future development of humanity’s oldest cultivated hemp crop that has an inherent potential for the biosynthesis of...
biofuels, bioplastics, greener hydrogen gas, drop-in-oils, and other value-added products. The biofuels synthesized from hemp fiber (cellulose and hemicellulose) or seed oil should be within the range of the global fuel specifications. The main shortcomings are high production cost, poor quality, and yield of the product. These drawbacks can be overcome by optimizing process parameters such as temperature, pH, catalyst concentration, and process duration. The manipulations in the genetic makeup of microbes at gene or protein levels can positively alter product quality and yields. Cannabis’s lignin is majorly disposed of, although it can be potentially used for bio-oil, synthetic gas, and bio-char production via the pyrolysis process. The chemical modifications of cannabis’s LCBs seem to be a galvanizing research area that makes it reliable for the synthesis of bio-adsorbents and bio-composites. Cannabis is a sustainable future raw material for the production of value-added products and this area needs to be explored further.

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Declarations

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Conflict of interest The authors declare no competing interests.

References

1. Rehman MSU, Rashid N, Saif A, Mahmood T, Han J-J (2013) Potential of bioenergy production from industrial hemp (Cannabis sativa): Pakistan perspective. Renew Sustain Energy Rev 18:154–164. https://doi.org/10.1016/j.rser.2012.10.019
2. Ginni G, Kavitha S, Kannan Y, Bhatia SK, Kumar A, Rajkumar M, Kumar G, Pugazhendhi A, Chi NTL (2021) Valorization of agricultural residues: different biorefinery routes. J Environ Chem Eng 9(4):105435. https://doi.org/10.1016/j.jece.2021.105435
3. Kostic M, Pejic B, Skundric P (2008) Quality of chemically modified hemp fibers. Bioresour Technol 99(1):94–99. https://doi.org/10.1016/j.biortech.2006.11.050
4. Carah JK, Howard JK, Thompson SE, Short Gianotti AG, Bauer SD, Carlson SM, Dralle DN, Gabriel MW, Hulette LL, Johnson BJ, Knight CA (2015) High time for conservation: adding the environment to the debate on marijuana legalization. Bioscience 65(8):822–829. https://doi.org/10.1093/biosci/biv083
5. Butsic V, Brenner JC (2016) Cannabis (Cannabis sativa or C. indica) agriculture and the environment: a systematic, spatially-explicit survey and potential impacts. Environ Res Lett 11(4):044023. https://doi.org/10.1088/1748-9326/11/4/044023
6. Mills E (2011) Energy up in smoke. The carbon footprint of indoor Cannabis production. https://doi.org/10.1016/j.enpol.2012.03.023
7. Parvez AM, Lewis JD, Afzal MT (2021) Potential of industrial hemp (Cannabis sativa L.) for bioenergy production in Canada: status, challenges and outlook. Renew Sustain Energy Rev 141:110784. https://doi.org/10.1016/j.rser.2021.110784
8. Raheja Y, Kaur B, Falco M, Tsang A, Chadha BS (2020) Secretome analysis of Talaromyces emersonii reveals distinct CAZymes profile and enhanced cellulase production through response surface methodology. Ind Crops Prod 152:112554. https://doi.org/10.1016/j.indcrop.2020.112554
9. Crome I, Williams R (2019) Substance misuse and young people: Critical issues. CRC Press. ISBN: 978-0-367-18740-8.
10. Gould J (2015) The cannabis crop. Nature 525:S2–S3. https://doi.org/10.1038/525S2a
11. Ruddick G (2011) GW signs Sativex cannabis-based drug deal with Novartis. The Telegraph. Retrieved 17 October 2018. (GW signs Sativex cannabis-based drug deal with Novartis (telegraph.co.uk)
12. Eichhorn Bilodeau S, Wu BS, Rufyikiri AS, MacPherson S, Lessard M (2019) An update on plant photobiology and implications for cannabis production. Front Plant Sci 10:296. https://doi.org/10.3389/fpls.2019.00296
13. National Academies of Sciences, Engineering, and Medicine (2017) Therapeutic effects of cannabis and cannabinoids. In: The health effects of cannabis and cannabinoids: the current state of evidence and recommendations for research. National Academies Press (US). (Therapeutic Effects of Cannabis and Cannabinoids - The Health Effects of Cannabis and Cannabinoids - NCBI Bookshelf (nih.gov)
14. Ko GD, Bober SL, Mindra S, Moreau JM (2016) Medical cannabis—the Canadian perspective. J Pain Res 9:735. https://doi.org/10.2147/JPR.S98182
15. Penn RA (2014) Establishing expertise: Canadian community-based medical cannabis dispensaries as embodied health movement organisations. Int J Drug Policy 25(3):372–377. https://doi.org/10.1016/j.drugpo.2013.12.003
16. Glauser D (2012) The economic effects of legalizing marijuana. Seniors Honors Thesis In: Partial Fulfillment of the Requirements of the Honors Bachelor of Science in Economics, University of Utah. https://www.scribd.com/document/246510320/The-Economic-Effects-of-Legalizing-Marijuana
17. Hajizadeh M (2016) Legalizing and regulating marijuana in Canada: review of potential economic, social, and health impacts. IJHPM 5(8): 453. https://doi.org/10.15171/ijhpm.2016.63
18. Murphy S (2020) How COVID-19 is impacting the Cannabis industry. (https://prohibitionpartners.com/2020/03/27/insight-the-coronavirus-pandemic-and-cannabis-consumer-behaviour-fi/)
19. Lamers M (2020) Canada classifies medical cannabis ‘essential’ amid COVID-19 pandemic. (https://mjbizdaily.com/canada-classifies-medic al-cannabis-essential-amid-covid-19-pandemic/)
20. Israel S (2020) As outdoor cannabis approvals grow in Canada, COVID-19 not expected to delay planting season. (https://mjbizdaily.com/2020/03/19/insight-the-coronavirus-pandemic-and-cannabis-consumer-behaviour-fi/)
21. Butsic V, Carah JK, Baumann M, Stephens C, Brenner JC (2018) The emergence of cannabis agriculture frontiers as environmental threats. Environ Res Lett 13(12):124017. https://doi.org/10.1088/1748-9326/aaeade
22. Kilmer B, MacCoun RJ (2017) How medical marijuana smoothed the transition to marijuana legalization in the United States. Annu
Rev Law Soc Sci 13:181–202. https://doi.org/10.1146/annurev-
lawsoosci-110615-084851

23. Industrial hemp licensing statistics (2018). (https://www.canada-
.ca/en/health-canada/services-drugs-medication/cannabis/produ-
cing-selling-hemp/about-hemp-canada-hemp-industry/statistics-
reports-fact-sheets-hemp.html#_2018)

24. Cannabis production in Canada industry trends (2014–2019, 2019. (https://www.ibisworld.com/canada/market-research-repor-
tcs/cannabis-production-industry/)

25. Krishna M (2019) 10 Canadian marijuana stocks for your portfo-
lio. (https://www.investopedia.com/investing/10-canadian-marij-
ana-stocks/)

26. Statistics Canada. Table 36–10–0597–01 Prevalence of can-
nabis consumption in Canada. https://doi.org/10.25318/36100
59701-eng

27. CBSA seizures (2020). (https://www.cbsa-ascfc.gc.ca/securi-
ty-)

28. Butler R, Jackiw R (2019) The highs and lows of cannabis waste
management regulations. (https://www.recyclingproductnews.
article/32589/the-highs-and-lows-of-cannabis-waste-manag
ement-regulations)

29. Nelson (2018) Sustainability. In: Environmental Economics and
Natural Resource Management, Routledge, pp 205–230. https:

30. Krishna M (2019) 10 Canadian marijuana stocks for your portfo-
lio. (https://www.investopedia.com/investing/10-canadian-marij-
ana-stocks/)

31. Bhatia SK, Joo HS, Yang YH (2018) Biowaste-to-bioenergy
conversion. (https://www.waste360.com/organics/aerobic-
digestion)

32. Harindintwali JD, Zhou J, Yu X (2020) Lignocellulosic crop
residue composting by cellulosic nitrogen-fixing bacteria: a
novel tool for environmental sustainability. Sci Total Environ
715:136912. https://doi.org/10.1016/j.scitotenv.2020.136912

33. Rivera R (2018) Cannabis organic waste disposal options.
(hippines.iscienceblog.com/blog/cannabis-organic-waste-disposal/)

34. Greenwalt M (2018) Aerobic digestion is key to Cannabis waste
conversion. (https://www.waste360.com/organics/aerobic-diges-
tion-key-cannabis-waste-conversion)

35. Dahmen N, Lewandowski I, Zibek S, Weidmann A (2019) In-
tegrated lignocellulosic value chains in a growing bioeconomy:
status quo and perspectives. GCB Bioenergy 11(1):107–117.

36. Legal marijuana market size, share & trends analysis report by
marijuana type (medical, adult use), by product type, by medical
application (cancer, mental disorders), and segment forecasts,
2020 – 2027. (https://www.grandviewresearch.com/industry-
analysis/legal-marijuana-market)

37. Global Cannabis Markets to Watch (2020). (https://www.240pr
operty.com/global-cannabis-markets-to-watch-in-2020/)

38. Schultz CJ, Lim WL, Khor SF, Neumann KA, Schulz JM, Ansari
O, Skewes MA, Burton RA (2020) Consumer and health-related
traits of seed from selected commercial and breeding lines of
industrial hemp, Cannabis sativa L. J Agric Food Res 2:100025.
https://doi.org/10.1007/s40643-019-0137-9

39. Brody H (2019) Cannabis Nature 572:S1. https://doi.org/10.
1038/d41586-019-01252-6

40. Aluafsi R, Zeman S, Bagar T, Chingwaru W (2020) Cannabis
sativa L. and its potential applications in environmental biore-
mediation. A review. Hmeljarski Bilten, (27).

41. Zabloski M (2019) How Alberta became Canada’s runway
 cannabis leader. (https://policyoptions.irpp.org/magazines/
december-2019/how-alberta-became-canadas-runway-canna-
bis-leader/)

42. Stevulova N, Cigasova J, Estokova A, Terpakova E, Gef-
fert A, Kacik F, Singovska E, Holub M (2014) Properties
characterization of chemically modified hemp hurds. Materials
7(12):8131–8150. https://doi.org/10.3390/ma7128131

43. Petit J, Gulisano A, Dechesne A, Trindade LM (2019) Pheno-
typic variation of cell wall composition and stem morphology in
hemp (Cannabis sativa L.): optimization of methods. Front Plant
Sci 10: 959. https://doi.org/10.3389/fpls.2019.00959

44. Wang Z, Dien BS, Rausch KD, Tumbleson ME, Singh V (2018)
Fermentation of undetoxified sugarcane bagasse hydrolyzes using
a two stage hydrothermal and mechanical refining pre-
treatment. Bioresour Technol 261:313–321. https://doi.org/10.
1016/j.biortech.2018.04.018

45. Abraham RE, Wong CS, Pur P (2016) Enrichment of cellulosic
waste hemp (Cannabis sativa) hurd into non-toxic microfibres.
Materials 9(7):562. https://doi.org/10.3390/ma9070562

46. Dussadee N, Unpaprrom Y, Ramaraj R (2016) Grass silage for
biogas production. Advances in Silage Production and Utilization
16:153. https://doi.org/10.5772/164961

47. Smuga-Kogut M, Kogut T, Markiewicz R, Słowiak A (2021) Use
of machine learning methods for predicting amount of bioetha-
hol obtained from lignocellulosic biomass with the use of ioni-
lc liquids for pretreatment. Energies 14(1):243. https://doi.org/10.
3390/en14010243

48. Zhao J, Xu Y, Wang W, Griffin J, Wang D (2020) Conversion
of liquid hot water, acid and alkali pretreated industrial hemp
biomasses to bioethanol. Bioresour Technol 309:123383. https:

49. Asgher M, Ahmad Z, Iqbal HNM (2013) Alkali and enzymatic
delignification of sugarcane bagasse to expose cellulose polymers
for saccharification and bioethanol production. Ind Crop Prod
44:488–495. https://doi.org/10.1016/j.indcrop.2012.10.005

50. Kumar AK, Sharma S (2017) Recent updates on different
methods of pretreatment of lignocellulosic feedstocks: a
review. Bioresour Bioprocess 4(1):7. https://doi.org/10.1186/
s40643-017-0137-9

51. Jędrzejczyk M, Soszka E, Czapnik M, Ruppert AM, Grösch A
(2019) Physical and chemical pretreatment of lignocellulosic bio-
mass. In: Second and third generation of feedstocks Elsevier, pp
143–196. https://doi.org/10.1016/B978-0-12-815162-4.00006-9

52. Brar KK, Chadha BS, Brar SK, Singh P (2020) Biotechnological
strategies for enhanced production of biofuels from lignocellu-
losic biomass. In: Valorization of biomass to value-added com-
modities Springer, Cham, pp 521–551. https://doi.org/10.1007/
978-3-030-38032-8_24

53. Marcolongo L, La Cara F, Ionata E (2021) Hemp waste valoriza-
tion through enzymatic hydrolysis for biofuels and biochemicals
production. Chem Eng Trans 86:127–132. https://doi.org/10.
3303/CE12186022

54. Liu Z, Fels M, Dragone G, Mussatto SI (2021) Effects of inhibi-
tory compounds derived from lignocellulosic biomass on the
growth of the wild-type and evolved oleanuginous yeast Rhod-
sporidium toruloides. Ind Crops Prod 170:113799. https://doi.org/
10.1016/j.indcrop.2021.113799

55. N Basotra B Kaur Y Raheja D Agrawal G Sharma BS Chadha
2021 Developing and evaluating lignocellulolytic hyper produc-
ding deregulated strains of Mycothermus thermophilus for hydrol-
ysis of lignocellulosics Biomass Convers Biorefin 1–14https://

56. KK Brar Y Raheja M Falco di A Tsang BS Chadha 2021 Novel
β-glucanases along with xylanase identified in Thermomyces
lanuginosus secretome for enhanced saccharification of differ-
ent lignocellulosics Biomass Convers Biorefin 1–14https://

57. Borah AJ, Singh S, Goyal A, Moholkar VS (2016) An assess-
m ent of the potential of invasive weeds as multiple feedstocks
for biofuel production. RSC Adv 6(52):47151–47163. https://doi.
org/10.1039/CSRA27787F
58. Francisco M, van den Bruijne A, Kroon MC (2012) New natural and renewable low transition temperature mixtures (LTTMs): screening as solvents for lignocellulosic biomass processing. Green Chem 14(8):2153–2157. https://doi.org/10.1039/C2GC35660K
59. Zhang CW, Xia SQ, Ma PS (2016) Facile pretreatment of lignocellulosic biomass using deep ionic wet solvents. Bioresour Technol 219:1–5. https://doi.org/10.1016/j.biortech.2016.07.026
60. An YX, Zong MH, Wu H, Li N (2015) Pretreatment of lignocellulosic biomass with renewable choline ionic liquids: biomass fractionation, enzymatic digestion and ionic liquid reuse. Bioresour Technol 192:165–171. https://doi.org/10.1016/j.biortech.2015.05.064
61. Kumar AK, Parikh BS, Pravakar M (2016) Natural deep eutectic solvent mediated pretreatment of rice straw: bioanalytical characterization of lignin extract and enzymatic hydrolysis of pretreated biomass residue. Environ Sci Pollut Res 23(10):9265–9275. https://doi.org/10.1007/s11356-015-4780-4
62. Xu GC, Ding JC, Han RZ, Dong JJ, Ni Y (2016) Enhancing cellulose accessibility of corn stover by deep ionic solvent pretreatment for butanol fermentation. Bioresour Technol 203:364–369. https://doi.org/10.1016/j.biortech.2015.11.002
63. Hou XD, Feng GJ, Ye M, Huang CM, Zhang Y (2017) Significantly enhanced enzymatic hydrolysis of rice straw via a high-performance two-stage deep ionic solvents synergistic pretreatment. Bioresour Technol 238:139–146. https://doi.org/10.1016/j.biortech.2017.04.027
64. Wu W, Wang Z, Jin Y, Matsumoto Y, Zhai H (2014) Effects of LiCl/DMSO dissolution and enzymatic hydrolysis on the chemical composition and lignin structure of rice straw. Biomass Bioenergy 71:357–362. https://doi.org/10.1016/j.biombioe.2014.09.021
65. Socha AM, Parhasarathi R, Shi J, Pattathil S, Whyte D, Bergeron M, George A, Tran K, Stavila V, Venkatachalam S (2014) Efficient biomass pretreatment using ionic liquids derived from lignin and hemicellulose. Proc Natl Acad Sci 111(35):E3587–E3595. https://doi.org/10.1073/pnas.1405685111
66. Wahlström R, Suurnäkki A (2015) Enzymatic hydrolysis of lignocellulosic polysaccharides in the presence of ionic liquids. Green Chem 17:694–714. https://doi.org/10.1039/C4GC01649A
67. Brandt A, Ray MJ, To TQ, Leak DJ, Murphy RJ, Welton T (2011) Ionic liquid pretreatment of lignocellulosic biomass with ionic liquid-water mixtures. Green Chem 13(9):2489–2499. https://doi.org/10.1039/C1GC13734A
68. Fockink DH, Andreuas J, Ramos LP, Luaskis RM (2020) Pretreatment of cotton spinning residues for optimal enzymatic hydrolysis: a case study using green solvents. Renew Energy 145:490–499. https://doi.org/10.1016/j.renene.2019.06.042
69. Hou XD, Li N, Zong MH (2013) Facile and simple pretreatment of sugar cane bagasse without size reduction using renewable ionic liquids-water mixtures. ACS Sust Chem Eng 1(1):519–526. https://doi.org/10.1021/sc300172v
70. Ezeilo UR, Zakaria II, Huyop F, Wahab RA (2017) Enzymatic breakdown of lignocellulosic biomass: the role of glycosyl hydrolases and lytic polysaccharide monooxygenases. Biotechnol Biotechnol Equip 31(4):647–662. https://doi.org/10.1007/s13301-017-030124
71. Chylenski P, Petrovic DM, Mller G, Dahlstrom M, Bengtsson O, Lersch M, Siika-Aho M, Horn SJ, Eijssink VG (2017) Enzymatic degradation of sulfite-pulsed softwoods and the role of LPMOs. Biotechnol Biofuels 10(1):177. https://doi.org/10.1186/s13068-017-0862-5
72. Aden A, Fousta T (2009) Techno-economic analysis of the dilute sulfuric acid and enzymatic hydrolysis process for the conversion of corn stover to ethanol. Cellulose 16(4):535–545. https://doi.org/10.1007/s10570-009-9327-8
73. Kazi FK, Fortman JA, Axen RP, Hsu DD, Aden A, Dutta A, Kothandaraman G (2010) Techno-economic comparison of process technologies for biochemical ethanol production from corn stover. Fuel 89:S20–S28. https://doi.org/10.1016/j.fuel.2010.01.001
74. Dutta A, Dowe N, Ibsen KN, Schell DJ, Aden A (2010) An economic comparison of different fermentation configurations to convert corn stover to ethanol using Z. mobilis and Saccharomyces. Biotechnol Prog 26(1):64–72. https://doi.org/10.1021/bp9002331
75. Patel AK, Singhania RR, Sim SJ, Pandey A (2019) Thermostable cellulases: current status and perspectives. Bioresour Technol 279:385–392. https://doi.org/10.1016/j.biortech.2019.01.049
76. Basotra N, Raheja Y, Kaur B, Chadha BS (2021) Thermophilic fungal lignocellulolytic enzymes in biorefineries. In: Progress in mycology. Springer, Singapore. https://doi.org/10.1007/978-981-16-3307-2_2
77. Sweeney MD, Xu F (2012) Biomass converting enzymes as industrial bio catalysts for fuels and chemicals: recent developments. Catalys 2(2):244–263. https://doi.org/10.3390/catal2020244
78. Cantarel BL, Coutinho PM, Rancurel C, Bernard T, Lombard V, Henrissat B (2009) The carbohydrate-active enzymes database (CAZy): an expert resource for glycogenomics. Nucleic Acids Res 37:D233–D238. https://doi.org/10.1093/nar/gkn663
79. Nakamura AM, Nascimento AS, Polikarpov I (2017) Structural diversity of carbohydrate esterases. Biotechnol Res Innovation 1(1):35–51. https://doi.org/10.3390/biri.2017.02.001
80. Ulaganathan K, Goud S, B Reddy M, P Kumar V, Balsingh J, Radhakrishna S (2015) Proteins for breaking barriers in lignocellulosic bioethanol production. Curr Protein Pept Sci 16(2):100–134. https://doi.org/10.2174/13892037160120150215165718
81. Filiatrault-Chastel C, Navarro D, Haon M, Grisel S, Herpoël-Gimbert I, Chevet D, Fanneul M, Henrissat B, Heiss-Blanquet S, Margeot A, Berrin JG (2019) AAA16, a new lytic polysaccharide monooxygenase family identified in fungal secretomes. Biotechnol Biofuels 12(1):55. https://doi.org/10.1186/s13068-019-1394-y
82. Levasseur A, Drula E, Lombard V, Coutinho PM, Henrissat B (2013) Expansion of the enzymatic repertoire of the CAZy database to integrate auxiliary redox enzymes. Biotechnol Biofuels 6(1):1. https://doi.org/10.1186/1754-6834-6-1
83. Kuglarz M, Gunnarsson IB, Svensson SE, Prade T, Johansson E, Angelidaki I (2014) Ethanol production from industrial hemp: effect of combined dilute acid/steam pretreatment and economic aspects. Bioreour Technol 163:236–243. https://doi.org/10.1016/j.biortech.2014.04.049
84. Sipos B, Kreuger E, Svensson S-E, Reczey K, Björnsson L, Zachchi G (2010) Steam pretreatment of dry and ensiled industrial hemp for ethanol production. Biomass Bioenergy 34:1721–1731. https://hal.archives-ouvertes.fr/hal-00748065
85. Gunnarsson IB, Kuglarz M, Karakashev D, Angelidaki I (2015) Thermochemical pretreatments for enhancing succinic acid production from industrial hemp (Cannabis sativa L.). Bioreour Technol 182:58–66. https://doi.org/10.1016/j.biortech.2015.01.026
86. Viswanathan MB, Park K, Cheng MH, Cahoon EB, Dweikat I, Clemente T, Singh V (2020) Variability in structural carbohydrates, lipid composition, and cellulose sugar production from industrial hemp varieties. Ind Crops Prod 157:112906. https://doi.org/10.1016/j.indcrop.2020.112906
87. Wang M, Han J, Dunn JB, Cai H, Elgowainy A (2012) Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellululosic biomass for US use. Environ Res Lett 7(4):045905. https://doi.org/10.1088/1748-9326/7/4/045905
88. Das A, Paul T, Jana A, Halder SK, Ghosh K, Maity C, Mohapatra PKD, Pati BR, Mondal KC (2013) Bioconversion of rice straw to sugar using multizyme complex of fungal origin and subsequent production of bioethanol by mixed fermentation of Saccharomyces cerevisiae MTCC 173 and Zyymomonas mobilis MTCC 2428. Ind Crops Prod 46:217–225. https://doi.org/10.1016/j.indcrop.2013.02.003
89. Boluda-Aguilar M, Lopez-Gomez A (2013) Production of bioethanol by fermentation of lemon (Citrus limon L.) peel wastes pretreated with steam explosion. Ind Crops Prod 41:188–197. https://doi.org/10.1016/j.indcrop.2012.04.031
90. Gupta A, Verma JP (2015) Sustainable bio-ethanol production from agro-residues: a review. Renew Sustain Energy Rev 41:550–567. https://doi.org/10.1016/j.rser.2014.08.032
91. Barta Z, Oliva JM, Ballesteros I, Dienes E, Ballesteros M, Reczey K (2010) Refining hemp hurs into fermentable sugars or ethanol. Chem Biochem Eng Q 24(3): 331–339. https://hcak.srcr.hr/59001
92. Kumar D, Singh V (2020) Bioconversion of processing waste from agro-food industries to bioethanol: creating a sustainable and circular economy. Waste Valorisation: Waste Streams in a Circular Economy, pp 161–181. https://doi.org/10.1002/9781119502753.ch7
93. Brazdauskas P, Paze A, Rizhikovs J, Puke M, Meile K, Veddernoks N, Tupciauskas R, Andzis M (2016) Effect of aluminium sulphate-catalysed hydrolysis process on furfural yield and cellulose degradation of Cannabis sativa L. shives. Biomass Bioenergy 89:98–104. https://doi.org/10.1016/j.biombioe.2016.01.016
94. Chen S, Wojcieszak R, Dumeignil F, Marceau E, Royer S (2018) Levoglucosan: a promising platform molecule. Chem Rev 118(22):11023–11117. https://doi.org/10.1021/acs.chemrev.8b00134
95. Junior II, Do Nascimento MA, de Souza ROMA, Dufour A, Wojcieszak R (2020) Levogulocas: a promising platform molecule? Green Chem 22(18):5859–5880. https://doi.org/10.1039/D0GC01490G
96. Zhao J, Xu Y, Wang W, Griffin J, Wang D (2020) High ethanol concentration (77 g/L) of industrial hemp biomass achieved through optimizing the relationship between ethanol yield/concentration and solid loading. ACS Omega 5(34):21913–21921. https://doi.org/10.1021/acsomega.0c03135
97. Green EM (2011) Fermentative production of butanol—the industrial perspective. Curr Opin Biotechnol 22:337–343. https://doi.org/10.1016/j.copbio.2011.02.004
98. Al-Shorgani NK, Abdul Hamid AA, Wan Yusoff WM, Kalil MS (2013) Pre-optimization of medium for biobutanol production by a new isolate of solvent-producing Clostridium. BioResources 8: 1420–1430. https://doi.org/10.15376/biores.8.1.1420-1430
99. Al-Shorgani NKN, Shukor H, Abdeshahian P, Mohd Nazir MY, Kalil MS, Hamid AA, Wan Yusoff WM (2015) Process optimization of butanol production by Clostridium saccharoperbutyl-acetoneum N1–4 (ATCC 13564) using palm oil mill effluent in acetone-butanol-ethanol fermentation. Biocatal Agric Biotechnol 4:244–249. https://doi.org/10.1016/j.bcab.2015.02.004
100. Zheng J, Tashiro Y, Wang Q, Sonomoto K (2015) Recent advances to improve fermentative butanol production: genetic engineering and fermentation technology. J Biosci Bioeng 119:1–9. https://doi.org/10.1016/j.jbiosc.2014.05.023
101. Qureshi N, Singh V, Liu S, Ezeji TC, Saha BC, Cotta MA (2014) Process integration for simultaneous saccharification, fermentation, and recovery (SSFR): production of butanol from corn stover using Clostridium beijerinckii P260. Bioresour Technol 154:222–228. https://doi.org/10.1016/j.biortech.2013.11.080
102. Dowson GR, Haddow MF, Lee J, Wingad RL, Wass DF (2013) Catalytic conversion of ethanol into an advanced biofuel: unprecedented selectivity for n-butanol. Angewandte Chemie Int Ed 52:9005–9008. https://doi.org/10.1002/anie.201303723
103. n-Butanol market by application (butyl acrylate, butyl acetate, glycol ethers, direct solvents, plasticizers), and region (Asia Pacific, North America, Europe, Middle East & Africa, South America)—global forecast to 2022: a report (CH1543). 2018.
104. Kumar R, Wyman CE (2009) Does change in accessibility with pretreatment affect hydrogenation and fermentation of corn stover using Actinobacillus succinogenes? Bioresour Technol 100(18):4193–4202. https://doi.org/10.1016/j.biortech.2008.11.058
105. Wang D, Li Q, Yang M, Zhang Y, Su Z, Xing J (2011) Efficient production of succinic acid from corn stalk hydrolysates by a recombinant Escherichia coli with ptsG mutation. Process Biochem 46:365–371. https://doi.org/10.1016/j.procbio.2010.09.012
106. Liu R, Liang L, Li F, Wu M, Chen K, Ma J, Jiang M, Wei P, Quyang P (2013) Efficient succinic acid production from lignocellulosic biomass by simultaneous utilization of glucose and xylose in engineered Escherichia coli. Bioresearch Technol 149:84–91. https://doi.org/10.1016/j.biortech.2013.09.052
107. Zheng P, Fang L, Xu Y, Dong J-JI, Ni Y, Sun Z-H (2010) Succinic acid production from corn stover by simultaneous saccharification and fermentation using Actinobacillus succinogenes. Bioresearch Technol 101:7889–7894. https://doi.org/10.1016/j.biortech.2010.05.016
108. Bao H, Liu R, Liang L, Jiang Y, Jiang M, Ma J, Chen K, Jia H, Wei P, Quyang P (2014) Succinic acid production from hemi-cellulose hydrolysate by an Escherichia coli mutant obtained by atmospheric and room temperature plasma and adaptive evolution. Enzyme Microb Technol 66:10–15. https://doi.org/10.1016/j.enzmictec.2014.04.017
109. Cheng K-K, Wu J, Wang G-Y, Li W-Y, Feng J, Zhang J-A (2013) Effects of pH and dissolved CO2 level on simultaneous production of 2,3-butanediol and succinic acid using Klebsiella pneumoniae. Bioresearch Technol 135:500–503. https://doi.org/10.1016/j.biortech.2012.08.100
110. Wang C, Yan D, Li Q, Sun W, Xing J (2014) Ionic liquid pretreatment to increase succinic acid production from lignocellulosic biomass. Enzyme Microb Technol 172:283–289. https://doi.org/10.1016/j.enzmictec.2014.09.045
111. Yan D, Wang C, Zhou J, Liu Y, Yang M, Xing J (2014) Construction of reductive pathway in Saccharomyces cerevisiae for effective succinic acid fermentation at low pH value. Enzyme Microb Technol 156:232–239. https://doi.org/10.1016/j.biortech.2014.01.053
112. Xiao M, Zhu X, Xu H, Tang J, Liu R, Bi C, Fan F, Zhang X (2017) A novel point mutation in RpoB improves osmotolerance and succinic acid production in Escherichia coli. BMC Biotechnol 17(1):1–11. https://doi.org/10.1186/s12896-017-0337-6
113. Zhu F, Wang Y, San KY, Bennett GN (2018) Metabolic engineering of Escherichia coli to produce succinate from soybean hydrolysate under anaerobic conditions. Biotechnol Bioeng 115(7):1743–1754. https://doi.org/10.1002/bit.26584
114. Kuglarz M, Alvarado-Moraes M, Karakashiev D, Angelidaki I (2016) Integrated production of cellulosic bioethanol and succinic acid from industrial hemp in a biorefinery concept. Biotechnology Bioeng 100:639–647. https://doi.org/10.1002/bit.26584
115. Sigurðarjónsdóttir MA, Orlygsson J (2012) Combined hydrogen and ethanol production from sugars and lignocellulosic biomass by Thermoaerobacterium AK54, isolated from hot spring. Appl Energy 97:785–791. https://doi.org/10.1016/j.apenergy.2011.11.035

Springer
116. Urbaniec K, Bakker RR (2015) Biomass residues as raw material for dark hydrocarbon fermentation—a review. Int J Hydrogen Energ 40:3648–3658. https://doi.org/10.1016/j.ijhydene.2015.01.073
117. Song Z-X, Dai Y, Fan Q-L, Li X-H, Fan Y-T, Hou H-W (2012) Effects of pretreatment method of natural bacteria source on microbial community and bio-hydrogen production by dark fermentation. Int J Hydrogen Energ 37:5631–5636. https://doi.org/10.1016/j.ijhydene.2012.01.010
118. Liu Y, Yu P, Song X, Qu Y (2008) Hydrogen production from cellulose by coculture of Clostridium thermocellum JN4 and Thermoanaerobacterium thermosaccharolyticum GD17. Int J Hydrogen Energ 33:2927–2933. https://doi.org/10.1016/j.ijhydene.2008.04.004
119. Wang J, Wan W (2009) Factors influencing fermentative hydrogen production: a review. Int J Hydrogen Energ 34:799–811. https://doi.org/10.1016/j.ijhydene.2008.11.015
120. Brar KK, Cortez AA, Pellegrini VO, Amulya K, Polikarpov I, Wang J, Wan W (2009) Factors influencing fermentative hydrogen production: a review. Int J Hydrogen Energ 34:799–811. https://doi.org/10.1016/j.ijhydene.2008.11.015
121. Almarsdóttir AR, Tarazewicz A, Gunnarsson IB, Örlygsson GD17. Int J Hydrogen Energ. https://doi.org/10.1016/j.ijhydene.2022.01.156
122. Almarsdóttir AR, Tarazewicz A, Gunnarsson IB, Örlygsson GD17. Int J Hydrogen Energ. https://doi.org/10.1016/j.ijhydene.2022.01.156
123. Chandra R, Takeuchi H, Hasegawa T, Kumar R (2012) Improving hydrogen production technology. Int J Hydrogen Energ. https://doi.org/10.1016/j.ijhydene.2012.01.010
124. Pakarinen A, Maijala P, Stoddard FL, Santanen A, Tuomainen J (2010) Hydrogen production from sugars and complex biomass by Clostridium species, AK14, isolated from Icelandic hot spring. CIEL AGRI. SCI. 23, 61–71. https://ias.js/wp-content/uploads/Icelandic_Agricultural_Sciences_23_2010/Hydrogen-production-from-sugars-and-complex-pdf
125. Lehtomäki A, Viinikainen TA, Rintala JA (2008) Screening and evaluation of annual bioenergy crops and crop residues for methane biofuel production. in: Environment technology. Part A: Recovery, Utilization, and Environmental Effects. ICEL. AGRIC. SCI. 23, 61–71. https://ias.js/wp-content/uploads/Icelandic_Agricultural_Sciences_23_2010/Hydrogen-production-from-sugars-and-complex-pdf
126. Prade T, Svensson SE, Andersson A, Mattsson JE (2011) Biomass and energy yield of industrial hemp grown for biogas and solid fuel. Biomass Bioenerg 35(7):3071–3078. https://doi.org/10.1016/j.biombioe.2011.04.022
127. Kreuger E, Sipos B, Zacchi G, Svensson SE, Björnsson L (2011) Bioconversion of industrial hemp to ethanol and methane: the benefits of steam pretreatment and co-production. Bioresour Technol 102(3):3457–3465. https://doi.org/10.1016/j.biortech.2010.10.126
128. Balodis O, Bartuševics J, Gaile Z (2011) Biomass yield of different plants for biogas production. in: environment technology. resources. Proceedings of the International Scientific and Practical Conference, pp 238–245. https://doi.org/10.10177/et12011vol1.884
129. Schroyen M, Van Hulle SW, Holemans S, Vervaeren H, Raes K (2017) Laccase enzyme detoxifies hydrolysates and improves biogas production from hemp straw and Miscanthus. Bioresour Technol 244:597–604. https://doi.org/10.1016/j.biortech.2017.07.137
130. Kreuger E, Prade T, Escobar F, Svensson SE, Englund JE, Björnsson L (2011) Anaerobic digestion of industrial hemp—effect of harvest time on methane energy yield per hectare. Biomass Bioenerg 35(2):893–900. https://doi.org/10.1016/j.biombioe.2010.11.005
131. Matassa S, Esposito G, Pirozzi F, Papirio S (2020) Exploring the biomethane potential of different industrial hemp (Cannabis sativa L.) biomass residues. Energies 13(13): 3361. https://doi.org/10.3390/en13133361
132. Gill P, Soni SK, Kundu K (2011) Comparative study of hemp and jatropha oil blends used as an alternative fuel in diesel engine. Agric. Eng. Int.: CIGR J 13(3). https://cigrjournal/index.php/Ejournall/article/view/1624
133. Wang W, Wei H, Knoshaug E, Van Wychen S, Xu Q, Himmel ME, Zhang M (2016) Fatty alcohol production in Lipomyces starkey and Yarrowia lipolytica. Biotechnol Biofuels 9:227. https://doi.org/10.1186/s13068-016-0647-2
134. Zhao C, Gu D, Nambou K, Wei L, Chen J, Imanaka T, Hua Q (2015) Metabolome analysis and pathway abundance profiling of Yarrowia lipolytica cultivated on different carbon sources. J Biotechnol 206:42–51. https://doi.org/10.1016/j.jbiotec.2015.04.005
135. Ledesma-Amaro R, Lazar Z, Rakicka M, Guo Z, Fouchard F, Crutz-Le Coq AM, Nicaud JM (2016) Metabolic engineering of Yarrowia lipolytica to produce chemicals and fuels from xyllose. Metab Eng 36:115–124. https://doi.org/10.1016/j.ymben.2016.07.001
136. Tai M, Stephanopoulos G (2013) Engineering the push and pull of lipid biosynthesis in oleaginous yeast Yarrowia lipolytica for biofuel production. Metab Eng 15:1–9. https://doi.org/10.1016/j.ymben.2012.08.007
137. Blazek J, Hill A, Liu L, Knight R, Miller J, Pan A, Otoupal A, Alper HS (2014) Harnessing Yarrowia lipolytica lipogenesis to create a platform for lipid and biofuel production. Nat Commun 5(1):1–10. https://doi.org/10.1038/ncomms4131
138. Xu P, Qiao K, Ahn WS, Stephanopoulos G (2016) Engineering Yarrowia lipolytica as a platform for synthesis of drop-in transportation fuels and oleochemicals. Proc Natl Acad Sci 113(39):10848–10853. https://doi.org/10.1073/pnas.1607295113
139. Qiao K, Waylenko TM, Zhou K, Xu P, Stephanopoulos G (2017) Lipid production in Yarrowia lipolytica is maximized by engineering cytosolic redox metabolism. Nat Biotechnol 35(2):173–177. https://doi.org/10.1038/nbt.3763
140. Tahir N, Tahir MN, Alam M, Yi W, Zhang Q (2020) Exploring the prospective of weeds (Cannabis sativa L., Parthenium hysterophorus L.) for biofuel production through nanocatalytic (Co, Ni) gasification. Biotechnol Biofuels 13(1):1–10. https://doi.org/10.1186/s13068-020-01785-x
141. Ahmad M, Ullah K, Khan MA, Zafar M, Tarig M, Ali S, Sul-tana S (2011) Physicochemical analysis of hemp oil biodiesel: a promising non edible new source for bioenergy. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 33(14):1365–1374. https://doi.org/10.1080/15567036.2010.499420
142. Gülüm M, Yesilyurt MK, Bilgin A (2020) The modeling and analysis of transesterification reaction conditions in the selection of optimal biodiesel yield and viscosity. Environ Sci Pollut Res 27(10):10351–10366. https://doi.org/10.1007/s11356-019-07473-0
143. Yesilyurt MK, Cesar C, Aslan V, Yılbasi Z (2020) The production of biodiesel from safflower (Carthamus tinctorius L.) oil as a potential feedstock and its usage in compression ignition engine: a comprehensive review. Renew Sust Energ Rev 119:109574. https://doi.org/10.1016/j.rser.2019.109574
145. Yiğbaşi Z, Yesilyurt MK, Arslan M (2021) The production of methyl ester from industrial grade hemp (Cannabis sativa L.) seed oil: a perspective from Turkey—the optimization study using the Taguchi method. Biomass Convers Biofuel, pp 1–21. https://doi.org/10.1007/s13399-021-01751-z
146. Xue SJ, Chi Z, Zhang Y, Li YF, Liu GL, Jiang H, Hu Z, Chi ZM (2018) Fatty acids from oleaginous yeasts and yeast-like fungi and their potential applications. Crit Rev Biotechnol 38(7):1090–1060. https://doi.org/10.1080/07328306.2018.1428167
147. Salami A, Heikkinen J, Tomppo L, Hyttinen M, Kekäläinen T, Jänis J, Vepsäläinen J, Lappalainen R (2021) A comparative study of pyrolysis liquids by slow pyrolysis of industrial hemp leaves, hurs and roots. Molecules 26(11):3167. https://doi.org/10.3390/molecules26113167
148. Adrio JL (2017) Oleaginous yeasts: promising platforms for the production of oleochemicals and biofuels. Biotechnol Bioeng 114(9):1915–1920. https://doi.org/10.1002/bit.26337
149. Zhou YJ, Buijs NA, Zhu Z, Qin J, Siewers V, Nielsen J (2016) Microbial production of fatty alcohols. Appl Microbiol Biotechnol 93:1917–1925. https://doi.org/10.1007/s00253-011-3718-0
150. Hu Y, Zhu Z, Nielsen J, Siewers V (2019) Engineering Saccharomyces cerevisiae cells for production of fatty acid-derived biofuels and chemicals. Open Biol 9(5):190049. https://doi.org/10.1098/rsob.190049
151. Rigouin C, Croux C, Borsenberger V, Khaled MB, Chandot T, Marty A, Bordes F (2018) Increasing medium chain fatty acids production in Yarrowia lipolytica by metabolic engineering. Microb Cell Fact 17(1):1–12. https://doi.org/10.1186/s12934-018-0989-5
152. Yaegashi J, Kirby J, Ito M, Sun J, Dutta T, Mirciaghi M, Sundstrom ER, Airdo A, Baido E, Tanjore D, Pray T (2017) Rhodopseudomonas paladina: a new platform organism for conversion of lignocellulose into terpene biofuels and bioproducts. Biotechnol Biofuels 10(1):1–13. https://doi.org/10.1186/s13068-017-0927-5
153. Sundstrom E, Yaegashi J, Yan J, Masson F, Papa G, Rodriguez A, Mirciaghi M, Liang L, He Q, Tanjore D, Pray TR (2018) Demonstrating a separation-free process coupling ionic liquid pretreatment, saccharification, and fermentation with Rhodopseudomonas paladina to produce advanced biofuels. Green Chem 20(12):2870–2879. https://doi.org/10.1039/C8GC00518D
154. Wichmann J, Starnmer ER, Rodriguez A, Baido E, Tanjore D, Pray T (2017) Coupling ionic liquid pretreatment, saccharification, and fermentation with Rhodopseudomonas paladina to produce advanced biofuels. Biotechnol Biofuels 10(1):1–13. https://doi.org/10.1186/s13068-016-0512-3
155. Rutter CD, Rao CV (2016) Production of 1-decanol by metabolically engineered Yarrowia lipolytica. Biotechnol Biofuels 9(1):1–10. https://doi.org/10.1186/s13068-016-0512-3
156. Oh YK, Hwang KR, Kim C, Kim JR, Lee JS (2018) Recent developments and key barriers to advanced biofuels: a short review. Bioresour Technol 257:320–333. https://doi.org/10.1016/j.biortech.2018.02.089
157. Song Y, Matsumoto K, Yamada M, Gohda A, Brigham CJ, Sinsky AJ (2012) Engineered Corynebacterium glutamicum as an endotoxin-free platform strain for lactate-based polyester production. Appl Microbiol Biotechnol 93:1917–1925. https://doi.org/10.1007/s00253-011-3718-0
158. Anjum A, Zuber M, Zia KM, Noreen A, Anjum MN, Tahmasb S (2016) Microbial production of polyhydroxyalkanoates (PHAs) and its copolymers: a review of recent advancements. Int J Biol Macromol 89:161–174. https://doi.org/10.1016/j.ijbiomac.2016.04.069
159. Khattab MM, Dahman Y (2019) Production and recovery of poly-3-hydroxybutyrate bioplastics using agro-industrial residues of hemp hurd biomass. Bioprocess Biosyst Eng 42(7):1115–1127. https://doi.org/10.1007/s00449-019-02109-6
160. Lakshaw SS, Pathak AN, Kulkarni M, Srikanth GV (2012) Mutagenesis of Azotobacter vinelandii strain and production of polyβ-hydroxybutyrate from distillery spent wash. BioProcess J 11(3). https://doi.org/10.12665/113.Pathak
161. Song Y, Matsumoto K, Yamada M, Gohda A, Brigham CJ, Sinsky AJ (2012) Engineered Corynebacterium glutamicum as an endotoxin-free platform strain for lactate-based polyester production. Appl Microbiol Biotechnol 93:1917–1925. https://doi.org/10.1007/s00253-011-3718-0
162. Anjum A, Zuber M, Zia KM, Noreen A, Anjum MN, Tabasum S (2018) Engineering Yarrowia lipolytica for production of fatty acid-derived biofuels and chemicals. Open Biol 9(5):190049. https://doi.org/10.1098/rsob.190049
163. Song Y, Matsumoto K, Yamada M, Gohda A, Brigham CJ, Sinsky AJ (2012) Engineered Corynebacterium glutamicum as an endotoxin-free platform strain for lactate-based polyester production. Appl Microbiol Biotechnol 93:1917–1925. https://doi.org/10.1007/s00253-011-3718-0
164. Lakhawat SS, Pathak AN, Kulkarni M, Srikanth GV (2012) Microbial production of polyhydroxyalkanoates (PHAs) and its copolymers: a review of recent advancements. Int J Biol Macromol 89:161–174. https://doi.org/10.1016/j.ijbiomac.2016.04.069
165. Brodin M, Vallejos M, Opdal MT, Area MC, Chinga-Carrasco G (2017) Lignocellulose as sustainable resources for production of bioplastics—a review. J Clean Prod 162:646–664. https://doi.org/10.1016/j.jclepro.2017.05.299
166. Zhao C, Jiang E, Chen A (2017) Volatile production from pyrolysis of lignin. Bioresour Technol 257:320–333. https://doi.org/10.1016/j.biortech.2018.02.089
175. Biddy MJ, Scarlata C, Kinchin C (2016) Chemicals from biomass: a market assessment of bioproducts with near-term potential. NREL Technical Report. (www.nrel.gov/publications)

176. Paduraru C, Tofan L (2008) Investigations on the possibility of natural hemp fibers use for Zn (ii) ions removal from wastewaters. EEMJ 7(6).

177. Tofan L, Teodosiu C, Paduraru C, Wenkert R (2013) Cobalt (II) removal from aqueous solutions by natural hemp fibers: batch and fixed-bed column studies. Appl Surf Sci 285:33–39. https://doi.org/10.1016/j.apsusc.2013.06.151

178. Tofan L, Păduraru C, Teodosiu C, Toma O (2015) Fixed bed columns study on the removal of chromium (III) ions from aqueous solutions by hemp fibres with improved sorption performance. Cellul Chem Technol 49:219–229

179. Tofan L, Păduraru C, Toma O (2016) Zinc remediation of aqueous solutions by natural hemp fibres: batch desorption/regeneration study. Des Water Treat 57:12644–12652. https://doi.org/10.1080/19443994.2015.1052566

180. Tofan L, Wenkert R, Păduraru C (2016) Natural and waste materials as green sorbents for Cd(II) removal from aqueous effluents. Environ Eng Manag J 15: 1049–1058. https://doi.org/10.30638/eemj.2016.116

181. Meng X, Scheidemantle B, Li M, Wang YY, Zhao X, Torogonzález M, Singh P, Pu Y, Wyman CE, Ozcan S, Cai CM (2020) Synthesis, characterization, and utilization of a lignin-based adsorbent for effective removal of azo dye from aqueous solution. ACS Omega 5(6):2865–2877. https://doi.org/10.1021/acsomega.9b03717

182. Supanchaiyamat N, Jetsrisuparb K, Knijnenburg JT, Tsang DC, Hunt AJ (2019) Lignin materials for adsorption: current trend, perspectives and opportunities. Bioreourc Technol 272:570–581. https://doi.org/10.1016/j.biortech.2018.09.139

183. Laurichesse S, Avéroù L (2014) Chemical modification of lignins: towards biobased polymers. Prog Polym Sci 39(7):1266–1290. https://doi.org/10.1016/j.progpolymsci.2013.11.004

184. Barana D, Orlandi M, Zoia L, Castellani L, Hanel T, Bolck C, Gosselink R (2018) Lignin based functional additives for natural rubber. ACS Sustain Chem Eng 6(9):11843–11852. https://doi.org/10.1021/acssuschemeng.8b02145

185. Brar KK, Magdouli S, Othmani A, Ghanei J, Narisetty V, Sindhu R, Binod P, Pugazhendhi A, Awasthi MK, Pandey A (2021) Green route for recycling of low-cost waste resources for the biosynthesis of nanoparticles (NPs) and nanomaterials (NMs)-a review. Environ Res 14:112202. https://doi.org/10.1016/j.envres.2021.112202

186. Thakur VK, Thakur MK, Raghavan P, Kessler MR (2014) Progress in green polymer composites from lignin for multifunctional applications: a review. ACS Sustain Chem Eng 2(5):1072–1092. https://doi.org/10.1021/sc500087z

187. Liu WJ, Jiang H, Yu HQ (2015) Thermochemical conversion of lignin to functional materials: a review and future directions. Green Chem 17(11):4888–4907. https://doi.org/10.1039/C5GC01054C

188. Tanase-Opedal M, Espinosa E, Rodriguez A, Chinga-Carrasco G (2019) Lignin: a biopolymer from forestry biomass for biocomposites and 3D printing. Materials 12(18):3006. https://doi.org/10.3390/ma12183006

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