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Transformation of Oil Palm Biomass into Value-Added Components

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ABSTRACT

Oil palm is currently the world's leading vegetable oil crop, with Indonesia and Malaysia as the two largest producers and exporters of palm oil in the world. In order to meet the demand for palm oil, the mills generate huge quantities of by-products causing an alarming concern on environmental impact. Hence, the effort to transform "waste to gold" is very crucial. This review focused on the extraction methods for holocellulose and lignin, as well as processing methods to produce value-added components such as nanoparticles, fermentable sugar, bioethanol, biochemicals, biofuel and phenolic compounds because the oil palm biomass (OPB) generated contain high amounts of nutritional or bioactive components. Processes such as chemical extractions, enzymatic hydrolysis, microorganism fermentation, organic solvent extractions and green extraction technology using deep eutectic solvents, protic ionic liquid, and supercritical fluid, were used to transform OPB into value-added bio-products for various industries especially food, agricultural, and pharmaceutical industries. Chemical extraction was crucial to extract cellulose and hemicellulose from the lignocellulosic material of OPB prior to other processing methods to produce a variety of valuable components. Sequential mild chemical extraction, cellulase cocktail hydrolysis, supercritical carbon dioxide extraction and ethanol extraction successfully extracted OPB value-added components with improved physical and chemical properties.

Keywords

Abbreviations

AAEM:	Alkaline earth metals	OPB:	Oil palm biomass
AHP:	Alkaline hydrogen peroxide	OPF:	Oil palm fronds
CRL:	Candida rugosa lipase	OPL:	Oil palm leaves
DC:	Decanter cake	OPMF:	Mesocarp fibre
DES:	Deep eutectic solvents	OPT:	Oil palm trunks
EFB:	Empty fruit brunches	PIL:	Protic ionic liquid
EOL:	Ethanol organosolv lignin	PKS:	Palm kernel shells
HBA:	Hydrogen bond acceptor	POME:	Palm oil mill effluent
HBD:	Hydrogen bond donor	PPF:	Palm-pressed fibre
MNP:	Magnetite	PyFor:	Pyridinium formate
MCC:	Microcrystalline cellulose	scCO$_2$:	Supercritical carbon dioxide
NCC:	Nanocrystalline cellulose	SFE:	Supercritical fluid extractions

1. Introduction

Oil palm tree (*Elaeis guineensis*) is a species of palm commonly known as African oil palm tree. It is an important perennial crop in Southeast Asia, South America and Africa [1]. Oil palm is a monocotyledonous and monoecious crop that bears both male and female flowers on the same tree [2]. A palm tree consists of fronds, trunk, fruits, and roots, at which the fronds can be separated into leaf and stem. Adult palm trees have a large leaf area index. Every part of this plant has its potential economic value and domestic usage. Oil palm is the most productive oil crop and promising vegetable oil because the oil itself can meet the growing demand around the world which is estimated to achieve 240 million ton by 2050 [3]. According to the Malaysia Palm Oil Council, Indonesia and Malaysia are the largest oil palm growers, which contributed to approximately 85–90% of palm oil production and export trade of the world. In 2020, one hectare of oil palm plantation in Malaysia produced approximately 16.7 ton of fresh fruit bunches (FFB), producing a total of 19.1 million ton of crude palm oil [4].

Apart from being recognized for its great contribution towards economic growth, oil palm industries have caused significant environmental pollution due to the enormous production of by-products during the oil processing starting from the plantations to the palm oil production with very limited usage of the wastes produced by the processes [5]. The oil palm tree produces only 10% of oil while the remaining of its 90% is waste. The examples of oil palm biomass (OPB) include oil palm trunks (OPT), oil palm fronds (OPF), oil palm leaves (OPL), empty fruit bunches (EFB), palm oil mill effluent (POME), decanter cake (DC), palm-pressed fibres (PPF), and palm kernel shells (PKS) [6]. Sulaiman *et al.* [7] outlined that two-third of the OPB (dry weight basis) are OPT and OPF while the remaining one-third are FFB residues. OPT and OPF are generated from the replanting process and pruning activity in the plantation sites, whereas EFB, POME, PPF, and PKS are generated in the mills during fresh fruit bunches processing to obtain the palm oil [8].

Although OPB are wastes, they contain a high amount of nutritional or bioactive components, which may exert health benefits to humans, thus the approaches of waste management are aimed to reduce and recycle the by-products to recover the valuable components in OPB [9]. The extractives and ash that present in minute amounts in OPB can potentially be used as reactive dyes [10], low-cost activated carbon or adsorbent for water treatment [11] and as a potential ingredient in concrete manufacturing due to its good mechanical strength [12], but OPB was reported to have limited usage. POME was mainly used as a fuel supply to produce biogas for power engine machines, while fruit shell and fibre are burnt to produce heat and electricity [13]. EFB and DC were used for composting, dumping in oil palm gardens and land covering, yet they caused environmental problems due to the overloading of biomass. OPF as one of the largest generated OPB was under-utilized, where it was usually piled up to be used as the recycling fertilizers. However, the piles guarded high humidity within them. The decomposition thus created a density gradient of humidity and humus from the piles to its base, contributing to a large number of epiphytes that surround the trunk [14].

The efforts in reducing the waste discharged were seen in the transformation of the by-products into value-added products by using different processing methods. The processes used to improve the quality of the value-added products from OPB included chemical extraction using strong or weak acid and alkaline, enzymatic hydrolysis, microorganism fermentation, organic solvent extractions and the green extraction technology such as deep eutectic solvents (DES), protic ionic liquid (PILs) and supercritical fluid [15, 16]. The chemical extraction was adopted by many researchers to extract hemicellulose, cellulose, lignin, and nanoparticles from OPB because of its lignocellulosic-rich materials especially in EFB, OPF, and mesocarp fibre (OPMF) [17], while enzymatic hydrolysis gained popularity among the researchers to produce fermentable sugar, biochemicals and biofuel due to environmental friendly processes by generating fewer fermentation inhibition products and milder reaction

conditions as compared to acid hydrolysis [18]. Besides, the green technologies had improved the quality of value-added components extracted from OPB such as cellulose, lignin, furfural, and biofuel. This review summarizes the processing methods used to produce a variety of value-added components from OPB. This review includes the extraction methods used to obtain holocellulose and lignin from OPB and the production of value-added components such as nanoparticles, fermentable sugar, bioethanol, biochemicals, biofuel, and phenolic compounds.

2. Value-added components from oil palm biomass

2.1 Holocellulose (cellulose and hemicellulose) and lignin

Hemicellulose and cellulose are important components extracted from OPB, where delignification or pre-treatment is usually used as the extraction process because the delignified hemicellulose and cellulose are further converted into other value-added components such as fermentable sugar, biochemicals and biofuel. Delignification of OPB is a very crucial pre-treatment because OPB contains a high amount of organic matter such as holocellulose (cellulose and hemicellulose), lignin and extractives [19]. Holocellulose is the main constituent in lignocellulosic materials at which hemicellulose is an alkaline-soluble polysaccharide while cellulose is an acid-soluble polysaccharide [20]. Lignin is also a major component in biomass that plays an important role as a binder to support cells and microfibrils that mediate structural ability in the lignocellulosic cell wall structure [21]. Delignification removes lignin and increases the porosity in the lignocellulosic structure of biomass, making cellulose and hemicellulose more available for hydrolysis and fermentation processes [22]. Most of the chemical extractions and enzymatic hydrolysis focused on hemicellulose and cellulose because lignin is seen as a by-product. However, lignin is the most abundant renewable aromatic compound, which exists as the only aromatic biopolymer in lignocellulosic biomass [23]. Its special aromatic structure consists of various functional groups such as *p*-coumaryl, coniferyl and sinapyl alcohols which further polymerize at different positions in the phenyl ring [24]. The common method used for delignification of OPB is chemical treatment using acid or base, while several new treatments using deep eutectic solvent (DES) [25, 26] and protic ionic liquid (PILs) [27, 28, 29] are reported to have successful extraction of lignin with good quality.

2.1.1 Acid or alkali extraction of hemicellulose and cellulose

Chemical extraction using acid or base is known to be a cost-effective process to decompose lignocellulosic materials. The extraction is widely used in delignification of OPB because the process is simple. Apart from that, the cost of acid and alkaline are cheaper than other extraction mediums to remove oil residues, lignin, and a small amount of acidic hemicellulose from the fibre surface which broadens the usage of OPB [30]. The chemical extraction includes bleaching process using sodium chlorite, $NaClO_2$, which turns the colour of the biomass from brown to white [31]. Other than that, delignification using diluted acid and alkaline is usually applied on biomass prior to enzymatic hydrolysis to increase the yield and reduce the cost of hydrolysis. The delignification increases enzymatic digestibility by revealing the silica body on the surface and pores on the fibre because lignin and hemicellulose will reduce the accessibility of enzymes to internal fibre such as cellulose [32]. Chemical extraction is usually targeted on OPB such as EFB, OPF, OPL, OPMF and OPT, which have high amounts of lignocellulosic materials.

Several studies reported that the use of an alkaline solution such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) with the presence of boric acid enhanced the release of hemicellulose. Commonly used acids were acetic acid (CH_3COOH), hydrochloric acid (HCl) and sulfuric acid (H_2SO_4). Moreover, weaker acids such as diluted H_2SO_4, diluted HCl, diluted nitric acid (HNO_3), CH_3COOH, and phosphoric acid (H_3PO_4) were commonly used to

hydrolyze lignocellulosic materials due to its simple reaction control and lesser corrosion problems compared to concentrated acids [33]. However, strong alkaline was more effective in removing residual oil of OPB compared to acids, as observed in a study that reported the NaOH is more effective than CH_3COOH [34]. On the other hand, acid-extracted fibre had a rougher surface with more silica bodies removed, revealing more pores on the fibre, thus enhancing chemical penetration into the fibre during pulping, as compared to alkali-extracted fibre [34].

Since acid and alkaline have different functions in the delignification process, many studies combined both into sequential steps to produce cellulose and hemicellulose with higher quality. Nasir and Saleh [35] reported that hemicellulose of EFB was extracted using 3.0 M KOH, followed by 50% acetic acid, and washed with 95% ethanol to remove residual acid. The results showed that sequential extraction was the most efficient method to isolate large amounts (up to 30%) of hemicellulose polysaccharides compared to a lower concentration of KOH (1.0 M). The predominant sugars found in the pre-treated EFB were xylose and arabinose, which were extracted with acid and alkaline combined with ethanol precipitation. This produced hemicellulosic fractions with more linear structures. Another study conducted by Nafu and Foba-Tendo [36] reported that EFB stalk extracted using diluted alkaline solution (2% NaOH), followed by strong alkali delignification [24% KOH–2% boric acid (H_3BO_3)] for 2 h produced feedstock fibre with higher potassium content and lower recalcitrance as compared to EFB spikelet. Therefore, the alkaline treated EFB spikelet fibres could be used as reinforcing fibres due to higher strength and recalcitrance properties.

Carpentier and Méndez [37] studied the enzymatic conversion of delignified EFB into fermentable sugars and found that the EFB treated sequentially with diluted acid (1.1% (v/v) H_2SO_4) and alkaline solution (4% (w/v) NaOH) at 121 °C for 27 and 30 min increased the percentage of cellulose from 24.53% (untreated EFB) to 43.16% (pre-treated EFB), respectively. The usage of peracetic acid (CH_3CO_3H) and alkaline peroxide extraction combined with NaOH solution removed 92–98% of lignin and produced fibre with high cellulose content (84%), whereas the untreated EFB fibres had a smooth surface with an outer layer made of lignin to protect the fibre against rupturing [32, 38]. In contrast, green extraction of EFB using 20% formic acid with 5% of hydrogen peroxide yielded 84.2% of α-cellulose with similar chemical properties as the standard cellulose [39]. Delignification of OPB using chemical extraction has been widely used, not only limited to the production of cellulose, hemicellulose, and fermentable sugar but also crucial for the production of biofuel. Ahmad *et al.* [39] revealed that improved microbial oil is successfully produced by using an oleaginous filamentous fungi *Mucor plumbeus* through chemical pre-treated EFB using 0.8% (w/v) H_2SO_4 at 170 °C for 15 min.

A recent study reported that repeated chemical treatments using diluted base and bleaching followed by high-pressure steaming had successfully extracted a high yield of cellulose from OPF with 4 g of cellulose extracted from every 10 g of OPF. The extracted cellulose had a high crystalline index (68.75%) and high thermal stability (350 °C) [31]. The autoclaved OPF was extracted using 4% NaOH and bleached using 1.7% $NaClO_2$ which changed the colour from brown to white, while the cellulose fibres extracted were smaller in diameter and smoother on the surface if compared to untreated fibres. This was due to the extensive removal of lignin and complex structure on the outer layer of the fibre. In addition, the extraction of EFB by using a combination of chemical and physical treatments through 1.0 M NaOH paired with an autoclave (121 °C, 15 psi, 1 h) had an increased amount of cellulose. The amount of glucose generated increased with an increasing amount of cellulose per unit of pre-treated EFB by generating 23.6–34.6 g/L after 72 h of fermentation [40]. The alkaline-treated EFB produced 2–3 times higher amounts of fermentable sugars than untreated EFB. Apart from high-pressure steaming, chemical extraction can be paired with radiation to improve the extraction outcome. A study done by Chin *et al.* [41] reported that acid hydrolysis by diluted H_2SO_4 (0.25–0.50 N) paired with microwave irradiation produced a high amount of glucose

and xylose as the end-product of the cellulose and hemicellulose hydrolysis of EFB. The kinetic study suggested that the use of higher temperature and acid concentration result in higher yields of glucose and xylose.

Cellulose fibre extracted from OPB can be further treated to extract microcrystalline cellulose (MCC). Xiang *et al.* [42] extracted MCC from the pre-treated α-cellulose fibres from EFB stalks and spikelet using 55% (w/w) H_2SO_4 solution. The first step of chemical delignification of EFB, EFB stalks and EFB spikelet to yield α-cellulose fibres prior to MCC extraction is acidification of 0.7% (w/v) of sodium chlorite ($NaClO_2$) solution, followed by 17.5% (w/v) NaOH treatment. The cellulose content found in MCC extracted from the stalk (SMCC) was higher than the EFB (EMCC) and spikelet (SPMCC) with 86.5, 81.1, and 84.5%, respectively. The extraction process had successfully removed a large amount of lignin and cellulose from EFB. The crystallinity indexes of EMCC (82.5%), SMCC (82.2%) and SPMCC (86.5%) were comparable to commercial MCC (81.9%), revealing that acid extraction improved the rigidity of cellulose structure and structural integrity of fibres that are suitable for bio-composite production. However, Haafiz *et al.* [43] reported that acid hydrolysis using 2.5 N HCl at 105 °C, followed by washing using 5% diluted ammonium hydroxide (NH_4OH) produced rough, compact, and regular spherical MCC particles. The high crystallinity index proved that acid hydrolysis did not alter the crystal structure, hence the MCC had good thermal stability and high potential to be used as good reinforcing material in polymeric materials [44]. Apart from that, Ismail *et al.* [44] reported that the MCC extracted from EFB using 5–25% H_2SO_4 under pressurized steam for 1 h showed maximal thermal durability which can be used as the nanocomposites. In contrast, Owolabi *et al.* [45] studied the influence of alkaline hydrogen peroxide (AHP) concentration on the pre-treatment process of OPF before bleaching with acidified $NaClO_2$ and acid hydrolysis using HCl. The AHP solution was prepared according to the percentage ratio of hydrogen peroxide to NaOH, namely AHP[1] - 1.5:1.0% (w/v), AHP[2] - 2.5:2.0% (w/v) and AHP[3] - 5.0:4.0% (w/v). The study found that increasing AHP concentrations increased the diameter of fibrous material extracted because more hemicellulose and lignin were removed. The MCC extracted from AHP pre-treated OPF were in nano-size ranged from 7.55–9.51 nm. The crystalline index and size of MCC increased to 55.8–62.3% and 9.17–10.11 nm respectively as the concentration of AHP increased, hence concluding that AHP concentration influences the quality of MCC produced.

Generally, sequential processes using acid treatment, alkaline treatment, $NaClO_2$ bleaching and high-pressure steaming showed higher efficiency in extracting cellulose and hemicellulose in terms of yield and quality. Various biomass extraction conditions such as prolonged time and pressure could be applied to further improve the quality of extracted components. Besides, acid hydrolysis was efficient in extracting MCC from various biomass. Future studies on the combination of acid hydrolysis and high-pressure steaming are recommended to extract MCC with improved quality.

2.1.2 Protic ionic liquid (PILs) and deep eutectic solvents (DESs) extraction of cellulose and lignin

Ionic liquids (ILs) are liquids composed of sole ions at a desired temperature with unique and tunable characteristics. ILs are classified into aprotic ionic liquids (AILs), solvate ionic liquids (SILs), and protic ionic liquids (PILs), while some are in "solvent in salt" systems and mixtures [46, 47]. PILs are one of the most popular categories among the ILs due to their simple synthesis of proton transfer using stoichiometric Brønsted acid-base reaction that involves only one type of discrete anion or cation [47]. On other hand, deep eutectic solvents (DESs) are made up of a variety of anionic and/or cationic in Brønsted acid-base reaction as a eutectic mixture. Thus, DES solvent comprises of hydrogen bond donor (HBD) and hydrogen bond acceptor (HBA) in the same solution [26]. Although the chemical properties of ILs and DESs differ, DESs share many characteristics and physical properties

as ILs such as low vapor pressure and wide liquid range. Thus, DESs are widely acknowledged as a new class of ILs recently [48].

The PILs have emerged as aspiring solvents due to their wide range of properties such as high thermal stability, low chemical reactivity (non-corrosive), high conductivity, low vapour pressure, short extraction time and high extraction yield [49, 50, 51]. PILs such as pyridinium formate (PyFor), 1-butyl-3-methylimidazolium chloride ([BMIN][Cl]) and hydrophilic IL, 1-ethyl-3-methylimidazolium diethyl phosphate ([EMIM][DEP]) improved lignin extraction process with higher yield using a more cost-effective and non-corrosive process [27, 28, 29]. The cellulose extracted from IL-treated OPF by enzymatic hydrolysis using Laccase had an increase in the yield of α-cellulose from 45.7 to 68.5% while the α-cellulose showed higher thermal stability than the untreated OPF [29].

Rashid *et al.* [27] reported that under mild conditions, PyFor had successfully extracted a high yield of lignin from EFB (92.0%), OPMF (91.2%) and PKS (90.7%). Another PIL, 1-butyl-3-methylimidazolium chloride ([BMIN][Cl]) increased the yield of small molecular weight and low polydispersity lignin extracted from EFB, OPF and OPT [28]. The yield of lignin extracted using [BMIN][Cl], followed by the precipitation using ammonium potassium sulphate dodecahydrate (CO_2-AlK$(SO_4)_2$) and acid solution of H_2SO_4 and HCl, was in decreasing order of OPT (22.8%) > OPF (19.1%) > EFB (9.2%). The extensive characterization of cellulose, hemicellulose, and lignin of EFB extracted using the same PIL and extraction conditions were studied [52]. The results showed that bundle-like cellulose with high crystallinity was extracted though fully amorphous hemicellulose could not be obtained.

A study reported that acid-based DES was efficient in lignin extraction with high yields [26]. The extensive delignification by DES gave a significant effect on the functional groups of extracted EFB solid fraction, at which lignin aromatic skeleton (1513 cm^{-1}) and C-O linkage between lignin and hemicellulose (1250 cm^{-1}) were diminished [25]. Nine acidic DES consisting of choline chloride (HBA) that paired with three groups of carboxylic acids (HBD), namely α-hydroxy (lactic, malic, and citric acid), linear saturated (formic, acetic, propionic, butyric, and succinic acid) and unsaturated carboxylic acid (maleic acid) were studied. The lactic acid-based DES showed the highest efficiency in extracting high lignin yield and phenolic hydroxyl content [25]. This was because the solubilized lignin was condensed and precipitated from the solution during conventional acid treatment, whereas the phenolic groups are ionized causing lignin solubilization in the aqueous solution during alkaline treatment [53]. In summary, OPB treatment with hydrophilic ILs had successfully increased the yield of α-cellulose extraction. PyFor was the most effective PILs in extracting lignin from OPB, especially EFB, while acidic DESs were recommended to be used to extract lignin with high phenolic content.

2.2 Nanoparticles
2.2.1 Acid extraction of nanoparticles

Recently, many studies reported on the nanoparticles produced from delignified cellulose such as nanocrystalline cellulose (NCC) and nanosilica, SiO_2 which were extracted using acid. These NCCs have a wide range of applications in the biomedical field including tissue engineering, drug delivery, medical implants, cardiac devices, and wound dressings, as well as high-capacity bio-sorbent in the fabrication industry [54, 55, 56]. Several studies reported that NCC had been successfully extracted from delignified and bleached OPB using 64–65% H_2SO_4 solution [17, 54, 55]. Alkaline delignification had successfully removed hemicellulose and lignin, while bleaching was used to break down phenolic compounds and chromophoric groups present in lignin. The remaining cellulose was hydrolyzed to cellulosic nanomaterial by removing the amorphous regions of the cellulose. Shanmugarajah *et al.* [54] reported on the production of high-capacity bio-sorbent using NCC for fabrication industry, at which the

adsorption rate increased rapidly from 60 to 87% with low NCC dosage (0.005–0.01 g of NCC), revealing that NCC could be a great bio-sorbent.

Besides, NCC extracted from OPF had an average width of 9.88 nm and 504.12 nm in length and had a higher crystallinity index (54.4%) compared to raw OPF (36.0%) [55]. The NCC was also successfully isolated from high cellulose OPMF (39.5% of cellulose) by using acid hydrolysis [17, 57]. These chemical pre-treatments were reported to have an increase in the cellulose content, from 32.22% (untreated) to 81.11% (pre-treated), whereas the acid hydrolysis increased the crystallinity of bleached OPMF and reduced the dimension of cellulose to a nanometre scale. The NCC produced using acid hydrolysis had a rod-like shape with an average diameter of 4.52 nm. The study concluded that NCC could be a potential reinforcing filler in various industries [17]. In terms of applications of NCC, the characteristics of cement mortar incorporated with EFB NCC were studied, where 64% (w/v) H_2SO_4 diffused into the pulp fibre and cleaved the glycosidic bonds in the cellulose polymer to form NCC [58]. The resultant NCC suspension was incorporated into the cement composite from 0–0.8% by volume of cement content. The results showed that the addition of NCC strengthened the inner structure of composites even after the curing process through the formation of C-S-H bond or $Ca(OH)_2$. NCC also gave a positive effect on the flexural strength of cement mortar that was increased by 20% when 0.4% of NCC was added. Hence, the NCC extracted from EFB is a promising green admixture in producing cement mortar with increased structural performance. On the other hand, Mehanny *et al.* [56] reported that the nanocellulose extracted from OPL using 10% NaOH or 20% H_2SO_4 and followed by neutralization using 5% of $NaHCO_3$ yielded 42–82 nm nanocellulose that could be used to remove heavy metals (cations) from the water.

Apart from NCC, a high amount of nanosilica, SiO_2 (95.2%) could be produced from OPB using acid and thermal extraction through the combination of acid (1.0 M HCl) and thermal treatment (heated to 100 °C) on OPL before calcination [59]. This is because the HCl treatment leached out most of the alkali and alkaline earth metals (AAEM), which exist as oxides, oxalates, carbonate, and chloride salts that are bound to hemicellulose or lignin in biomass. The untreated OPL ash was found to have a high amount of AAEMs such as calcium, magnesium, and potassium, which caused the oxidation of silica and thus lowered the amount of SiO_2 in untreated OPL ash. Amorphous silica extracted from OPL has many new applications in various industries, such as being a carrier for enzyme immobilization in the pharmaceutical industry [60], as well as nanoscale optical sensors and optical coupler or ring resonators in photonic applications due to its high thermal and mechanical stabilities [59]. The combination of the acid-extracted SiO_2 with magnetite (MNPs) could form nanosilica (SiO_2-MNPs) or activated SiO_2-MNPs (Gl-A-SiO_2-MNPs) compounds [61]. The immobilized *Candida rugosa* lipase (CRL) (CRL/Gl-A- SiO_2-MNPs) compound demonstrated higher catalytic performance over lyophilized CRL, with a 13% higher yield of ester after 3 h of incubation. This suggested that the CRL/Gl-A- SiO_2-MNPs compound is a cost-effective biocatalyst for butyl butyrate production in large-scale industries. The production of nanoparticles especially NCC and nanosilica from OPB can be produced efficiently using sequential chemical extraction. Sulfuric acid (64–65% (w/v)) has been widely used to produce NCC and claimed as a good bio-sorbent and green admixture. Thus, other acids such as HCl and HNO_3 are recommended to be further studied in the production of nanoparticles from OPB. Besides, the study to transform OPB to bio-nanocomposite film is highly recommended because the bio-nanocomposite film has been reported to exhibit excellent mechanical and barrier properties as a biodegradable packaging material [62].

2.3 Fermentable sugar

2.3.1 Enzymatic hydrolysis of fermentable sugar

Enzymatic hydrolysis is widely used to extract fermentable sugar from OPB due to cost and energy efficiencies. A high yield of fermentable sugar was successfully extracted from delignified OPB using commercial enzymes such as Cellic Ctec2, Celluclast and Acellerase® [32, 37]. The efficiency of enzymatic hydrolysis is affected by the condition of OPB, including the amount of solid loading and concentration of protein loading. The amount of solid loading is the amount of raw material used in the extraction while the concentration of protein loading is the concentration of enzyme used to extract the raw material. A higher yield of fermentable sugar will be obtained if more cellulose fraction of the delignified OPB is exposed to enzyme during hydrolysis. Thus, high solid loading paired with low protein loading during enzymatic hydrolysis resulted in economic viability through cost and energy savings. Carpentier and Méndez [37] found that acid pre-treated EFB was effectively hydrolyzed by Cellic Ctec2 enzyme with a solid loading of 243.4 g/L and protein loading of 22 mg/g cellulose, releasing a total of 74.8 g/L of glucose. Besides, the types of enzyme used to extract fermentable sugar from OPB plays a crucial role in the yield, where Salleh *et al.* [63] found that the combination of *Humicola insolens* recombinant endoglucanase and commercial cellulases (Celluclast and Acellerase®) had enhanced the extraction yield of simple sugars from delignified EFB. The mixture of Celluclast with CMC3 gene from *H. insolens* at a ratio of 1:100 successfully increased glucose and xylose content as compared to using Celluclast enzyme alone, from 1.22 to 1.95 mg/mL (59% increment) and 1.22 to 1.55 mg/mL (27% increment), respectively. Another cellulose cocktail which comprised of different concentrations of Celluclast (20 to 100 filter paper unit (FPU)) and fixed concentration of Novozyme 188 (40 cellobiase unit (CBU) per gram of cellulose) was reported to produce 2–3 times higher amount of fermentable sugars from alkaline delignified EFB than untreated EFB after 72 h of fermentation [40]. The amount of glucose generated increased to 23.6–34.6 g/L with the increasing amount of cellulose per unit pre-treated EFB. Besides, enzymatic hydrolysis on acid delignified EFB using Accellerase® 1500 extracted a high yield of fermentable sugars, 118.52 g/L glucose, 955 g/L xylose and 1.00 g/L arabinose [39]. The combination of commercial enzymes, Accellerase® 1500 enzyme and Accellerase® XC was found to be more efficient in producing fermentable sugar from EFB. Accellerase® 1500 enzyme possessed strong cellulose and β-glucosidase activities, while Accellerase® XC enzyme possessed endoglucanase and xylanase activities, thus producing a high glucose yield of 629.8 ± 0.5 g glucose per kg of dry EFB biomass [32]. The sugars produced from delignified OPB could be further fermented to biochemicals, especially bioethanol and biofuel. A combination of enzymes cocktail was found to be more effective than a single enzyme in extracting fermentable sugars. Hence, it is suggested that various types of enzyme combinations with different ratios of enzymes be used in future studies to aim for producing a higher yield of fermentable sugars.

2.4 Biochemicals

2.4.1 Enzymatic hydrolysis and microorganism fermentation of biochemicals

Microorganisms are commonly used to produce bioethanol, succinic acid, and furfural from delignified OPB, especially EFB. Cellulose and hemicellulose can be enzymatically hydrolyzed to glucose and a variety of pentose or hexose sugars, which can be further fermented to produce bioethanol. Four major steps are required to produce bioethanol, which are physical and chemical delignification of lignocellulosic biomass, enzymatic hydrolysis of lignocellulosic biomass, fermentation of resulting sugars and distillation of bioethanol [64]. The delignification is considered the most important step in saccharification efficiency because it determines the yield of bioethanol production [65]. Besides, the yield of bioethanol is widely affected by the type of yeast used to ferment sugar from

delignified OPB. Kim [40] reported that *Saccharomyces cerevisiae* was the best ethanol producer compared to *Kluyveromyces marxianus* and *Scheffersomyces stipitis*, with the production of 21 g/L ethanol within 28 h.

Fermentable sugar can be further processed into succinic acid using anaerobic fermentation. The common microorganism that plays a vital role in producing succinic acid is *Actinobacillus succinogenes* 130Z which was reported to produce high yields of approximately 35% of succinic acid from OPB [66, 67]. The major factor that impacts the yield of succinic acid produced from OPB is the delignification process of OPB. In the past, inorganic acids such as H_2SO_4, H_3PO_4 and HNO_3 were used extensively due to their high catalytic performance and low cost but some drawbacks were observed such as corrosion, formation of undesirable by-products and low reaction selectivity [68]. Organic acids such as citric acid, formic acid and oxalic acid were used as alternatives to inorganic acids for the pre-treatment to produce succinic acid from biomass due to lower hazardous properties. Succinic acid and its derivatives produced from biomass can be used directly as a source of food additives, pharmaceuticals, solvents, detergents, biodegradable plastics, surfactants, and fuels [69]. Luthfi *et al.* [66] reported that high yields of succinic acid (36.6 g/L with a yield of 35.7%) were produced from alkaline pre-treated OPF bagasse after 60 h of anaerobic fermentation. However, organic acid pre-treated OPT was reported to produce a lower amount of succinic acid [67]. The study reported that citric acid gave the highest yield of succinic acid compared to formic acid and oxalic acid with 10.6 g/L, 1.1 g/L and 2.6 g/L, respectively. This could be due to the efficiency of citric acid in hydrolyzing cellulose to release glucose, where higher glucose formation led to a higher yield of succinic acid production. Generally, a combination of extraction processes on OPB from the delignification process, the production of fermentable sugar and finally the production of bioethanol or succinic acid was crucial in determining the end-product yield, where alkaline pretreatment followed by enzymatic hydrolysis was more favorable to produce succinic acid from OPB.

2.4.2 Supercritical fluid extraction (ethanol) of furfural

The bioethanol produced from delignified OPB using enzymes and microbes can be further used to produce furfural, a valuable bio-based chemical. The process is self-sustainable because the main solvents used are the biomass-derived supercritical ethanol while formic acid is used as a catalyst, which is a by-product of furfural production. Supercritical fluid is a homogenous liquid-gas phase where the liquid and gaseous state of the liquid are merged because of the pressure and temperature of the liquid are higher than its critical point [70]. The extraction is efficient in time, yield, cost, while being non-toxic, non-flammable and environmentally friendly because supercritical fluid is recyclable and low in by-products. Generally, furfural is one of the highest value-added bio-based chemicals, where it can be used to produce a wide range of non-petroleum derived chemicals such as furan, furfuryl alcohol and tetrahydrofuran, besides its application in food (flavouring), pharmaceuticals (tuberculosis remedies), medicine plastics (resins) and agriculture (herbicides, fungicides, insecticides) [71]. A study revealed that OPF with high hemicellulose content (40.4%) was crucial for furfural production due to its production from xylose units of xylan in hemicellulose. The production of furfural from OPF by using supercritical ethanol with formic acid as a catalyst was successful and reported to give the highest yield of 35% [72] compared to other commercial and conventional methods such as high-temperature diluted-acid hydrolysis [73] and high-temperature sequential hydrolysis using acid, ethanol, and water [74]. The yield was enhanced by higher reaction temperature and acid concentration, as well as a low amount of solid loading. Thus, hydrolysis using supercritical ethanol and formic acid is recommended.

2.5 Biofuel

2.5.1 Microorganism fermentation of biofuel

OPB could be treated with fungi to produce value-added biofuel. The most crucial step to produce microbial oil through the biochemical conversion of sugars in lignocellulosic biomass by oleaginous microorganisms is the pre-treatment process which consists of the combination of delignification process and enzymatic hydrolysis of lignocellulosic biomass [39]. The microbial oil serves as the feedstock to produce second-generation biodiesel through the transesterification process. It has several advantages including high productivity, low labour cost and only consumes a small area of land if compared to the first-generation biodiesel produced from plant oils [75]. Oleaginous filamentous fungi especially *Mucor plumbeus* can tolerate low concentrations of growth inhibitors resulting from chemical delignification of lignocellulosic biomass. Besides, these fungi can grow on a broad range of carbon substrates such as glucose and xylose, making them promising microbes for microbial oil production from biomass [76]. Ahmad *et al.* [39] reported that improved yields of microbial oil were produced from pre-treated EFB using *Mucor plumbeus*. The study reported that higher sugar concentration led to higher oil accumulation by oleaginous microorganisms. However, higher oil yield was accumulated by lowering yeast content with optimum parameters of 30 g/L of sugar concentration and pH 5.0 resulting in 2.6 g/L oil concentration with an oil yield of 84 mg/g. The oil produced from EFB could be used to produce biodiesel with a 7.3% lower cost of production than glucose-derived oil.

2.5.2 Supercritical fluid extractions (carbon dioxide and water) of biofuel

Supercritical fluid extractions (SFE) have gained high research interest to produce biofuel from OPB. SFE is an alternative technique to produce bio-oils by using green solvent, carbon dioxide under mild conditions that is able to prevent degradation or chemical alteration of thermal sensitive compounds. Thus, SFE is environmentally friendly and cost-effective in fractionating crude bio-oil due to minimum chemical residues and recyclable solvents [77]. Extraction parameters influencing the yield and quality of bio-oil extraction include the type of supercritical fluid, supercritical conditions such as temperature, pressure, and flow rate of the extraction, reaction time and type of catalyst used during liquefaction. Chan *et al.* [16] reported that the fractionation of pyrolysis oil using supercritical carbon dioxide ($scCO_2$) extraction at 48 °C, 28.2 MPa, 8.0 cm^3 min^{-1} CO_2 flow rate gave a maximum yield of 30%, with acids and esters being enriched in the bio-oil extract. Another study reported that bio-oil was produced using supercritical hydrothermal liquefaction at the supercritical condition of water (390 °C and 25 MPa), with the optimum reaction time for EFB and OPMF as 120 min while PKS as 240 min [78]. Hydrothermal liquefaction of EFB was preferred to fast pyrolysis in producing bio-oil because hydrothermal liquefaction resulted in approximately 50% lesser global warning potential impact due to lower operating temperature and energy demand during drying [79]. Further to that, Yim *et al.* [15] studied the effectiveness of metal oxides catalysts, zinc oxide (ZnO), calcium oxide (CaO), magnesium oxide (MgO), aluminium oxide (Al_2O_3), cerium (IV) oxide (CeO_2), nickel (II) oxide (NiO), manganese (II) oxide (MnO), tin (II) oxide (SnO) and lanthanum oxide (La_2O_3), in the bio-oil production. CeO_2, MnO, La_2O_3 and CaO were found to be the most effective catalysts. The bio-oils produced using these catalysts were highly volatile, so they were easily combusted and consumes lesser energy. Generally, the outcome of $scCO_2$ and metal oxides in producing bio-oil via liquefaction of biomass is promising, thus detailed studies on the combination of these chemicals are recommended since the process is environmental-friendly and cost-effective.

2.6 Phenolic compounds

2.6.1 Organic solvents extractions of phenolic compounds

Organic solvents such as ethanol and acetone are commonly used to extract phenolic compounds from OPF that possess bioactivities including antioxidant [80] and antimicrobial properties [81]. The modified OPF lignin using *m*-cresol treatment was studied for its antioxidant properties by Sa'don *et al.* [80]. OPF was pre-treated using acetone solution containing 6% of *m*-cresol at 27 °C, followed by hydrolysis at 150 °C for 6 h. The hydrolyzed OPF was then treated with 65% ethanol (v/v) and 0.5% (w/w) H_2SO_4 as a catalyst for 60 min at 190 °C, followed by precipitation of ethanol organosolv lignin (EOL) using distilled water. *m*-Cresol pre-treatment had improved the quality of EOL, at which the pre-treated EOL showed good solubility in water (42%) compared to untreated EOL. This is attributed to the production of small lignin fragments with low molecular weight and polydispersity. Similarly, pre-treated EOL had higher reducing power than untreated EOL, suggesting that the improvement in physicochemical and structural properties of pre-treated EOL resulted in a broader value-added application of lignin isolated from OPF. Besides, the extraction which was carried out using 95% ethanol for 24 h produced steroids and tannins that exhibited antimicrobial properties against *Staphylococcus aureus* (gram-positive) and *Escherichia coli* (gram-negative) [81]. Since phenolic compounds can be extracted using organic solvents, further studies on the combination of extraction parameters such as different types of organic solvents (acetonitrile and water), time of hydrolysis (6–48 h) and composition of solvent (65–99%) are recommended to extract phenolic compounds with higher yield and bioactivities.

3. Overview on the processing methods to produce various OPB value-added components

The most common extraction method of OPB was the delignification or pre-treatment process using acid, alkaline, DES or PIL. This process was crucial to enhance the final yield and quality of cellulose, hemicellulose, lignin, and nanoparticles, and subsequently improve the value-added components extracted from OPB. Many types of chemical extraction were reported for delignification where this review summarized that the best method to produce high-quality end-products was sequential acid, alkaline and bleaching. The combination of mild chemicals such as diluted H_2SO_4, HCl, NaOH and $NaClO_2$ together with high pressure steaming gave high efficiency in extracting cellulose and MCC, whereas acidic DESs were able to produce lignin with high phenolic content. However, strong acids were not recommended due to corrosion on laboratory equipment. Since a combination of mild chemicals produced high yields of cellulose and hemicellulose, different extraction conditions such as prolonged extraction time and pressure, different types of chemicals and combinations of more chemicals are recommended to be studied to increase the yield of cellulose and hemicellulose with enhanced physical properties.

The valuable components of fermentable sugars that are transformed from the delignified OPB (cellulose and hemicellulose) can be further processed into environmentally friendly and self-sustainable biochemicals including bioethanol, succinic acid, furfural as well as biofuel. High yield of fermentable sugars, especially glucose and pentoses can be produced through enzymatic hydrolysis using Celluclast and Accellerase® cocktails on chemical delignified OPB. The combination of enzymes was seen to be more effective than a single enzyme in extracting a high yield of fermentable sugar, where enzymatic hydrolysis with high solid loading with low protein loading contributed to a more cost-saving process. Hence, a combination of various cellulases at different ratios is proposed for future work. Furthermore, fungi, $scCO_2$ and metal oxides catalysts can be used to improve the quality of bio-oil and reduce the cost of transforming fermentable sugars into biofuel. SFE is highly recommended as an efficient alternative to traditional pyrolysis to produce high-quality bio-oil because SFE brings lesser harm to the environment while lowering the chemical alteration on thermal sensitive compounds in bio-oil. Lastly, phenolic compounds

Table 1: The processing methods of OPB into its value-added components

Value-added product	Processing methods	Raw material	Processing conditions	Findings	Reference
Cellulose	Acid and alkaline	EFB	• CH_3COOH • NaOH	• CH_3COOH – rougher surface with more silica bodies removed • NaOH – more effective in removing oil residue	[34]
			• Diluted alkaline solution (2% NaOH) • 24% KOH - 2% boric acid (H_3BO_3)	• EFB stalks – more promising feedstock fibre with higher potassium content and lower recalcitrance • EFB spikelet – lower potassium content and higher recalcitrance	[36]
			• CH_3CO_3H • Alkaline peroxide	• Extracted cellulose-rich fraction with 84% of cellulose, removing 92% of lignin	[81]
			• 20% formic acid • 5% hydrogen peroxide	• Extracted 84.2% α-cellulose that showed similar chemical properties as the standard cellulose	[38]
	Physical treatment Alkaline	OPF	• Autoclave • 4% NaOH • 1.7% sodium chlorite ($NaClO_2$)	• High yield of cellulose from OPF (4 g of cellulose extracted from every 10 g of OPF) with high crystalline index (68.8%) and high thermal stability (350 °C) • Cellulose changed from brown to white in color and the cellulose had a smaller diameter and smoother surface compared to untreated fibres	[31]
	Ionic liquid (IL) Enzymatic hydrolysis	OPF	• Hydrophilic IL [EMIM][DEP] (1-ethyl-3-methylimidazolium diethyl phosphate) • Laccase and a mediator, 1-hydroxybenzotriazole (HBT)	• Treated OPF – α-cellulose increased from 45.7–68.5%, while lignin and hemicellulose content had reduced to 8.5 and 12.1%, respectively • The enzymatic hydrolyzed IL-treated OPF cellulose – higher thermal stability than the untreated OPF	[29]
Hemicellulose	Acid, alkaline, and solvent (ethanol)	EFB	• KOH • 50% acetic acid • 95% ethanol	• Alkali extraction – an efficient method to isolate a large number of hemicellulose polysaccharides	[35]
Lignin	Deep eutectic solvent (DES)	EFB	• 9 acidic DES - alpha-hydroxy (lactic, malic, and citric acid), linear saturated (formic, acetic, propionic, butyric, and succinic acid), and unsaturated carboxylic acid (maleic acid)	• Formic acid and lactic acid-based DES – the highest yield of lignin while their pretreated solid fractions are enriched with glucan content • Lactic acid-based DES extracted lignin – the highest phenolic hydroxyl group yield • Acidic DES – significant impact on the functional groups of lignin in EFB	[25]
	Protic ionic liquids (PILs)	EFB, OPMF, PKS	• Pyridinium Formate (PyFor)	• PyFor extraction – the highest lignin extracted was from EFB (92.0%) followed by OPMF (91.2%) and PKS (90.7%)	[27]

		EFB, OPF, OPT	• 1-butyl-3-mtheyl-imidazolium chloride ([BMIN][Cl]) • CO_2-AlK$(SO_4)_2$ (ammonium potassium sulfate dodecahydrate) • H_2SO_4 and HCl	• Sequential extraction – the yield of lignin extracted – OPT > OPF > EFB, with small molecular weight and low polydispersity • The study reported that about 54% of lignin was recovered from OPB	[28]
Microcrystalline cellulose (MCC)	Acid and alkaline	EFB	• 0.7% (w/v) of acidified $NaClO_2$ • 17.5% (w/v) NaOH • 55% (w/w) H_2SO_4 solution	• MCC extracted from the stalk (SMCC) (86.5%) – higher cellulose content than the EFB (EMCC) (81.1%) and spikelet (SPMCC), (84.5%) • Crystallinity index EMCC (82.5%), SMCC (82.2%) and SPMCC (86.5%) – comparable to commercial MCC (81.9%)	[42]
			• 2.5 N HCl • 5% diluted ammonium hydroxide (NH_4OH)	• Acid hydrolysis – rough, compact, and regular spherical MCC particles, with high crystallinity index and good thermal stability	[43]
			• 2.5 N HCl • 5% diluted ammonium hydroxide (NH_4OH)	• MCC with maximal thermal durability - can be used as nanocomposites for various applications	[44]
		OPF	• Alkaline hydrogen peroxide (AHP) • Acidified $NaClO_2$ • Percentage ratio of AHP to NaOH; AHP[1] - 1.5:1.0% (w/v), AHP[2] - 2.5:2.0% (w/v) and AHP[3] - 5.0:4.0% (w/v)	• Increasing AHP concentrations – increased the diameter of fibrous material extracted • More hemicellulose and lignin were removed • Increasing AHP concentrations – increased crystalline index and size of MCC from 55.8–62.3% and 9.17– 10.11 nm	[45]
Nanocrystalline cellulose (NCC)	Acid and alkaline	EFB	• 4% NaOH solution • $NaClO_2$ • 64% H_2SO_4 (sulfuric acid) solution	• Sequential treatments – successfully removed hemicellulose and lignin, while the remaining cellulose was hydrolyzed to the cellulosic nanomaterial • Sequential treatments – increased the adsorption rate rapidly from 60–87% with low NCC dosage (0.005–0.01 g of NCC), successfully produced high capacity NCC bio-sorbent	[54]
		OPF	• $NaClO_2$ and 10% (v/v) CH_3COOH solution • KOH • 64% (v/v) H_2SO_4 hydrolysis	• Acid hydrolysis – NCC extracted with an average width of 9.88 nm and 504.12 nm in length • Acid hydrolysis – NCC had a higher crystallinity index (54.4%) compared to raw OPF (36.0%)	[55]
		OPMF	• 4% NaOH and $NaClO_2$ • 65% H_2SO_4	• Chemical pretreatments – increased the cellulose content, from 32.2% (untreated) to 81.1% (pretreated) • Acid hydrolysis – increased the crystallinity of bleached OPMF and reduce the dimension of cellulose to nanometer scale	[17]

				• Acid hydrolysis – produced rod-like shape NCC with an average diameter of 4.52 nm	
		OPL	• 10% NaOH • 20% H_2SO_4 • 5% $NaHCO_3$	• Yielded 42–82 nm nanocellulose that could be widely used to remove heavy metals (cations) from water	[56]
Nanosilica, SiO_2	Acid and thermal treatment	OPL	• 1 M HCl • Thermal treatment (heated to 100°C)	• HCl treatment – High amount of nanosilica, SiO_2 (95.2%), with major amorphous silica	[59]
Fermentable sugar	Alkaline Enzymatic hydrolysis	EFB	• 5% (w/v) NaOH • Enzyme loading between Celluclast and recombinant endoglucanase (CMC3 gene from *H. insolens*) – a ratio of 1:100 • Accellerase® at 116 mg/mL	• Enzyme cocktail – increased glucose content as compared to Celluclast enzyme alone, from 1.22 to 1.95 mg/mL (59% increment) • Enzyme cocktail – increased xylose content 1.22 to 1.55 mg/mL (27% increment)	[63]
			• Peracetic acid and alkaline peroxide • Accellerase® 1500 enzyme and Accellerase® XC enzyme	• Chemical treatment – removed more than 98% of lignin • Enzymatic hydrolysis – produced higher value fermentable sugar from pretreated EFB, with a glucose yield of 629.8 ± 0.5 g glucose per kg of dry EFB biomass	[32]
	Acid Physical treatment (microwave radiation)	EFB	• Diluted H_2SO_4 (0.25 – 0.50 N) • Microwave irradiation	• Acid hydrolysis – produced a high amount of glucose and xylose from EFB • The kinetic study of this research suggested that higher temperature and acid concentration gave a higher yield of glucose and xylose	[41]
Bioethanol from fermentable sugar	Alkaline, Physical treatment Enzymatic hydrolysis	EFB	• 1.0 M NaOH • Autoclave (121 °C, 15 psi, 1 h) • Cellulase cocktails (Celluclast 1.5 L and Novozyme 188) • *Saccharomyces cerevisiae, Kluyveromyces marxianus,* and *Scheffersomyces stipites* fermentation	• The alkali-pretreated EFB – produced 2–3 times higher amounts of fermentable sugars as compared to untreated EFB, generating 23.6– 34.6 g/L after 72 h of fermentation • *Saccharomyces cerevisiae* – is the best ethanol producer (producing 21 g/L ethanol within 28 h) compared to *Kluyveromyces marxianus* and *Scheffersomyces stipitis*	[40]
Succinic acid	Alkaline Enzymatic hydrolysis	OPF	• 4.42% NaOH • Cellulase and hemicellulose • *A. succinogenes* 130Z	• Increasing hydrolysis time – the glucose production has increased (27.9–40.3%), with 72 h being the ideal hydrolysis time • 60 h of anaerobic fermentation – produced the highest yield of succinic acid (36.6 g/L with a yield of 35.7%) from alkaline pretreated OPF bagasse	[66]
	Acid Enzymatic hydrolysis	OPT	• Organic acid (citric acid, formic acid and oxalic acid) • Commercial cellulase (Cellic Ctech2)	• Oxalic acid – very effective in hydrolyzing hemicellulose to release a high amount of xylose with 61.2% recovery, but it is ineffective in hydrolyzing	[67]

				• *A. succinogenes* 130Z	cellulose to release a high amount of glucose • Citric acid – produced the highest succinic acid yield compared to other organic acids and H_2SO_4 pretreated hydrolysates	
Furfural	Supercritical fluid (ethanol)	OPF	• Ethanol • Formic acid	• Supercritical ethanol with formic acid – produced the highest furfural yield of 35%. • The furfural yield was enhanced by higher reaction temperature and acid concentration, as well as a low amount of solid loading		[72]
Biofuel	Acid Enzymatic hydrolysis	EFB	• 0.8 wt% H_2SO_4 • Accellerase® 1500 at 50°C	• The optimum parameters – 30 g/L of sugar concentration and pH 5.0, resulting in 2.6 g/L oil concentration with oil yield of 84 mg/g • EFB-derived oil – cheaper cost of biodiesel production (7.3% lower) than glucose-derived oil		[39]
	Supercritical fluid (carbon dioxide)	PKS	• Supercritical carbon dioxide extraction ($scCO_2$) (48 °C, 28.2 MPa, 8.0 cm^3 min^{-1} CO_2 flow rate)	• $scCO_2$ extraction – the maximum pyrolysis oil yield of 30.0%, with acids and esters were found to be enriched		[16]
	Supercritical fluid (water)	EFB, OPMF, PKS	• Supercritical water (390 °C and 25 MPa)	• Optimum reaction time – EFB and OPMF was 120 min while PKS was 240 min		[78]
Phenolic compounds		OPF	• Acetone solution containing 6% of *m*-cresol • 65% ethanol (v/v) and 0.5% (w/w) H_2SO_4 • Distilled water	• *m*-cresol pre-treatment – modified OPF lignin structure and greatly improved the quality of ethanol organosolv lignin (EOL) • Pre-treated EOL – good solubility in water (42%) as compared to untreated EOL, due to the production of small lignin fragments with low molecular weight and polydispersity		[80]

Notes: EFB – Empty fruit bunches; OPF – Oil palm fronds; OPMF – Oil palm mesocarp fibre; PKS – Palm kernel shell; OPT – Oil palm trunk; OPL – Oil palm leaves

Table 2: The advantages and disadvantages of the processing methods

Processing method	Advantages	Disadvantages
Chemical extraction	• Cost-effective process • Very efficient in removing residual oil	• Concentrated acid causes corrosion • Difficult to control reaction using concentrated acid or alkaline • Formation of undesirable by-products
Deep eutectic solvent (DES) extraction	• High extraction yield	• Acid-based solvent might cause corrosion
Protic ionic liquids (PILs) extraction	• High thermal stability • Low chemical reactivity (non-corrosive process) • Low vapour pressure • Short processing time • High extraction yield	• Shortage of types of ILs at room temperature
Enzymatic hydrolysis	• Cost-effective process due to high solid loading paired with low protein loading	• Long extraction time

	• High sensitivity • Energy saving • High hydrolysis yield	
Microorganism fermentation	• Environmentally friendly • High extraction yield and specificity • Low energy requirement • Simple process	• Tedious in growing to ensure no contamination
Supercritical fluid extraction	• Mild conditions • High extraction yield • Environmentally friendly • Cost-effective • Non-toxic, non-flammable	• Require special experimental setup (equipment consideration)
Organic solvents extraction	• Efficient in extracting phenolic compounds	• High cost of purchasing solvents

extracted from OPB using ethanol exhibit bioactivities such as antioxidant and antimicrobial properties, hence different types of organic solvents such as acetonitrile and water, paired with the time of hydrolysis should be further investigated to increase the yield of phenolic compounds. The processing methods used to produce value-added components from OPB are presented in Table 1 while their advantages and disadvantages are summarized in Table 2.

4. Conclusion

The oil palm industry is an important sector in Asia due to the high demand of oil palm globally. However, it results in a huge amount of wastes (OPB) that are detrimental to the environment. Hence, the effort to transform biomass into value-added products is crucial. The processing methods of OPB were reviewed in terms of its transformation into valuable components. Processes that were cost-effective and environmentally friendly with improved physical and chemical properties were summarized. Sequential mild chemicals extractions paired with heat treatment extracted high yields of cellulose and hemicellulose from OPB. Apart from that, enzyme cocktails consisting of Celluclast and Accellerase® produced high yields of fermentable sugars especially glucose and pentoses from delignified OPB. The OPB bio-oil extracted using fungi, $scCO_2$ and metal oxides catalyst was highly volatile and consumes lesser energy during combustion. Ethanol-extracted phenolic compounds of OPB showed good antioxidant and antimicrobial properties. Generally, this review indicates that OPB is a renewable and sustainable source of material, thus further investigation to enhance the yield and quality of value-added components extracted from OPB is recommended. For instance, various extraction conditions such as duration and pressure of the process, types of chemical and catalyst, the concentration of enzyme should be further studied.

Acknowledgements

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