Review Article

Recent Situation and Progress in Biorefining Process of Lignocellulosic Biomass: Toward Green Economy

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Abstract

Towards the rising trends of Bio Economy, Circular Economy and Green Economy (BCG economy) concept, biorefining process has been developed continuously to improve the utilizations of unused lignocellulosic biomass to produce value-added chemicals and products. During the early era of biorefining process, the major focuses of biorefining products were dedicated to biofuels, especially bioethanol and biobutanol due to the coherent situation of rising crude oil price. Currently, the targeted products of biorefining processes are directed to platform chemicals, which their purposes are not limited to fuels, but are expanded to various downstream industries. However, most of developed processes are still unable to overcome the numbers of concerns, especially economic issue and scaling up technology. This review explores the recent pretreatment technologies of lignocellulosic biomass and addresses the direction of development to provide the updated situation of biorefining process for peer-researchers and related industries.

Keywords: Platform chemicals, Biorefining process, Lignocellulosic biomass, Pretreatment, Specialty products

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1 Introduction

Biorefining is the production process of multiple products from natural biomass. This terminology is initiated from petroleum refinery that uses crude oil as a feedstock [1]. The concept has been introduced to research communities, industrial sectors, and governmental units since early 20th century with the aim to reduce the environmental impacts generated from human and industrial activities. Currently the concept of green economy or zero waste has been adopted and integrated to society to reduce the intensification of greenhouse effect worldwide. Additionally, biorefining activities have been promoted based on the situations of crude oil pricing because biorefining products have potential and expectation to replace or substitute the use of petroleum refining products.

Crude oil is a major feedstock of petroleum refinery and its price is fluctuated based on the world economic situations. In 2008, the crude oil price was increased up to 140 USD/Barrel during the Gulf war, and then the price was continuously reduced to 90–100 USD/Barrel during 2010–2014. Recently, 2017–2019, crude oil price still was decreased to 50–60 USD/Barrel due to the competition of shale oil technology, and the current market price in 2020 is about 30 USD/Barrel. Concurrently, bioethanol price, a major biorefining product available in commercial scale of production, has been also fluctuated depending on the production technology, raw material price and crude oil price. In comparison with the same period, in 2008, bioethanol price was set at 61.27 USD/Barrel and it was declined to 48–53 USD/Barrel in 2010–2014. In 2017–2019, the price of bioethanol was reduced to 35 USD/Barrel and dropped to 33 USD/Barrel in 2020. Considering to these competitive pricing trends of crude oil and bioethanol, it could be seen that the pricing gap between them was slimmer since 2008 [2]. This small gap draw attention from different sectors, including researchers, industries and government to invest their budgets and to develop policies to support the production of biorefining products. Yet, due to the current crude oil pricing competition around the world, the crude oil price was dropped further to lower rates than bioethanol resulting in incompetency of bioethanol to compete with crude oil in the market.

2 Platform Chemicals

In the current scenario, the position of bioethanol has been threatened by the crude oil price. Platform chemicals have been developed in the same time to bioethanol due to their potential pricing and specialties. Platform chemicals are introduced into the market as small chemical molecules, which are subsequently function as intermediates or substrates for subsequent chemical reactions or enzymatic reactions to produce more complex chemicals, compounds or polymers used in various downstream industrial processes [3], [4]. The global markets of bio-based platform chemicals are expected to grow up to 20 billion in 2022. While, the current majority of sharing product volumes is C-3 platform chemicals, especially glycerol, which related to the activities of biodiesel productions [4]. However, in these recent years, other platform chemicals, especially C2–C5 molecules, have been received spotlights from various stakeholders, especially in the terms of value added products, such as bioplastics and pharmaceutical compounds [5].

Regarding to different classification methods, biorefinery could be grouped based on 4 systems that are 1) platform system, 2) end product system, 3) feedstock system and 4) process system. Platform system categories the biorefinery based on the types of intermediated compounds/chemicals produced from the facilities, such as C3–C6 carbohydrates, lignin derivatives, pyrolytic liquid and gas, syngas. End product system classifies the biorefinery depending on the purposes of end products of processes, such as biofuels, fuel additives, chemicals, materials and plastics. Feedstock system sorts the facilities by the types of biomass such as dedicated crops, residues from processing industries, aquacultures and agricultural wastes. Lastly, process system classifies the biorefinery based on the reactions, for example chemical, biochemical, physical, and mechanical processes [6], [7].

One of the classical way to group the platform chemicals derived from biomass is depended on the numbers of carbon atoms in each molecule as shown in Table 1. Based on our survey in this review, these platform chemicals are currently fit in the current applications of industries in various sectors, ranging from biofuels, chemicals (solvents, intermediates), polymers, textiles, feedstocks, agricultures, cosmetics, pharmaceuticals, human supplementary diets. These demands of platforms chemicals are currently supplied from petroleum based feedstocks. Therefore, to make the platform chemicals survive in the market, it is still needed continuous affords to overcome several barriers, including pricing, technology, and consumer acceptance.

Although, many types of platform chemicals are produced from natural biomass and they have the potentials to be used as intermediate compounds for productions of high value products. These bio-based chemicals have been challenged with conventional production from petroleum feedstocks. In case of itaconic acid, it has the potential to be a substitute of biodegradable plastic monomer. It is currently consumed in a niche market for synthesis of latex, polyester resin and absorbent polymer [8]. However, these final products nowadays have feedstock supplies from petroleum sources with competitive pricing and quantities. Therefore, market competition of itaconic acid has to be gone through development of production technology and expanding users in high-value product sectors, such as biotechnological and pharmaceutical uses. It has been predicted that the itaconic acid will be able to compete with petroleum-based chemicals when the price of itaconic acid is lower than 1.5 USD/kg [8].

Another potential bio-based platform chemical is furfural, which is currently used as a solvent in lube oils, feedstocks for polymers, fuels. Furfural derivatives are consumed as substrates for production of furan resins, industrial adhesives, agricultural products and high-value chemicals. Since furfural has many derivatives and a major form of furfural in the market is furfural alcohol, which is a value added furfural. The current value of furfural is around 2.0 USD/kg with expanding demand in global pharmaceuticals and oil refining industries [9]. These two bio-based platform chemicals were recently reported to mainly produced in China, followed by other parts of the world, such as Europe, USA and Japan.

Table 1: Platform chemicals derived from lignocellulose biomass and their uses in the current market [3]–[7]

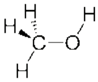
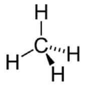
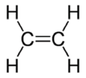
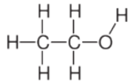
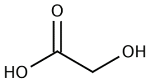
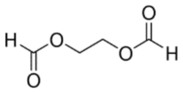
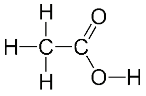
No. of C	Chemical	Chemical Formular	Chemical Structure	General Use
1	Methanol	CH_3OH		Generic solvent, substrates and intermediate chemicals in chemical synthesis reactions.
	Methane	CH_4		Fuels, substrates in chemical synthesis reactions
	Syngas	CO, H_2O, CO_2 and H_2		Fuels, electricity generation, substrates in chemical synthesis reactions
2	Ethylene	$CH_2{=}CH_2$		General adhesives and binding agents, monomers for polymerization of lubricants, plastics
	Ethanol	C_2H_5OH		Generic solvents, beverage ingredients and food products
	Glycolic acid	$HOCH_2CO_2H$		Flavoring agents, a preservative in the pharmaceutical and cosmetic industry, dyeing and tanning agent in textile industry
	Ethylene glycol	CH_2OHCH_2OH		Solvent in paint and plastic, antifreezing agents in cooling and heating systems, hydraulic liquid in brake, electrolytic condensers
	Acetic acid	CH_3COOH		Substrate for chemical reactions and analysis, etching chemicals, dyeing agents for fabric and tanning agent in leather

Table 1: Platform chemicals derived from lignocellulose biomass and their uses in the current market [3]–[7] *(Continued)*

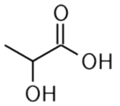
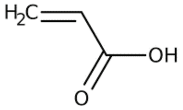
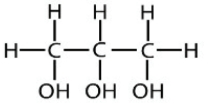
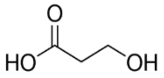
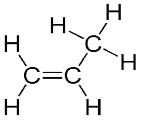
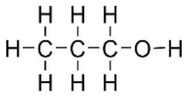
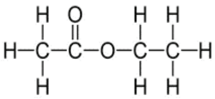
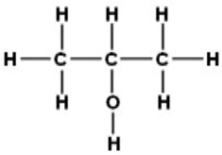
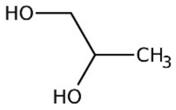
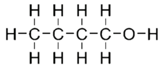
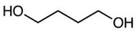
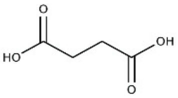
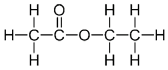
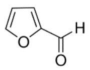
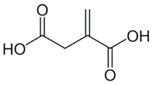
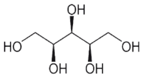
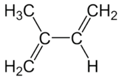
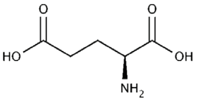
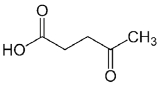
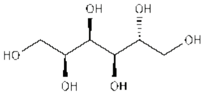
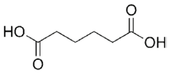
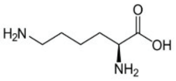
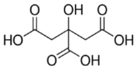
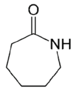
No. of C	Chemical	Chemical Formular	Chemical Structure	General Use
3	Lactic acid	$CH_3CH(OH)$ $COOH$		Plasticizers, adhesives, additives in pharmaceuticals, tanning industry
	Acrylic acid	CH_2=CHCOOH		Monomers of plastics, additives in paints, leather, paper coatings, detergents, automotive fluid products, specialty inks, adhesives, substrates for disposable diapers, applications in medical treatment as orthopedic cement and in dentistry as artificial teeth
	Glycerol	$C_3H_8O_3$		Generic solvents, substrate and intermediate chemicals in chemical synthesis reactions, soaps, detergents and glycerol esters.
	3-Hydroxy propionic acid	$C_3H_6O_3$		Monomers and substrates for biodegradable plastics
	Propylene	C_3H_6		Monomers and substrates for biodegradable plastics and substrates for chemical reactions
	1,3-Propanediol	$C_3H_8O_2$		Generic solvents, intermediate chemicals and solvents in chemical synthesis
	Propanol	C_3H_8O		Generic solvents, intermediate chemicals in chemical synthesis for production of adhesives, binding agents in agricultural products
	Ethyl lactate	$C_5H_{10}O_3$		Solvents in pharmaceutical industries, food additives, fragrances, solvens in production of nitrocellulose, cellulose membranes
	Isopropanol	C_3H_8O		General solvents of household chemicals, chemical ingredients in antiseptics and disinfectants
	Propylene Glycol (1,2- Propanediol)	$CH_3CH(OH)$ CH_2OH		Bulking agents in pharmaceutical industries, chemical feedstocks for the production of polyester resins, and substrates of polyurethanes

Table 1: Platform chemicals derived from lignocellulose biomass and their uses in the current market [3]–[7] *(Continued)*

No. of C	Chemical	Chemical Formular	Chemical Structure	General Use
4	Butanol	$C_4H_{10}O$		Fuels, solvents in chemical and textile industries, solvents in surface coatings, hydraulic and brake fluids
	1,4-Butanediol	$C_4H_{10}O_2$		Solvents in the manufacturing of plastics and pharmaceuticals, substrates for production of polymeric fibers
	Succinic acid	$(CH_2)_2(CO_2H)_2$		Precursors to biodegradable polymers and resins, food additives and dietary supplements, flavoring agents in food products and pharmaceuticals
	Ethyl acetate	$CH_3COOC_2H_5$		Additives for hardening agents in paints, varnishes and plastics
5	Furfural	C_4H_3OCHO		Chemical feedstocks, solvents, flavoring agents, resins in polymeric matrix, adjuvants in herbicides
	Itaconic acid	$C_5H_6O_4$		Building blocks for biopolymers used in construction and infrastructure (such as flooring, insulation, tile), food packaging, sanitary products
	Xylitol	$C_5H_{12}O_5$		Sweeteners, additives and bulking agents in pharmaceutical products, dietary supplements, confections, toothpaste, chewing gum
	Isoprene	C_5H_8		Monomers for products for cleaning and caring for automobiles (i.e. shampoo, polishing wax, brake grease), natural rubbers
	Glutamic acid	$C_5H_9NO_4$		Dietary supplements, food flavoring agents, food additives, pesticides, and medicines.
	Levulinic acid	$CH_3C(O)$ $CH_2CH_2CO_2H$		Precursors of biofuels, pharmaceuticals, plasticizers, building blocks for other chemicals
6	Sorbitol	$C_6H_{14}O_6$		Sweeteners, laxative compounds, components in cosmetics, thickening agents, soft gel capsules of medicines
	Adipic acid	$HOOC(CH_2)_4$ $COOH$		Precursors of nylon, polyurethane, plasticizers of PVC
	Lysine	$C_6H_{14}N_2O_2$		Dietary supplements, food additives,
	Citric acid	$C_6H_8O_7$		Dietary supplements, food flavoring, acidifiers, chelating agents, acidulants in cosmetic products (creams, gels, liquids)
	Caprolactam	$C_6H_{11}NO$		Substrate for production of synthetic fibers, nylons, textile stiffeners, film coatings, synthetic leathers, plastics, polyurethanes

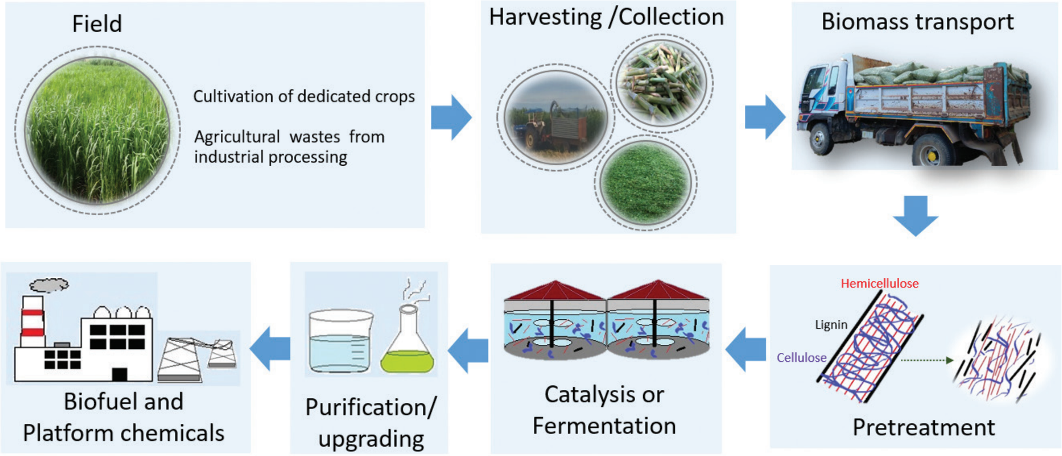


Figure 1: Workflow of biorefining process involved in lignocellulosic biomass.

3 Biorefining Process of Lignocellulosic Biomass

Lignocellulosic biomass is one of the most abundant and the highest potential feedstock for biorefining process. The annual production of lignocellulosic biomass was reported to be 150 × 10^9 tons in 2008, which mainly obtained from agricultural activities [10]. Currently, there are many attempts to gather many types of lignocellulosic biomass to utilize in several ways, most of them are used in combustion process in industries as fuels to generate electricity. However, this action brings pollution problems to environment by generating PM 10 and PM 2.5 in the worldwide scale, which this air pollution gets worsen every year. On the other hand, the biorefining process of lignocellulosic biomass has been developed to gather those leftover agricultural wastes and convert them to value-added products (Figure 1).

4 Lignocellulosic Biomass Pretreatment

Biorefining process of lignocellulosic biomass generally composes of 4 steps, including, 1) biomass collection, 2) biomass pretreatment, 3) biomass hydrolysis and conversion, 4) product recovery and purification [10]. Lignocellulose biomass could be agricultural by-products that are gathered on-fields after harvesting seasons, or from processing industries. This biomass could also be dedicated crops. Thus, the collection and logistic activities are needed to be done to transfer the biomass from original plantation locations to the processing facilities. Then, the biomass is processed through the pretreatment to physically break down from big bulk biomass to smaller particles. Pretreatment process has been developed continuously as it promotes the efficiency of hydrolysis and conversion reaction [10], [11]. Lignocellulosic biomass, in fact, has strong chemical components and physical structures as these characteristics help to protect plants from natural pests and phytopathogens. After pretreatment process, the biomass is then subjected to hydrolysis reaction or conversion reaction to digest large polymeric molecules of lignocellulosic biomass to smaller polymeric molecules or monomers. The monomers are subsequently converted to targeted products or value-added products via chemical reactions, enzymatic reactions or fermentations [12]. Finally, the biochemical products are recovered and purified to achieve the criteria and standards of the targeted markets and consumers. Due to the complexity of biorefining process, the design and execution of the biorefinery facilities are needed to consider about feasibility in terms of financial, resource management, operation, social acceptance, environment, and government policy.

Among all steps in biorefining process, pretreatment and hydrolysis have been marked as the main barrier for process feasibility, in terms of financial investment and time consuming [13]. Pretreatment is a process to alter physical and chemical properties of biomass to be more vulnerable to hydrolysis, therefore improves hydrolysis efficiency. In general, pretreatment methods can be categorized to physical, chemical, biological and combined methods (Table 2) [10], [11]. In fact, all types of lignocellulosic biomass are needed to be pretreated by using any physical methods, such as ball milling and screw press, to reduce their bulky size down to handling size [3]. As shown in Table 2, many cases of recent pretreatment research were demonstrated by using different methods. Most of research was conducted by using chemical pretreatment, especially using conventional chemicals, such as sulfuric acid and sodium hydroxide.

Table 2: Examples of recent research and development activities in various pretreatment methods of lignocellulosic biomass during 2015–2020

Pretreatment	Substrate	Testing Condition	Yield	Ref.
Acid pretreatment with sulfuric acid	Pineapple peels	Biomass loading ratio at 1:20, 1:50 and 1:100, pretreatment time 0–60 min, pretreatment temperature at room temperature, 5% acid concentration	Total sugar 252.28 g/L (at 1:100, 60 min), reducing sugar 158.92 g/L (1:100, 60 min)	Sukkaew *et al.* [14]
Alkaline pretreatment with sodium hydroxide	Pineapple waste (core and peel)	Pretreatment time 30–60 min, 1–2% alkaline concentration	Total reducing sugar 218.41 mg/g dried sample (2% NaOH, ultrasound 60 min)	Soontornchaiboon *et al.* [15]
Acidic and alkaline pretreatment	Pineapple peels	- Acidic pretreatment Pretreatment time 6–46 min, pretreatment temperature 75–115°C, 0–2% H_2SO_4 concentration - Alkaline pretreatment Pretreatment time 55–95 min, pretreatment temperature 20–40°C, 2–10% H_2O_2 concentration	- Acidic pretreatment Cellulose 43%, Hemicellulose 77%, Lignin 32.3% (2% w/v, 60 min at 121°C) - Alkaline pretreatment Cellulose 39%, Hemicellulose 71.34%, Lignin 61% (7.5% w/v, 3 g dry mass, 130 rpm, 75 min at 30°C)	Dahunsi [16]
Alkaline pretreatment with potassium permanganate solution (APP)	Corncob	Biomass loading ratio at 1:10–1:30, pretreatment time 1–8 h, pretreatment temperature 30–70°C, 0.5–4% APP concentration	- Cellulose recovery 94.56%, Hemicellulose recovery 81.47%, Lignin removal 46.79% (2% w/v, 1:10, 6 h at 50°C)	Ma *et al.* [17]
Screw Press and ionic liquid pretreatment [AMIM]Cl	Rice straw	Biomass loading ratio at 1:20, pretreatment time 1–6 h, pretreatment temperature 100–150°C, 0–100% [AMIM]Cl concentration	Total reducing sugar 68.26% (50% concentration of [AMIM] Cl at 150°C)	Sriariyanun *et al.* [18]
Chemical pretreatment with Sodium percarbonate (SP)	Corncob	Biomass loading ratio at 1:5–1:25, pretreatment time 0.5–8 h, pretreatment temperature 30–70°C, 1–8% APP concentration	Cellulose recovery 91.06%, Hemicellulose recovery 84.07%, Lignin removal 34.09% (4% w/v, 1:10, 4 h at 60°C)	Ma *et al.* [19]
Thermo-chemical pretreatment	Catalpa sawdust	Biomass loading ratio at 1:20, pretreatment time 1 h, pretreatment temperature 100°C, 5% concentration of NaCl, $Ca(OH)_2$, H_2SO_4, and HCl 5% (w/v)	Hemicellulose 45.9% and 33.4% (Thermo-NaOH and Thermo-$Ca(OH)_2$), Reducing sugar 518.14 mg/g (Thermo-$Ca(OH)_2$)	Jin *et al.* [20]
Ionic liquid pretreatment with EMIMAc	Yellow Pine	Biomass loading ratio at 1:20, pretreatment time 15–45 min, pretreatment temperature 140°C	Glucose 56% (500–850 μm particle size, 5% biomass concentration, 140°C, 45 min)	Bağder *et al.* [21]
Sodium alkaline pretreatment	Sugarcane bagasse	Biomass loading ratio at 1:12, pretreatment time 1 h, pretreatment temperature 100–180°C, 0.25–0.50 M of sodium carbonate (Na_2CO_3), sodium sulfite (Na_2SO_3), and sodium acetate (CH_3COONa)	Glucan 46%, Xylan 20%, Lignin 20% (0.5 M Na_2SO_3 at 140°C)	Nosratpour *et al.* [22]
Alkali pretreatment	Sugarcane bagasse	Biomass loading ratio at 1:20, pretreatment time 20 min, pretreatment temperature 60°C, 0.10–1.50 M of Na_2CO_3, $Ca(OH)_2$, KOH, NaOH	Lignin 45.57%, Cellulose 43.34%, Hemicellulose 4%, Total sugar 487.72 g/kg (0.3 M NaOH, 60°C, 20 min)	Hilares *et al.* [23]

Table 2: Examples of recent research and development activities in various pretreatment methods of lignocellulosic biomass during 2015–2020 *(Continued)*

Pretreatment	Substrate	Testing Condition	Yield	Ref.
Ultrasound assisted potassium permanganate pretreatment	Spent coffee waste (SCW)	Biomass loading ratio at 1:10, pretreatment time 10–40 min, pretreatment temperature at room temperature, 1–5% $KMnO_4$ concentration combining with ultrasound radiation at 47 kHz and an emission power of 310 W	1.7 fold increase in reducing sugar ($KMnO_4$ concentration of 4%, 20 min)	Ravindran *et al.* [24]
Low-temperature sodium hydroxide pretreatment	Sugarcane bagasse (SCB)	Biomass loading ratio at 1:5–1:20, pretreatment time 0.5–4 h, pretreatment temperature 30–80°C, 0.01–0.04% (m/v) NaOH concentration	Glucan 58.11%, Xylan 24.36%, Klason lignin 4.29% (solid-liquid ratio 1:9.1, 3% NaOH, 50°C for 4 h)	Wang *et al.* [25]
Organic acid pretreatment	Corncob	Gluconic acid concentration, 0.25–1.0 M, reaction time, 15–75 min, temperature, 130–170°C;	Glucose yield 86.4% (0.6 M Gluconic acid at 154°C for 47 min)	Han *et al.* [26]
Organic acid pretreatment	Oil palm trunk	Biomass loading ratio at 1:10, pretreatment time 30–60 h, pretreatment temperature 100–140°C, 5–15% concentration of acetic acid, oxalic acid and citric acid	Reducing sugars at 144 mg/g-pretreated biomass (100°C, 60 min, 15% oxalic acid)	Rattanaporn *et al.* [27]
Alkaline pretreatment with potassium permanganate	Corncob	Biomass loading ratio at 1:10–1:30, pretreatment time 1–8 h, pretreatment temperature 30–70°C, 0.5–4% (w/v) potassium permanganate	9.05 g/L reducing sugar yield	Araújo *et al.* [28]
Combined sulfuric acid and sodium hydroxide pretreatment	Macaranga tanarius	- Acid pretreatment Biomass loading ratio at 17.64% w/v, pretreatment time 30 min, pretreatment temperature 90°C, 0.12 M sulfuric acid - Alkaline pretreatment Biomass loading ratio at 11.11% w/v, pretreatment time 120 min, pretreatment temperature 90°C, 0.22 M sodium hydroxide	Glucose recovery at 25.4% by using acid pretreatment, and 44.6% by using alkaline pretreatment	Cheng *et al.* [29]
Diluted sulfuric acid	Water hyacinth	Acid concentration 1–4%v/v, pretreatment temperature 80–100°C, pretreatment time 30–60 min	Maximum cellulose recovery at 68%	Boontum *et al.* [30]
Sequential acid/alkali pretreatment	Calophyllum inophyllum fruit shell	Biomass loading ratio at 20% w/v; 1% w/w H_2SO_4 at 90°C for 1 h and 1% w/w NaOH at 50°C for 1 h	Reducing sugars at 0.24 g/g pretreated shell	Cheng *et al.* [31]
Ensilage pretreatment	Marcoalgae (Ulva lactuca)	Addition of both cellulase complex at 10 carboxymethyl cellulose unit (CMCU)/g dry biomass and inoculum of Lactobacillus plantarum at 106 cfu/g dry biomass	Retaining 92% solid and most of the carbohydrates, Reducing Sugars at 155 mg/g dry biomass	Wu *et al.* [32]

In terms of research communities, different pretreatment methods have been developed in many labs worldwide. During 2010–2019, publications with keywords of "pretreatment" have been growing almost 10 times (Figure 2) [33]. Among that, chemical pretreatment has the highest numbers of publications, following by biological and physical pretreatment, respectively. The reason for that most of research focused on chemical pretreatment could be due to simplicity, cost, consistency, and technology transfer readiness that are more applicable compared to biological and physical pretreatment.

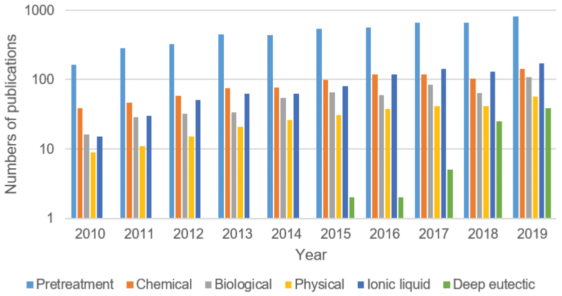


Figure 2: Numbers of publications in ScienceDirect database during 2010–2019 with different keywords, including pretreatment, chemical pretreatment, biological pretreatment, physical pretreatment, ionic liquid pretreatment, deep eutectic pretreatment.

Chemical pretreatment methods could be conducted by using different conventional chemicals, such as acid, alkaline, oxidizing agent, organic acid, organic solvent, inorganic salt. Since last decade, ionic liquid was introduced to be pretreatment chemicals, due to its properties, including recyclability, low corrosiveness, low volatility, low viscosity, chemical inertness, good thermal stability [34], [35]. Ionic liquid is salt with liquid phase at room temperature. It is used as electrolyte, solvent and hydraulic liquid in different industries. Ionic liquid has been demonstrated to disrupt the hydrogen bonds between cellulose fibrils, enabling disintegration of lignocellulose fibrils [35]. Additionally, ionic liquid was shown to remove lignin from biomass, thus improve hydrolysis efficiency [35]. Nowadays, several types of ionic liquids, such as EMIM-Ac, EMIM-Cl, AMIM-Cl, BMIM-Cl, Choline-Ac, were demonstrated in pretreatment of lignocellulosic biomass [36]–[40]. Altogether, ionic liquid pretreatment has been shown to be a high efficient method for various types of lignocellulosec biomass, therefore it gains popularity in research and development worldwide with rapidly growing of publications (Figure 2). However, a major bottleneck of ionic liquid pretreatment is related to its price, and also its inhibitory effect to hydrolysis enzymes. Therefore, several strategies have been established to assist ionic liquid pretreatment including recycling of ionic liquid [38], [41], increasing biomass loading rate, selecting ionic liquid with low inhibitory effect to hydrolysis enzyme [40], or finding hydrolysis enzyme with high resistance to ionic liquid [36], [42].

Another trend of newly developed chemical pretreatment is deep eutectic solvent and its popularity starts to grow steadily since 2015 (Figure 2). Deep eutectic solvent was originally reported since 2003 as a synthetic green solvent system composing of at least two chemicals as hydrogen bond acceptor and donor [43]. Eutectic mixture is made of two or three compounds, which its mixtures has lower melting points compared to each compounds. Due to this property, it makes deep eutectic solvent become easier to handling in pretreatment process of lignocellulosic biomass. It is proposed to be an alternative option to ionic liquid due to its relatively lower cost.

Nowadays, several systems of deep eutectic solvents have been demonstrated for lignocellulose pretreatments, such as ChCl-glycerol, ChCl-formic acid, ChCl-acetic acid, ChCl-ethylene glycol, and triethylbenzyl ammonium chloride/lactic acid [44]–[47]. Similar to ionic liquid pretreatment, there are many operational factors that have been proved to determine the recovery of sugars and removal of lignins from lignocellulosic biomass, for example types of lignocellulosic biomass, biomass loading ratio, types of deep eutectic solvents, pretreatment temperature and pretreatment retention time. Still, the need to study on the mechanism of how deep eutectic system functions in disintegration of lignocellulosic biomass is marked to gain understanding in the process and to provide the clue how to improve the process efficiency.

5 Insect Based Biorefinery: An Alternative Way to Achieve Circular Economy

Insect-based biorefinery has currently advocated as an innovative approach that employs insects to convert agro-industrial waste biomass into biofuel, animal feed, chemical, and organic fertilizer (Figure 3). Many species of insects have been found capable of consuming various organic wastes and some insect larvae are effective in converting organic wastes into insect biomass without severe pretreatments [48], [49]. There has also been a growing interest in searching for higher value-added products to expand the new value chain of insect-based biorefinery. For example, using the chitin derived from insect biomass as a platform feedstock for fine chemicals and applications. Insect protein could also be utilized as sustainable source

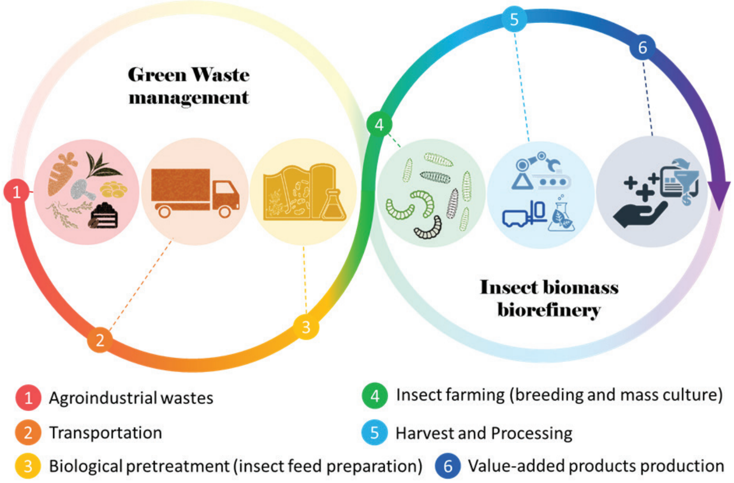


Figure 3: The concept of insect based biorefinery procedure.

in the biotechnological industry for the discovery of functional peptides [50], [51]. The insect oil could also be used to prepare nano-emulsion for high-value added applications [52]. Because of the potentiality of insect based biorefinery, there are some startup companies currently established around the world. However, the development of insect-based biorefinery is still at its infancy stage. There are still many challenges that could limit the commercial development of the insect-based biorefinery, including the government policies. Therefore, like the other biorefinery platforms, the investment in research and cooperation among government, academia, and industry will be critical to ensure the future development insect based biorefinery.

6 Conclusions

Biorefining process of lignocellulose biomass has been continuously promoted and supported from different stakeholder sectors. The growing of research, production technology and facility of biorefining process have been demonstrated and established in worldwide scale. The competition in the current market is not yet in advantageous position due to the availability and securities of supplies of petroleum-based chemicals, which currently have relatively lower price compared to bio-based chemicals. However, the situation of bio-based chemicals could be better positions depending on the fluctuation of world crude oil price, which rely on several factors, especially political situation. Furthermore, bio-based products have unique benefits compared to petroleum-based products because of the global awareness of greenhouse effect, which currently adopted into political and governmental policies. Last but not least, bio-based chemicals have been also recognized as feedstocks, solvents, and intermediates for production of high-value products with sensitive sensations of consumers, especially in human dietary supplements, medicals, biotechnological products, cosmetics, and pharmaceuticals, which draw attention to the industrial investments in biorefining process.

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