Reaktor

p-ISSN 0852 – 0798
e-ISSN 2407 – 5973

Acredited: SK No.: 60/E/KPT/2016
Website : http://ejournal.undip.ac.id/index.php/reaktor/

Reaktor, Vol. 19 No. 3, September Year 2019, pp. 101-110

Second-Generation Biobutanol: An Update

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(Received: July 26, 2019 Accepted: October 17, 2019)

Abstract

Butanol, a rising star in biofuel, can be produced by two approaches, petrochemically and biologically. Currently, the most promising route for butanol production is by fermentation using Clostridium species through an anaerobic condition. However, similar to other biofuels, feedstock has greatly influenced the production of biobutanol and the search for inexpensive and abundant raw material is an absolute requirement for a cost-effective process. Second-generation biobutanol which is produced from lignocellulosic biomass of agricultural and forestry waste not only meets the requirement but also alleviates competition with food crops and thereby solves the problems of food scarcity from the first generation biobutanol. This paper delivered the latest and update information regarding biobutanol production specifically second-generation biobutanol in terms of production method, recovery, purification, status, and technoeconomic.

Keywords: *biobutanol; lignocellulose; purification; recovery; technoeconomic*

How to Cite This Article: Burhani, D., Triwahyuni, E., and Setiawan, R. (2019), Second-Generation Biobutanol: An Update, Reaktor, 19(3), 101-110, http://dx.doi.org/10.14710/reaktor.19.3.101-110.

INTRODUCTION

As a consequence of Presidential Instruction No.1/2006 on the provision and utilization of biofuel, Indonesia has been promoting biofuel as an alternative for fossil fuel. The demand for biofuel is continuously increasing which makes the need for an innovative and efficient method to convert biomass to biofuels is crucial. Bioethanol and biodiesel alone could not cover the increasing demand for biofuels (Ibrahim *et al.*, 2017). Therefore, a substantial need for another biofuel which has superior fuel characteristic, for example, butanol becomes urgent.

Butanol, four-carbon alcohol, has remarkable fuel characteristics which make it protruding and considered to be an advanced promising candidate

Table 1. Characterization comparison between alcohols and petroleum fuel (Jin *et al.*, 2011; Ndaba, Chiyanzu and Marx, 2015; Procentese, 2015; Lee *et al.*, 2016; Trindade and Santos, 2017)

Characteristic	Ethanol	Butanol	Gasoline	Diesel
Molecular Formula	C_2H_5OH	C_4H_9OH	$C_4 – C_{12}$	$C_{12} – C_{25}$
Boiling Point (°C)	78	118	25 – 215	180 – 370
Energy Density (MJ/Kg)	26,9	33,1	32	35.8
Air Fuel Ratio	9,0	11,2	14.6	14.7
Research Octane Number (RON)	129	96	88 – 98	0
Motor Octane Number (MON)	102	78	80 – 88	0
Cetane Number	8	25	0 – 10	40 – 55
Auto Ignition Temperature (°C)	434	385	~300	~210
Heat of Vaporiation (MJ/Kg)	0,92	0,43	0.36	
Viscosity (mm^2/s) at 40 ^0C	1.08	2.63	0.4 – 0.8 (20 °C)	1.9 – 4.1
Oxygen content (% weight)	34.8	21.6	-	-
Water solubility (mL/100 mL)	miscible	9.1	<0.01	
Stoichiometric ratio	9.02	11.28	14.7	14.3
Flammability Limits (%vol)	4.3 – 19	1.4 – 11.2	0.6 – 8	1.5 – 7.6

among other biofuels. Table 1 exhibits the comparison of butanol with other fuels in several parameters.

Butanol has a higher energy density than ethanol and almost similar to gasoline and diesel. Therefore, it is expected that, when compared to ethanol, the engine running on butanol will have lower fuel consumption and better mileage. Butanol can be completely dissolved even in low temperatures, less susceptible to separation in the presence of water, which makes it more suitable for distribution through pipelines. Moreover, its gasoline-octane rating and air-fuel ratio which close to petrol allowing the possibility of direct application in automobile engines without modification makes butanol an ideal candidate to even replace gasoline (Noomtim and Cheirsilp, 2011; Yadav *et al.*, 2014; Yang *et al.*, 2014; Zheng *et al.*, 2014; Ndaba, Chiyanzu and Marx, 2015; Zhang *et al.*, 2017).

Butanol is less polar than ethanol since butanol has longer hydrocarbon chains. It makes butanol can be blended with gasoline at any concentration. Additionally, butanol has less affinity for water which makes it less hygroscopic and therefore making it less corrosive and more suitable for distribution through pipelines. When compared to biodiesel, biobutanol contains more oxygen content which further leads to the reduction of soot. Correspondingly, a lower Reid vapor pressure making butanol less explosive (Jin *et al.*, 2011; Ndaba, Chiyanzu and Marx, 2015; Ibrahim *et al.*, 2017; Trindade and Santos, 2017).

The volatility of alcohol is inversely proportional to the increase in carbon content. Correspondingly, it means that butanol has less tendency to vaporization which implies that it will have less tendency to cavitation and vapor lock problem. Therefore, an engine running on butanol will be easier to start summer and winter months than one running with ethanol. In addition, the low autoignition temperature of butanol leads to fewer ignition problems at cold start or low load conditions (Jin *et al.*, 2011). Moreover, a higher flash point of butanol (in regard to ethanol) indicate that butanol is likely safer when used in high temperature (Trindade and Santos, 2017).

Despite all the benefits, several potential issues should be considered when butanol is applied directly in the engine. For example, butanol has a lower heating value than gasoline. Therefore, there is a possibility that the engine running on butanol will have lower performance than the same engine running on gasoline. Additionally, the lower heating value also affected the utilization of butanol fuel which demands more injection than gasoline (higher fuel consumption). Butanol has a lower octane number than ethanol and lower cetane number compared to biodiesel which makes butanol less efficient and reduces autoignition (Trindade and Santos, 2017).

Butanol is generally produced by two fundamentally different approaches, including petrochemically (Oxo process), in which propylene is hydroformulated to butyraldehyde and then hydrogenated to produce butanol (Xue, Zhao, *et al.*, 2017). Secondly, biologically through microbial fermentation which is also known as biobutanol. However, the production cost of petrochemical synthesis is directly associated with the propylene market and highly fluctuated according to the price of crude oil (Yadav *et al.*, 2014). Therefore, the production of butanol using microbial fermentation can be a promising alternative to comply with the current need for butanol. However, it also faces a major drawback in terms of low yield and high production cost. Many attempts were conducted to solve this problem, including finding a low-cost substrate, such as lignocellulosic biomass from agricultural waste which is characterized as second-generation biobutanol.

We review the current status of biobutanol from lignocellulosic biomass through biological processing, including the fermentation process integrated with recovery technology. We hope this review could give insight and new perspectives which leads to the efficiency improvement of second-generation biobutanol production.

SECOND-GENERATION BIOBUTANOL

Economically, biobutanol production through fermentation depends on the feedstock (Gapes, 2000; Qureshi and Blaschek, 2000, 2001; Kumar and Gayen, 2011). There are three categories of biobutanol according to its feedstocks, namely the first, second, and third generation. First-generation biobutanol uses food crop biomass as a substrate. This causes a significant conflict as it affects food security and increases food prices (Ndaba, Chiyanzu and Marx, 2015). Second generation biobutanol uses agricultural wastes which are non-edible biomass diminishing the competition between food crops. Meanwhile, third-generation biobutanol uses algae (micro and macroalgae) as the raw material. Low yield and high-cost pretreatment, specifically in the harvesting stage making the technoecomic of third-generation biobutanol is debatable. This study focusses on second-generation biobutanol as it is considered the most ideal candidate to produce cost-efficient biofuels.

Fermentation Method

Biobutanol is produced by anaerobic fermentation of sugar using Clostridia strain along with acetone and ethanol as major products, which is also known as "Acetone-Butanol-Ethanol (ABE) Fermentation". The ration among these products is 3:6:1 for acetone, butanol, and ethanol, respectively with a maximum concentration of 20 g/L and by-products including carbon dioxide and hydrogen (Durán-padilla *et al.*, 2014). Despite all the benefits characteristic of biobutanol, in terms of stoichiometric conversion, when compared to another biofuel, such as bioethanol, butanol shows lower theoretical maximum yield per unit glucose (Equation 1 and 2) (Hoogewind, 2014).

$$C_6H_{12}O_6(180.16\ kg) \rightarrow 2C_2H_5OH(92.34\ kg) + 2CO_2(88.02\ kg) \quad (1)$$

$$C_6H_{12}O_6(180.16\ kg) \rightarrow C_4H_9OH\ (74.12\ kg) + 2CO_2(88.02\ kg) + H_2O(18.02\ kg) \quad (2)$$

Basically, there are two major processes for the production technology of biofuels, namely separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF) (Sasaki *et al.*, 2014). For biobutanol, it seems that SHF method is more preferable although several researches have used SSF method. Dong (2016) used hydrolysates of corn stover to produce biobutanol with SSF using *Clostridium beijerinckii* DSM 13864. Compared to SHF method, a significant increase of 59% was achieved in productivity (Dong *et al.*, 2016). Sasaki et al (2014) compared SHF and SSF methods using wood chips of *Quercus acutissima* as a carbon source and *Clostridium acetobutylicum* NBRC 13948 to produce butanol. SHF method was found to be more effective than SSF as the maximum ABE concentration from SHF method was 15.29 g/L in 120 h. Meanwhile, 13.41 g/L ABE was obtained in 144 hours from SSF method (Sasaki *et al.*, 2014).

In addition to the sequence of fermentation, it is also important to consider how the cell of fermentation is handled. There are two fermentation techniques for handling the cells, including free cells and immobilized cells (Axelsson *et al.*, 2012). Between the two techniques, the free cell is more flexible and simple, however, it has the lowest productivity. Therefore, it needs other supporting tools, such as agitation or gas dispersion to increase its performance. Immobilized cell using fibrous bed bioreactor (FBB) which is integrated with a recovery method is currently dominating as it can increase the yield to tenfold (Xue *et al.*, 2012; Xue, Liu, *et al.*, 2016; Xue, Zhang, *et al.*, 2017). *Clostridium acetobutylicum* and *Clostridium beijerinckii* are dominating the fermentation with a better yield of butanol. Fermentation conditions with a temperature of 37 °C and pH in the range of 6 to 7 are preferred. In some cases, *Clostridium acetobutylicum* even cannot stand pH below 7 since it will go through autolysis (Croux *et al.*, 1992).

Recovery Method

Despite the superior characteristic of biobutanol, the separation and purification process of biobutanol from fermentation broth are costly and more complex than bioethanol. The major reasons lie to the low concentration of butanol in broth (about 2%, less than ethanol which is ~15%), the azeotropic boiling point of butanol/water (117.7 °C/100 °C) and low final distilled butanol concentration which is only 55.5% (Durre, 2011; Abdehagh, Tezel and Thibault, 2014; Huang, Ramaswamy and Liu, 2014). A robust separation technique, such as distillation needs higher energy requirements as butanol has a higher boiling point than water (Nanda *et al.*, 2017). Therefore, efficient and cost-effective recovery techniques are essential to increase its economic efficiency (Jiménez-Bonilla and Wang, 2017).

In situ product recovery (ISPR) including gas stripping and pervaporation removes product (butanol) during fermentation as soon as it formed which diminished its toxicity effect leading to an increase in productivity The compatibility of the ISPR techniques with the ABE fermentation process depends on these three following key criteria, including its ability to remove butanol from the broth, energy requirement, and technoeconomic (Roffler, Blanch and Wilke, 1984; Ezeji, N and Blaschek, 2003; Xue *et al.*, 2012; Outram *et al.*, 2017; Xue, Zhang, *et al.*, 2017).

Gas Stripping (GS)

Gas stripping is a simple recovery method that is conducted by bubbling inert gas such as CO_2 and H_2 from the fermentation into the fermentation broth to stimulate the evaporation of volatile compounds in the gas stream and then condensed by the condenser

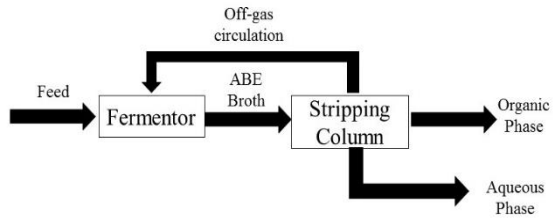

Figure 1. Process flow diagram of gas stripping

(Jiménez-Bonilla and Wang, 2017). Gas stripping is considered easy and simple to operate which no risk of fouling to the culture. However, butanol selectivity of gas stripping is still limited due to the equilibrium of butanol and water on interfacial gas bubbles. Although an excessive amount of foam resulted from the gas stripping could be a drawback, the addition of antifoam agents can solve the problem (Xue, Zhao, *et al.*, 2017). A schematic representation of the gas stripping process is shown in Figure 1.

Maintaining low butanol concentration in the fermentation broth is essential due to its toxicity that could induce sporulation and culture degeneration that would inhibit fermentation. Furthermore, butanol concentration higher than 8 g/L is more preferred to gas stripping as the condensed vapor gas stripping would have butanol concentration higher than its solubility (~7.8 g in 100 g water) which resulted a highly concentrated organic phase with ~80% (v/v) butanol (Xue *et al.*, 2012).

Pervaporation (PV)

Regarding energy consumption, pervaporation has potential as a promising recovery method since it does not require heating as in the distillation process. Pervaporation is more preferred in separating azeotropic mixtures and thermally sensitive liquids. In this process, ABE broth will contact with one side of a semi-permeable membrane, while a vacuum is applied at the other permeate side of the membrane to induce a chemical potential difference so that the separation can occur (Ong *et al.*, 2016).

The component selectivity for butanol is also higher than gas stripping (Qureshi *et al.*, 2001). The selectivity of the membrane is the most significant parameter as the ideal membrane should allow ABE compound to diffuse selectively while retaining butyric acid, acetic acid, and other minor compounds. It should not also be easily blocked by cells to minimize fouling (Outram *et al.*, 2017). However, there is a competition between the selectivity with flux. Flux can be improved by using higher temperature (65 – 80 °C). In addition, Qureshi and Blaschek (1999) found that the application of vacuum on the permeate side can increase the flux, that is why current researches center on vacuum (Qureshi and Blaschek, 1999) (Zhou *et al.*, 2011; Van Hecke *et al.*, 2012; Wu *et al.*, 2012; Van Hecke, Hoffman and Wever, 2013). A schematic design of the pervaporation process is illustrated in Figure 2.

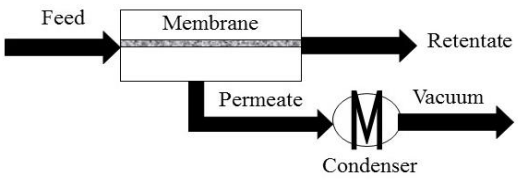

Figure 2. Schematic design of pervaporation (Adopted from Ong et al (2016))

Two-stage integrated techniques

Despite the simple scale up and easy operation of gas stripping, the butanol titers recovered from this method were less than 230 g/L (180 g/L butanol) and consumes high energy during product recovery and purification (Xue *et al.*, 2013; Cai *et al.*, 2016). Pervaporation which has high selectivity for butanol (2 – 209) is too reliant on the structure and characteristic of the membrane (Fadeev *et al.*, 2001; Vane, Namboodiri and Meier, 2010; Xue *et al.*, 2012). Therefore, an advanced process needs to be developed to make up for the weaknesses (Zhu *et al.*, 2018).

Vapor stripping-vapor permeation (VSVP), membrane-assisted vapor stripping combines the advantageous characteristic of pervaporation and gas stripping. VSVP is reported to at least 65% more energy efficient than other conventional distillation techniques and could prevent membrane fouling which caused by the contact of volatile organic compound with the membrane during mass transfer (Vane and Alvarez, 2013; Xue, Wang, *et al.*, 2016) (Xue, Zhang, *et al.*, 2017). In VSVP process, the mixtures are vaporized by gas stripping. The vapor mixture will be diffused into the membrane and transferred to the permeate side under a vacuum. The vapor then condensed at low temperatures (~-196 °C) (Xue, Wang, *et al.*, 2016). Xue et al (2016) attempted the VSVP process from corn stover hydrolysate and produced condensate containing 212.0 – 232.0 g/L butanol (306.6 – 356.1 g/L ABE) from fermentation broth containing ~10 g/L (~17 g/L ABE) which was more effective than pervaporation and gas stripping (Xue, Wang, *et al.*, 2016). Zhu et al (2018) conducted the VSVP process which was developed with temperature different control for single-stage butanol recovery. The integrated VSVP process generated a highly concentrated permeate containing 212.7 g/L butanol (339.3 g/L ABE) (Zhu *et al.*, 2018).

Two-stage gas stripping integrated with ABE fermentation and cell immobilization in a fibrous bed bioreactor was conducted by Xue et al (2014). Condensate containing 147.2 g/L butanol (199.0 g/L ABE) was produced from the first stage of gas stripping. The second-stage gas stripping increased the concentration of the condensate to 515.3 g/L butanol (671.1 g/L ABE) (Xue *et al.*, 2014). Figure 3 illustrates two-stage recovery integrated with fermentation as conducted by Xue et al (2015). Xue et al (2015) developed a two-stage gas stripping-pervaporation

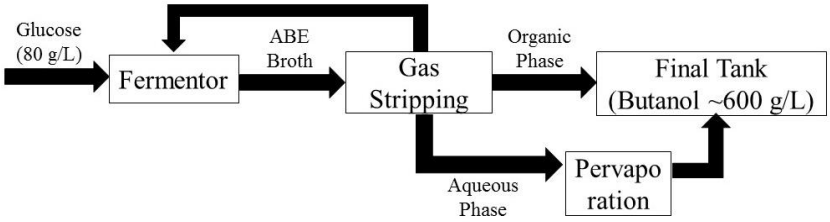

Figure 3. Schematic Diagram for ABE fermentation integrated with gas stripping-pervaporation method (Modified from Xue et al (2015))

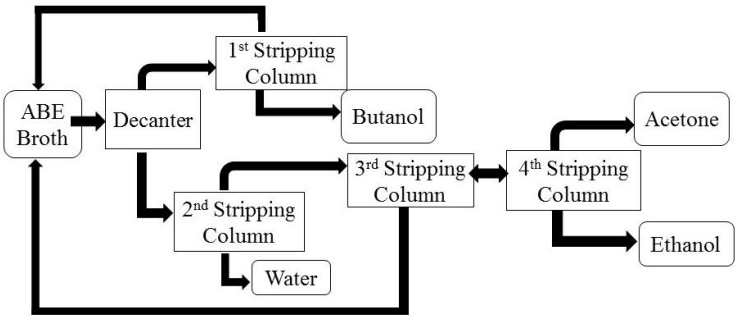

Figure 4. Flowsheet of the decanter-distillation purification process (adopted from Patrascu et al (2017))

process integrated with acetone-butanol-ethanol (ABE) fermentation. Gas stripping is conducted in the first stage followed by pervaporation using carbon nanotubes (CNTs) filled with polydimethylsiloxane (PDMS) mixed matrix membrane (MMM) and obtained a high concentration of butanol about 521.3 g/L (622.9 g/L ABE).

Purification Method

The ABE mixture from the recovery process is then further separated and purified. As the most volatile among other components, acetone is the first to be separated by a simple distillation column. Next, ethanol is separated into another distillation column. Ethanol-water homogeneous azeotrope will exit through the top of the column, while butanol-water heterogeneous azeotrope comes out at the bottom (Huang, Ramaswamy and Liu, 2014). Luyben (2008) used the two-column and decanter system by Doherty and Malone (2001). Luyben used Aspen Technology Simulation Software for steady-state and dynamic studies. The UNIQUAC physical property is used for the thermodynamic model. The design feed flow rate is 1000 kmol/h with product purities of 99.9 mol%. Another method was proposed by Qureshi et al (2013). Qureshi et al used hydrophilic membrane pervaporation for butanol dehydration (Qureshi *et al.*, 2013). Meanwhile, Kaymak (2018) proposed a novel process including reactive distillation columns to consume water recycling in the process. Butanol with a purity of 99.5% mole was obtained which also decreases ~40% reboiler heat duty. Reactive distillation columns are designed using the rigorous RadFrac model in Aspen Plus.

Patrascu et al (2017) performed a combination of decanter-distillation units which was simulated and optimized using Aspen Plus. Plant capacity of 40 ktpy butanol was used as a reference that obtained high purity of butanol (99.4 %wt), 99.4 %wt acetone and 91.4 %wt ethanol. The process was effectively lower the costs and emission to 1.24 kWh/kg butanol.

Figure 4 illustrates the flowsheet of the purification process by Patrascu et al (2017) using the decanter-distillation unit. The first unit is decanter, where the aqueous phase which is rich in water is removed from butanol rich organic phase. The organic phase is then fed to the 1st stripping column to separate butanol as a bottom product. Meanwhile, the water-rich top stream is recycled to the decanter. The aqueous phase is fed to the 2nd stripping column to remove water from the system. The upper stream of this column which contains acetone rich mixture from the distillate stream is fed to the 3rd stripping column. The bottom stream which contains a butanol-water mixture is recycled to the decanter. Finally, the 4th stripping column separates ethanol and acetone from the distillate stream.

Current Status

Butanol production from ABE fermentation was first registered in the United Kingdom around 1912. In 1920, Commercial Solvent Corporation purchased a license patented by Weizmann (US Patent 13155, 1919) and established a butanol production at Terre Haute, Indiana, USA. During 1924 – 1927, the corporation extended plant in Peoria, Illinois with 96 fermentors (capacity 567,750 l). Afterward, within 1936, several countries including Japan, India,

Australia, and South Africa followed by establishing other plants. However, when synthetic equivalents which gave better prices due to the availability of cheaper crude oil raised in the 1950s, biobutanol was left out. China, nevertheless, which kept the production of biobutanol for several decades, eventually closed several plants in the 1990s (Kumar and Gayen, 2011; Xue, Zhang, *et al.*, 2017).

Biobutanol regains its place in 2005 when David Ramey drove unmodified vehicles fueled only by butanol across the USA (Durre, 2007). BP and DuPont produced 30,000 t butanol per year in 2006 in a modified ethanol facility of British Sugar in the UK. They tested the use of biobutanol in 2008 and found that it can increase the blending in gasoline better than ethanol without compromising its performance. In addition, several biotechnology companies which support the biobutanol fermentation commercially in term of providing strains including Butyl Fuel, Cathay Industrial Biotech, Cobal Biofuels, Green Biologics, Metabolic Explorer, Tetravitae Bioscience, and others around the world also emerge (Jin *et al.*, 2011; Kumar and Gayen, 2011).

Since 2006, China restarted ABE fermentation plants using corn starch as feedstock. In 2009, China built over a dozen plants for ABE production, with a capacity of >200,000 tons. However, they had been closed after four years of running due to the rapid decrease in crude oil prices (Xue, Zhao, *et al.*, 2017). More than $200 million has been invested in China to install 0.2 million tons per annum of solvent capacity which expected to expand to 1 million tons per annum. Six major plants produced around 30,000 tons per annum butanol from corn starch in a semi-continuous system. Most of the plants were built next to ethanol plants to cut down the operating and utility cost (Green, 2011).U.S company which are involved in butanol production are Du Pont and BP and Gevo (*Alternative Fuel Data Center*, 2017; Procentese *et al.*, 2017). Green Biologics produced n-butanol through fermentation from renewable feedstocks, including corn cobs and corn stover resulting in high purity renewable butanol (*Green Biologics*, 2017). Currently, some of the major producer of butanol in industrial-scale are BASF SE (Germany), The Dow Chemical Company (US), BASF-YPC Ltd. (China), OXO Corporation (US), Sasol Ltd (South Africa), Formosa Plastics Corporation (Taiwan), Eastman Chemical Company (US), Oxichimie SAS (France), KH Neochem Co. Ltd (Japan) and CNPC (China). Meanwhile, Brazil (Brotas-SP) is also operating pilot-scale production using sugarcane bagasse as feedstock.

Presently, the demand for butanol worldwide keeps expanding by 3% per year, which expected to reach $9.9 billion by 2020 (Nanda *et al.*, 2017). Therefore, many biorefinery industries are attempting to improve biobutanol technology in order to achieve cost-effective and efficient biobutanol, including GranBio (Alagoas, Brazil) and Rhodis (Belgium) which collaborated to produce 100 kilotons biobutanol from sugarcane bagasse. British Petroleum (United Kingdom) and DuPont (USA) partnered and established Butamax^{TM} Advanced Biofuels, which produced butanol from a variety of feedstocks, including corn and sugarcane. Other companies, such as GreenBiologics (Oxon, UK), Cobalt Biofuels (California, USA), Tetravitae Bioscience Inc.(Illinois, USA), Gevo (Colorado, USA), METabolics Explorer (Clermont-Ferrard, France), Butalco (Furigen, Switzerland) and Cathay Industrial Biotech (Shanghai, China) are also developing biobutanol to commercial scale (Nanda *et al.*, 2017).

BP, DuPont, Cobalt and Chevron Oronite are working together to commercialize butanol for blend use in spark-ignition or as a precursor to replacing hydrocarbon biofuels. In 2011, Cobalt Technologies and American Process, Inc., partnered to establish the first industrial-scale butanol. Also in 2011, Cobalt built a demonstration plant in Alpena funded by The Whittemore Collection Ltd which has a capacity of 470,000 gal/year n-butanol. The UK-based company, Green Biologics invested £4.9 million (US$7.2 million) for commercialization of biobutanol (Tao et al 2013).

However, In Indonesia, biobutanol is still in the research step. Several raw materials including sawdust, waste of tofu production, oil palm empty fruit bunch are used to produce biobutanol using Clostridia strain.

Technoeconomy

In biofuels, the raw material is the vital parameter to assure the economic benefit. Therefore, lignocellulosic material is acknowledged as the most promising substrate due to its abundant availability, low-cost and averagely high sugar content. However, the estimated energy to increase butanol concentration from 0 to 99% wt in a binary system butanol-water is nearly 79.5 MJ/kg, which is greater than the energy contained in butanol itself (Qureshi *et al.*, 2005; Mariano *et al.*, 2012). Therefore, an integrated system of fermentation and recovery is proposed where the products can be collected right away after fermentation to avoid product inhibition which further increases the concentration of the final products. Several studies regarding technoeconomic of biobutanol have been conducted. Quiroz-Ramirez et al (2018) simulated and optimized a process to produce butanol from corn grain, wheat and wheat straw using MATLAB. The whole process was evaluated in terms of the environmental, economic and energetic objective function using a hybrid stochastic method, differential evolution with tabu list. The result showed that the best scenario to produce and purify butanol was simultaneously fermenting glucose and xylose using *Clostridium acetobutilicum* followed by a thermally coupled column to purify acetone, butanol and ethanol. The result also found that the total annual cost, environmental impact and exergy efficiency of the proposed system to be 0.138 $/kg$_{butanol}$, 0.132 points/kg$_{butanol}$ and 66.8, respectively. In addition, the proposed system presented low energy requirement per

kg of produced butanol with 5.7 MJ/$kg_{butanol}$ which is only 16% of the energy contained in 1 kg of butanol (2018). Salemme et al (2017) compared the techno-economic analysis of butanol from ABE fermentation broth based on gas stripping technique with a recovery process based on conventional distillation. Both of the processes were modeled using Aspen Plus to assess energy and material balance. The estimation of the investment cost was conducted using Aspen Icarus and approximated methodologies typical of the process engineering. The result showed that, the gas stripping method was the most beneficial economically to recover butanol from the broth.

Baral et al (2016) assessed the techno-economic feasibility of commercial-scale ABE fermentation of corn stover for a 113.4 million liter/year (30 million gallons/year) butanol production using modeling software-SuperPro Designer. The production cost was estimated to be $1.8 liter which can be reduced to $0.6/liter depends on feedstock, butanol yield, and recovery, sugar conversion tare, heat recovery, and energy-efficient stillage utilization.

Jang and Choi (2018) analyzed techno-economic of the biobutanol process which is comprised of the concentrated acid pretreatment and hydrolysis process for sugar production using concentrated sulfuric acid and continuous fermentation. Data were obtained from the pilot and demonstration-scale plant by GS Caltex Corporation, Republic of Korea and the analysis was conducted using Aspen Plus®. From the analysis, it was found that fixed capital investment and feedstock price added 85% of the production cost, pretreatment and hydrolysis unit contributed 50% of the fixed capital investment and a calculated minimum butanol selling prices was 5,668 $/t at the base case.

CONCLUDING REMARKS AND FUTURE DIRECTION

Although the development of biobutanol for fuel has been conducted for decades, its application directly to the engine is still far to be accomplished. Like any other biofuel, many improvements should be employed regarding its complex process from pretreatment to purification, strain ability to convert glucose to butanol, solvent toxicity, and multiple end products (acetone, ethanol and off-gas) which also considering its impact to the environment and its sustainability.

Securing abundant and inexpensive raw material, specifically from lignocellulosic biomass is a reliable option as its utilization for fuel will not affect negatively the price of the feedstock for food and also very much reduce the production cost. Reducing the complex and multiple processes of the production by consolidated bioprocessing (CBP) method seems to be a good idea, however, insufficient knowledge of the microbial genome becomes a great obstacle for this to be applied commercially. Nevertheless, many researches regarding this area are progressing rapidly. For now, developing efficient fermentation integrated with the recovery process shows promising results with a high titer, yield, and productivity.

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