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Review on Sustainability Assessment of Integrated Biorefineries based on Environmental, Health and Safety Perspectives

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The depletion of fossil fuel reserves and increment of concern on environmental sustainability has motivated industries to search for alternatives for both energy generation and production of chemicals and materials. Among the alternative sources which are deemed to be viable, biomass has been identified as one of those with the highest potential sources to replace fossil fuel. In order to convert biomass into biofuels, bioenergy and biochemical, a sustainable integrated biorefinery is needed to integrate multiple biomass conversion processes with minimum impact to the environment, health and safety aspects. Currently, integrated biorefinery is designed primarily based on economic performance and environmental impact as these are the most important factors for decision makers especially for the development of new processes. However, the challenge is mounted up in a way that the design of an integrated biorefinery needs to also simultaneously consider other factors such as energy utilization, inherent occupational health and safety hazard. The increasing number of technologies available in the market will add to the complexities in the synthesis and design of an integrated biorefinery. Hence, the aim of the current paper is to conduct a review on the sustainability assessment methodologies which was used during the process synthesis of an integrated biorefinery system.

1. Introduction

According to Kathryn (2014), approximate 88 % of global energy needs from the developing countries are mainly supplied from fossil fuel sources such as coal (28 %), oil (40 %) and natural gas (20 %). Due to the world is heavily dependence on fossil fuels, the planet had already experienced warming by 0.8 K over the past 100 y (Northon, 2015). This is caused by human activities, primarily burning of fossil fuels that release carbon dioxide as well as other greenhouse gases into the atmosphere. The changes on the planet from the effect of global warming have been observed such as melting of glaciers on both the polar ice caps, change of animals' migration patterns, as well as extreme weather, either hot or cold, in some part of the world. According to Church (2008), the rise of sea level has accelerated from the average of 1.7 mm per year in the 20th century to the average rate of 3 mm per year through 2006 and 2007. This is a sign of acceleration in response to global warming and the impacts of sea-level rise include the severity and frequency of flooding especially in the low-lying area and tsunami. Rockstrom et al., (2009) introduced the concept of planetary boundaries, which refers to a number of measurable environmental parameters (e.g. climate change, biodiversity loss, nitrogen and phosphorous cycles, ozone depletion, ocean acidification, global freshwater use, land use, atmospheric aerosol loading, and chemical pollution) that should not be surpassed to avoid unacceptable environmental changes and to preserve the environmental equilibrium. This somehow indicates that the transition to a clean energy economy cannot be achieved simply from the concern over the scarcity of fossil fuels; rather, it must be driven by a

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concerted effort to keep the climate liveable and healthy. This is the only way to prevent the worst impacts that could happen due to climate change.
Biomass, or more specifically lignocellulosic biomass, is proposed as a promising, environmentally compatible and sustainable renewable resource to replace fossil fuels. Biomass refers to all organic materials that stem out from green plants as a result of photosynthesis reaction, which converts the solar energy into chemical energy. This energy is stored in the form of oils, carbohydrates, protein and other biomolecules. It can be released when the chemical bonds between carbon, hydrogen and oxygen molecules are broken by thermochemical or biochemical processes (Zhang et al., 2010).

2. The Concept of Integrated Biorefinery

Integrated biorefinery is a processing facility that integrates biomass conversion process as a whole to produce fuels, power and value-added chemical from biomass (Fernando et al., 2006). As mentioned earlier, lignocellulosic biomass is a promising feedstock for the biorefinery, because it is readily available, renewable, low cost and abundant (FitzPatrick et al., 2010). However, unlike petroleum feedstock, lignocellulosic feedstock typically has a lower thermal stabilities and higher degree of functionality. In order to convert them into valuable products within a biorefinery, several technological processes such as biochemical, thermochemical, mechanical and chemical processes must be jointly applied. The major platforms for biorefinery are biochemical (also known as sugar platform) and thermochemical (also known as syngas platform) (Schlosser and Blahusiak, 2011). The technologies applied in the biochemical platform are fermentation and enzymatic treatment, whereas in the thermochemical platform, the conversion technologies are combustion, pyrolysis, gasification and liquefaction. Two main products are produced from biorefinery, which can be classified into bioenergy and biochemical products. The most important bioenergy based products are gaseous biofuels (syngas, biomethane, hydrogen), solid biofuels (lignin and charcoal), and liquid biofuels for transportation (bioethanol, biodiesel, bio-oil), whereas among the chemical products are organic acids (succinic, lactic, itaconic), fertilizers, chemical (building blocks, bulk chemical and fine chemicals, polymers and resins (Cherubini, 2010).

3. Process Integration Approach in the Synthesis and Design of Integrated Biorefinery

Process integration is a holistic approach for process design, retrofitting and operation which emphasizes the unity of the process (El-Halwagi, 1997). Process integration is useful at the concept-based level analysis during the development and process design phase of chemical processes. For example, it is used to identify the potential processing pathways among all the biomass conversion processes, ahead of detailed evaluations and flowsheeting studies. The important steps in process integration can be classified into synthesis, analysis and optimization. Generally, process synthesis is to design an optimum process flow sheet in order to meet the given objectives (e.g., maximize profit or economic performance, minimize waste or environmental impact) by providing the condition data (i.e., chemical reaction, conversion rate, chemical component) on the chemical processing pathway. Once the flow sheet is synthesized, the detailed characteristics of the process stream condition (e.g., temperature, pressure, flowrate) are predicted using analysis techniques (Foo, 2012). These techniques include mathematical models, empirical correlation and computer-aided process simulation tools. Synthesis and analysis activities are iteratively continued until the objectives are achieved. Finally, optimization is applied in the selection of the “best” process concept among all the alternatives. For example, Ng (2010) extended the automated targeting approach (Ng et al. 2009) which was developed for the synthesis of resource conservation network to determine the maximum biofuel production and revenue levels in an integrated biorefinery. On the other hand, Pham and El-Halwagi (2011) presented a synthesis approach to generate possible reaction pathway in a biorefinery.
In the recent years, many new biomass processing technologies have been proposed but most of them are still in the developing stage or lab scale. There are only few of the technologies have been scaled-up and applied in the industry. The implemented technologies can be generally classified as biochemical (i.e., fermentation process to produce alcohol, transesterification to form biodiesel, anaerobic digestion for formation of biogas) and thermochemical (i.e., pyrolysis to produce bio-oil, gasification process to produce syngas and combustion to generate electricity). Hence, the level of complexity to design and synthesis of a biorefinery increases, as there are an increase in the degree of freedom in feedstock and product selection, the processing technologies, energy consumption and also the environmental impact (Andiappan et al., 2015). The main challenge is to integrate multiple processing technologies as well as identify potential pathways based on the sustainability criteria.

4. Sustainability Aspects of Biorefineries

Sustainability can be defined as 'meeting the needs of the present without compromising the ability of the future generation to meet their own needs' (Anon, 1989). The importance of sustainability is to ensure that we have and will continue to have water, materials and resources to protect human health and the environment. The term "footprint" is important and can be used to describe how human activities impose different types of burden on the environment and thus impact the global sustainability (UNEP/SETAC, 2009). In the last two decades, several footprints in different aspects such as environmental (e.g., carbon footprint [CF], nitrogen footprint [NF], land footprint [LF] and water footprint [WF]), economic (e.g., economic footprint), and social (e.g., social and poverty footprint) have been developed to assess sustainability (Čuček et al., 2012). Indeed, sustainability will be one of the main drivers for innovation in order to allow the technical industries to care for the well-being of consumers in a safe and healthy environment (Hofer and Bigorra, 2007). The sustainability of a biorefinery depends on the comprehensive utilization of the biomass feedstock so as to give a diverse product portfolio. Economic, social and environment are the three important aspects to determine whether a biorefinery system is sustainable or not. Next, some of the sustainability assessment methodologies based on environmental, economic, energy, occupational health and safety aspects are discussed and identified. These methodologies can be used to screen the conversion processes based on the availability of information at the early design stages.

4.1 Sustainability Assessment Methodologies on Environmental Aspect

Life Cycle Assessment (LCA) is used to evaluate the environmental impacts over the entire life cycle of a process or product. The procedures of LCA are defined by the ISO 14040 series, which consist of three main steps such as goal and scope definition, life cycle inventory analysis and life cycle impact assessment (Guinée, 2002). This assessment has been widely applied in process synthesis and design of an integrated biorefinery. For example, Uihlein and Schebek (2009) performed LCA on the lignocellulose feedstock (LCF) biorefinery system and compared the environmental impacts with the conventional fossil alternatives. Mu et al. (2010) conducted LCA to compare the environmental performance of two primary routes for lignocellulosic ethanol production such as biochemical conversion and thermochemical conversion by including direct (i.e., greenhouse gases emission) and indirect (i.e., fossil fuel and fresh water consumption) environmental impacts factors. Gonzalez-Garcia et al. (2011) also applied LCA to identify and quantify the environmental impacts over the whole cycle of a Swedish softwood-based biorefinery, which is covering from the forestry activities to the output of the biorefinery mill.

4.2 Sustainability Assessment Methodologies on Economic Aspect

As shown in the literature, there are some studies have been conducted to analyze the economic aspect of biorefinery. Sammons et al. (2008) proposed a general systematic framework for optimizing the product portfolio and process configuration in an integrated biorefinery, while maximizing stakeholder value. Economic performance analysis on a gasification-based integrated biorefinery was also performed by Tay and Ng (2012) via multiple-cascade automated targeting approach. Moreover, Zondervan et al. (2011) developed a complete biorefinery model that can be used to compute the optimal production routes based on specific optimization objective such as maximizing yield or minimizing waste, fixed capital cost or operation cost. This model is very complex because it considers 72 processing steps (including different pre-treatment steps, hydrolysis, fermentation, several separation processes as well as fuel blending steps) that can be used to process two different types of feedstock. The case studies based on the production of ethanol, butanol, succinic acid or ethanol-gasoline and butanol-gasoline blend, were carried out to demonstrate this approach. This model is useful to quickly scan through abundant of processing steps and determine the best process pathway in the early stage of design.

4.3 Sustainability Assessment Methodologies based on Multiobjective Optimization

It should be noted that the aforementioned works are limited to single optimization objective. As most of the sustainable aspects are conflicting with each other, thus, multiobjective optimization is used in synthesizing a sustainable integrated biorefinery. As shown in the previous works, most of the studies are focussing on the environmental and economic aspects. For example, De Benedetto and Klemes (2009) realized that using LCA as an input for strategic decision-making from the environmental perspective has the disadvantage of limited inclusion of cost and investment considerations. Hence, they introduced a new graphical representation which is known as the Environmental Performance Strategy Map (EPSM), which allows the combination of the main environmental indicators (footprints) with the additional dimension of cost. On the other hand, Tay et al. (2011) adopted fuzzy mathematical programming in their work to synthesize a sustainable integrated biorefinery with maximum economic performance while minimum environmental impact. Furthermore, Kasivisvanathan et al. (2012) identified the optimum pathway to retrofit a palm oil mill into a palm oil-based integrated biorefinery with the consideration of both economic and environmental aspects. Luo et al. (2010) focused on the technical design, economic and environmental analysis of lignocellulosic feedstock biorefinery producing ethanol, succinic acid, acetic acid and electricity. Besides, Dias et al. (2013) analysed the integration between the first and second generations ethanol production from sugarcane based on economic and environmental point of view. An analysis tool which considers economic and environmental performance was also developed by Martinez-Hernandez et al. (2013). The concept of economic value and environmental impact (EVEI) analysis are included in the tool. It allows the decision makers to consider environmental and economic at the same time, in order to achieve a sustainable biorefinery design. Then, Martinez-Hernandez et al. (2014) further extended their previous work by introducing an economic and environmental impact profile of biorefinery products. EVEI is a multi-level methodology, which was developed for different economic marginal analysis from process steams to networks. The extended methodology is to support the process integration strategies that allow for achieving policy compliance of biorefinery products in term of greenhouse gas emission savings. On the other hand, Kelloway and Daoutidis (2014) developed a biorefinery superstructure and formulated a mixed integer nonlinear program which is used to determine the optimal biorefinery configuration that can produces fuels and chemicals from a variety of feed stocks. They further investigated the trade-offs between net present value and carbon efficiency as well as analyse the robustness of the biorefinery system subjected to economic uncertainty. Based on different perspectives, Lim et al. (2014) developed a systematic optimisation approach to design a sustainable efficient rice mill which is aimed to maximize the profitability while minimizing the environmental impact of its by-product utilization.

The multi objectives optimization models discussed above considered the economic and the environmental aspects only. According to the ICCA Worldwide Voice of the Chemical Industry (2013), many chemical production processes are energy intensive. The chemical industry consumes roughly 10 % of the total worldwide energy demand. Therefore, it is critical for industrial processes to reduce energy intensity. Due to the above issue, energy consumption within the synthesized integrated biorefinery should be taken into consideration. Consonni et al. (2009) conducted a study to synthesize an integrated pulp mill biorefineries based on black liquor and wood residue. This study included detailed mass-energy balance simulation, financial analyses, energy and environmental benefits estimates for seven pulp mill biorefinery process configurations. Andiappan et al. (2015) presented a systematic multiobjective optimization approach to synthesize an integrated biorefinery which considers economic, environmental and energy performances simultaneously. The Incremental Environmental Burden Assessment (IEBA) method was developed to quantify the environmental impact of a given reaction pathway in an integrated biorefinery. IEBA uses environmental potency factors to calculate incremental environmental burden score for each pathway based on per tonne of product formed. The method to analyse the energy consumption is based on the heat of reaction required for each chemical reaction pathway.

With the increasing attention towards sustainable development, integrated biorefinery cannot be concerning only on the environmental and economic aspects but also other sustainable indicators, i.e. safety and occupational health, which are an important social issues. Recent research works have considered social related issue during the synthesis and design of an integrated biorefinery. For example, Posada et al. (2013) adapted multi-criteria approach, quantitative and qualitative proxy indicators to perform a quick screening and subsequently identifying the most promising bioethanol derivatives. Then, they conducted a comparison on various alternative processes for bioethanol conversion from a sustainability point of view which covers economic, environmental, health and safety aspects. Ng et al. (2013) applied fuzzy multiobjective optimisation approach to synthesize and optimize a sustainable integrated biorefinery which simultaneously considers economic, environmental, inherent safety and inherent occupational health performances. The optimized network configuration with trade-offs between the four main objectives can be identified before detailed design. As presented in Ng et a. (2013), inherent Safety Index (ISI) and the Inherent Occupational Health Index (IOHI) are selected to evaluate the safety and health impacts of the process. ISI was developed by Heikkila et al. (1996), in which all the factors affecting the inherent safety of a process are considered, both from the process and the chemical standpoint. On the other hand, IOHI was developed by Hassim and Hurme (2010) to evaluate the inherent occupational health in the R&D stage. The level of health hazards in the process is estimated based on the information available at the R&D stage such as reaction chemistries, types and properties of the chemicals used in the process as well as the reaction conditions. IOHI is mainly used to compare the health hazard level of alternative chemical synthesis routes during the screening process.

5. Conclusions

Biomass can be considered as one of the most promising alternative sources to replace fossil fuels. Hence, systematic synthesis and design of biorefinery has gained much interest from the industries and academicians. System engineering tools such as synthesis, optimization and modelling could have a huge impact on the development of units, processes, supply chains and the biorefinery concept itself. This is due to more biomass processing technologies are in the developing stages but some of these technologies are ready to be implemented in the industry. As a result, the complexity to synthesize a sustainable integrated biorefinery increases, due to the increasing in degree of freedom in several factors including feedstock variety, processing technologies and product selection. The design of sustainable integrated biorefinery can be considered through three main aspects such as economic, environmental and social aspect. LCA can be used to quantify the environmental impact of a biorefinery. Besides, it can be regarded as an important tool to capture the complex features and interdependency of material flows of a production system, process and product. IEBA is another assessment available quantifying environmental impact by adapting the environmental potency factors in calculating the incremental environmental burden score for each pathway based on per tonne of product formed. As most of the sustainable aspects are conflicting with each other, thus, multiobjective optimization is used in synthesizing a sustainable integrated biorefinery. When dealing with multiobjective optimization for synthesizing an integrated biorefinery, fuzzy optimization is adapted to determine the favoured alternatives in solving an objective function and constraints simultaneously. Recently, social related issues such as safety and health hazard are also considered in the conceptual design stage of an integrated biorefinery. Several methods are available for this purpose including the ISI for inherent safety and The IOHI for the inherent health assessment.

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