CHEMICAL ENGINEERING TRANSACTIONS
VOL. 70, 2018

A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš

ISBN 978-88-95608-67-9; **ISSN** 2283-9216

DOI: 10.3303/CET1870035

Sustainability Vector: A Graphical Representation Method for Effective Evaluation and Analysis

Bing Shen How*, Sue Lin Ngan, Hon Loong Lam

Department of Chemical and Environmental Engineering, Faculty of Engineering,University of Nottingham Malaysia Campus, Jalan Broga, 43500 Semenyih, Selangor Darul Ehsan, Malaysia
BingShen.How@gmail.com

In tandem with the growing concern on sustainable development, green supply chain (GSC) management has received greater attention from both academicians and industry players. Numerous works have been conducted to overcome the operational gaps (i.e., not all decision-makers acquired strong engineering or programming background) which have been a key barrier of the linkage between academic and industry. This work presents a modified graphical illustration method which expressed the economic and environmental performance of a given process in the form of vector (or sustainability vector). With the aid of this sustainability vector, the tendency of the process towards each sustainability dimension is now visualised and thus it can be read and analysed easily and effectively. The conceptual idea of sustainability vector was introduced in the previous work. Then, this paper further enhances the formulation in order to avoid the misleading representation issue of the former method. In this work, the sustainability vector is demonstrated by using a case study which incorporated various types of biomass conversion pathways.

1. Introduction

Green supply chain (GSC) management has received the greatest attention in the recent decades, which is mainly driven by the exponential growth of public awareness in sustainable development. Among all the cleaner production technologies and options, biomass valorisation has been widely cited as one of the prospective alternatives in attaining higher sustainable goals (Wan Alwi et al., 2014), especially in the context of tropical countries which blessed with abundant natural resources (Raychaudhuri and Ghost, 2016).

To-date, substantial amount of researches have incorporated sustainable evaluations into the conventional biomass supply chain modelling. For instance, How and Lam (2017a) had developed a green integrated biomass supply chain in Malaysia (aiming to maximise the annual revenue and minimise the environmental impacts simultaneously) by using a novel principal component analysis (PCA) based optimisation approach. Lately, Pavlov et al. (2016) evaluated the supply chain system, in terms of task times, quality and monetary flow based on a functional modelling methodology. In terms of social assessment, Mota et al. (2015) measured the social benefits of a supply chain based on a regional job creation index which considered the local population density (i.e., job creation in less developed region is more preferable). More recently, Wan et al. (2016) had considered workplace footprint (WPFP) as the social indicator to quantify the work-related casualties of a sago value chain. It can be determined based on (i) reported lost days of work per unit of products (De Benedetto and Klemeš, 2009); or (ii) statistical fatality rate per unit of economic activity (Wan et al., 2016).

Apart from the mathematical model development, some scholars also focussed on graphical decision-making tools development which aims to narrow down the operational gaps between industry practice and academic research. For instance, Lim and Lam (2014) had introduced a novel biomass element life cycle analysis (BELCA) to free up the biomass technology limitation (i.e., normally technology is designed for a specific types of biomass). With the graphical radar chart, decision-makers can determine the possibility of using other underutilised biomass as alternative feedstocks without changing the current design of the operating units. On the other hand, How et al. (2016) had tackled the transportation design issue by developing a graphical transportation decision tool. With the aid of this tool, decision-makers can determine the optimal transportation

Please cite this article as: How B.S., Ngan S.L., Lam H.L., 2018, Sustainability vector: a graphical representation method for effective evaluation and analysis , Chemical Engineering Transactions, 70, 205-210 DOI:10.3303/CET1870035

mode for their specific case easily based on two user-inputs (i.e., amount of material to be delivered and distance travelled). Lately, Lam et al. (2017) had proposed a debottlenecking framework that incorporates P-graph to determine the possible bottlenecks of a biomass supply chain. Due to the visualised encoding features offered by P-graph, decision-makers with minimal programming background can also model and subsequently debottleneck their system easily.

On top of that, the sustainability performance of a given process, system and design can also be represented by using graphical method. Notably, De Benedetto and Klemeš (2015) introduced the Environmental Performance Strategy Map (EPSM) which presents the environmental footprints (e.g., carbon footprint, water footprint, etc.) on a specific spider web. On the other hand, Tjan et al. (2010) had extend the application of carbon emission pinch analysis (CEPA) in providing company-level evaluation and visualisation of carbon emission reduction options in chemical processes (i.e., carbon footprint composite curve with economic value on the horizontal axis and CO_2 emission on the vertical axis).

All the aforementioned works are admirable, but there is still lack of graphical representation method that able to visualise the tendency of the system toward each of the sustainability dimension which can be understood easily by the decision-makers from different background. In order to resolve this research gap, How and Lam (2017b) attempted to use of sustainability vector as a representation approach. In this first attempt, the sustainability performance is transformed into vector form based on a direct adaptation of the degree of satisfaction of each sustainability dimension. However, this might lead to some misleading results. By using this method, the sustainability vector when zero effort is committed (i.e., when no biomass is processed) is not fixed at (0,0) (note that first numerical scale refers to economic satisfaction; while the latter refers to environmental satisfaction). This is confusing as (0,0) often refers to the origin which indicates the initial states (i.e., before changes made). In order to overcome this issue, this work proposes an alternative way to formulate the sustainability vector. With the aid of this graphical tool, the tendency of the process toward each sustainability dimension can be clearly seen, at the same time, the aforementioned drawbacks are avoided. The sustainability performance of various biomass (including empty fruit brunch (EFB), palm kernel shell (PKS), rice husk, paddy straw, sugarcane bagasse, pineapple peel) conversion pathways are evaluated and represented in the form of sustainability vector.

2. Method

Figure 1 shows the general research chart used in this work. The detailed description is given in the subsections below:

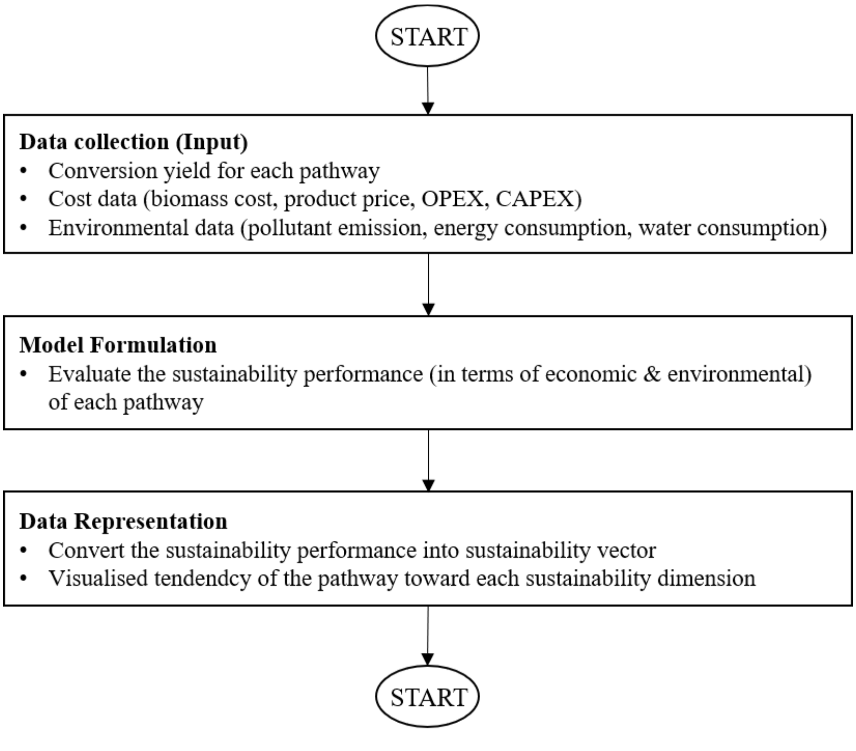

Figure 1: Research flow chart for this work

2.1 Data collection and model formulation

Firstly, data required for the sustainability evaluation of each conversion pathway (e.g., conversion yield, biomass and product price, pollutants emissions, etc.) is collected. In this work, six types of biomass and multiple technologies (e.g., fermentation, pyrolysis, combustion, etc.) are considered (see Figure 2). Note that the data used in this work is adapted from How et al. (2016). Similar to the previous work, the sustainability performance of each dimension is expressed in terms of degree of satisfaction (see Eq(1) and Eq(2), where λ^{EC} and λ^{EN} refer to the degree of satisfaction for economic and environmental dimension; C^{NP} refers to the net profit obtained; EI refers to the total environmental impact exerted; while superscripted (U) and (L) denote the maximal and minimal value of the corresponding variable). Please refer to How and Lam (2017b) for detailed model formulation.

$$\lambda^{Ec} = \frac{C^{NP} - C^{NP(L)}}{C^{NP(U)} - C^{NP(L)}} \qquad (1)$$

$$\lambda^{En} = \frac{EI^{(U)} - EI}{EI^{(U)} - EI^{(L)}} \qquad (2)$$

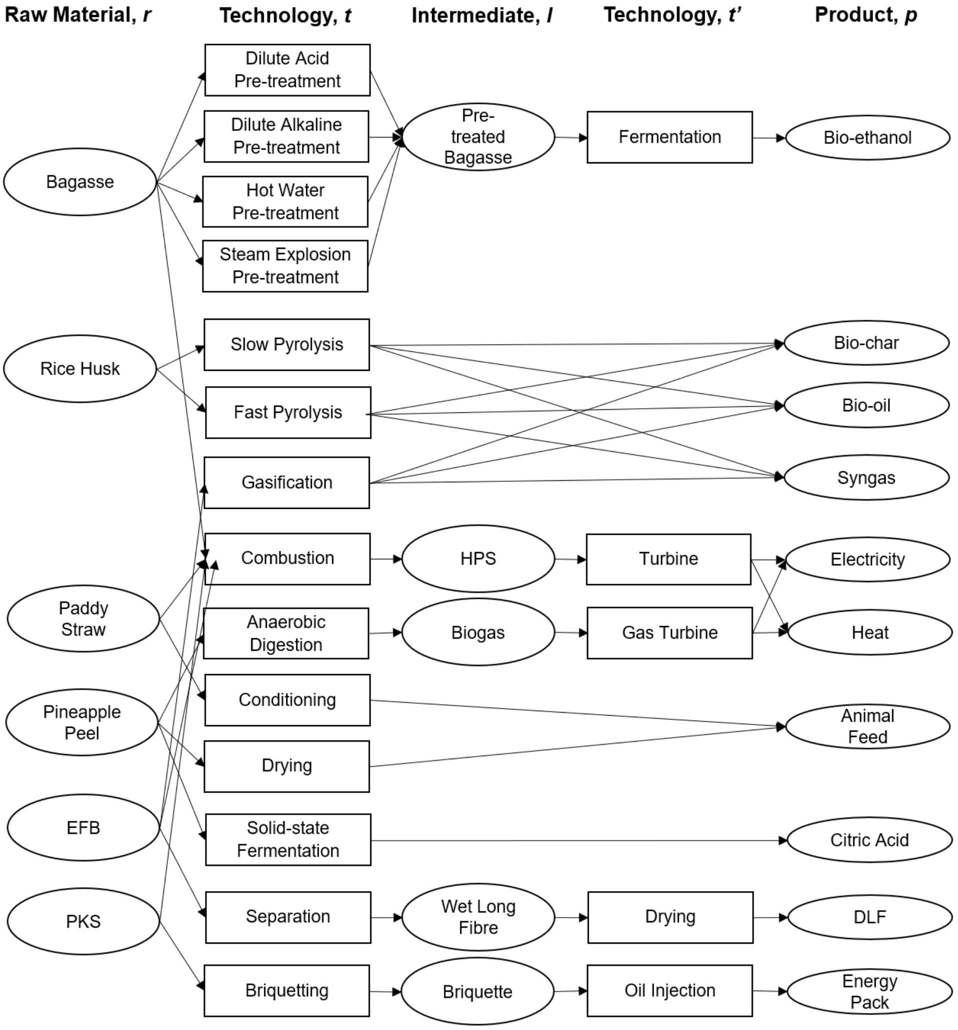

Figure 2: Superstructure of biomass conversion pathway (modified from How et al. (2016))

2.2 Data representation (sustainability vector development)

Sustainability vector was firstly introduced by How and Lam (2017b). It was constructed by using the degree of satisfaction on economic dimension as x-direction, while degree of satisfaction on environmental dimension as y-axis (i.e., Vector (λ^{EC}, λ^{EN})). As mentioned, this method did not constraint the sustainability vector when zero effort is committed at the origin. This might lead to incorrect interpretation from decision-makers as origin should reflect the initial state (i.e., before changes made). To overcome this issue, the sustainability vector is redefined as Vector (Obj^{EC}, Obj^{EN}). Note that the new components are defined in Eq(3) and Eq(4) (note that the superscripted (Ref) denotes the degree of satisfaction when zero effort is committed. By using this conversion, the sustainability vector when zero effort is committed is fixed at (0,0). In other word, any positive attributes (e.g., profit gained, negative carbon footprint) will lead to a positive value in the vector; contrarily, any negative attributes (e.g., profit loss, carbon emission) will lead to a negative value in the vector. Note that this is not guaranteed previously. The vector can be plotted in a quadrant diagram, while decision-makers can now classify the activities based on this graphical representation tool. Figure 3 demonstrates the quadrant diagram which representing the vector for various activities.

$$Obj^{EC} = \frac{\lambda^{EC} - \lambda^{EC\,(Ref)}}{1 - \lambda^{EC\,(Ref)}} \tag{3}$$

$$Obj^{EN} = \frac{\lambda^{EN} - \lambda^{EN\,(Ref)}}{1 - \lambda^{EN\,(Ref)}} \tag{4}$$

To illustrate, the conventional practices that often relied on fossil-based energy are normally plotted on the forth quadrant (positive attribute on economic but negative attribute to environment). On the other hand, the activities that fall on second quadrant are related to some of the non-economically profitable “green policies” (e.g., reforestation) that raised by the environmentalists. In addition, the un-matured green technologies which are yet to be economic-feasible and other treatment facilities (e.g., wastewater treatment) also fall on this quadrant. The activities that falls on the third quadrant should be avoided since these activities will lead to negative impact on both economic and environmental objectives. Disasters, such as plant fire and explosion will fall on this quadrant as well. Finally, the ideal goal is to emerge the green technologies into the first quadrant (provide positive attribute to both objectives), in order to enhance the sustainable development.

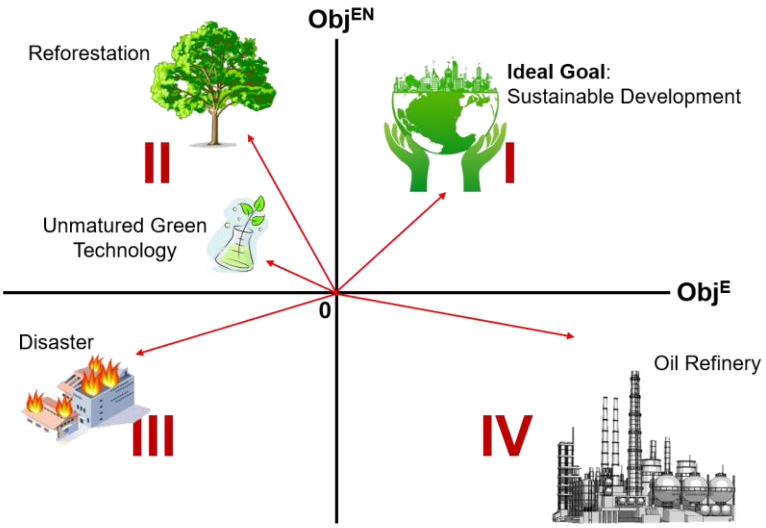

Figure 3: Quadrant diagram for sustainability vector

Similar to the previous work, sustainability vector can also be expressed in polar form (i.e., Vector (θ, Mag)), where θ is the angle that reveals the tendency of the system toward economic or environmental dimension; while Mag refers to the magnitude of the sustainable vector (determined through Eq(5) and Eq(6)). They can be used to evaluate the sustainability of each process. In the first quadrant, the process with a smaller θ, indicates that this process has a higher tendency toward economic sustainability. Therefore, decision-makers can select the process path which meets their personal preference in each sustainability dimension based on this θ value. For processes with same or near-range of θ (± 5 °), Mag is used as selection reference as the process with larger Mag indicates that the degree of satisfaction on both economic and environmental dimensions of this process is relatively higher.

$$\theta = \tan^{-1} \frac{Obj^{EN}}{Obj^{EC}} \tag{5}$$

$$\mathrm{Mag}=\sqrt{\mathrm{Obj}^{\mathrm{EC}^2}+\mathrm{Obj}^{\mathrm{EN}^2}} \qquad (6)$$

Note that for second quadrant (90 °< θ <180 °), smaller θ indicates better performance in environmental sustainability (but with negative economic sustainability); for forth quadrant (270 °< θ <360 °), larger θ indicates better performance in economic sustainability (but with negative environmental sustainability); while for third quadrant (180 °< θ <270 °), smaller θ indicates that this process has a higher tendency toward environmental sustainability. In addition, in the case where process integration is taking part, the new sustainability performance of the integrated process (i.e., Vector (θ^{New}, $\mathrm{Mag}^{\mathrm{New}}$) can be determined easily through the concept of vector addition, where $\Sigma_n \mathrm{Mag}_n \cos\theta_n$ indicates the net economic performance of the integrated process; $\Sigma_n \mathrm{Mag}_n \sin\theta_n$ indicates the net environmental performance of the integrated process; while *n* denotes the process alternatives:

$$\theta^{\mathrm{New}}=\tan^{-1}\frac{\Sigma_n \mathrm{Mag}_n \cos\theta_n}{\Sigma_n \mathrm{Mag}_n \sin\theta_n} \qquad (7)$$

$$\mathrm{Mag}^{\mathrm{New}}=\sqrt{(\Sigma_n \mathrm{Mag}_n \cos\theta_n)^2+(\Sigma_n \mathrm{Mag}_n \sin\theta_n)^2} \qquad (8)$$

3. Case study demonstration

The sustainability vector for each biomass conversion pathway is constructed and presented in Figure 4 (pathways for paddy and palm biomass) and Figure 5 (pathways for sugarcane bagasse and pineapple peel).

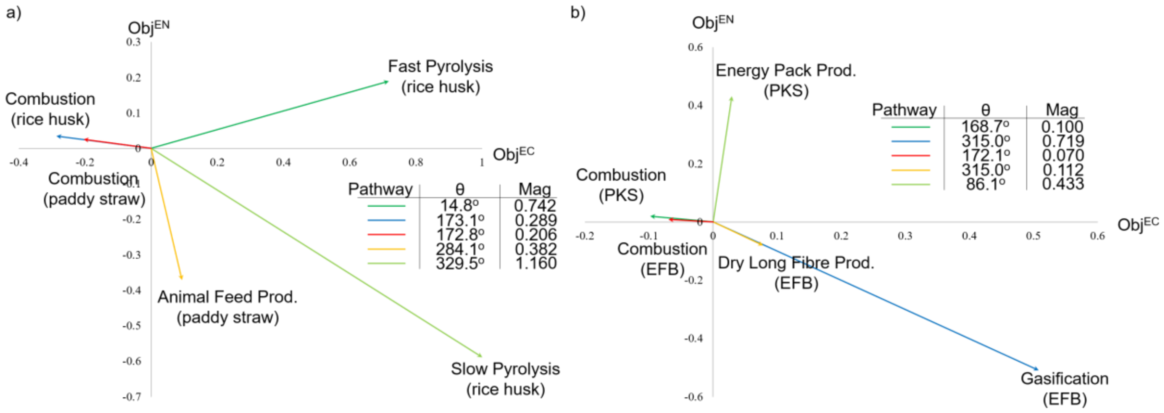

Figure 4: Sustainability vector of each conversion pathway for (a) paddy biomass and (b) palm biomass

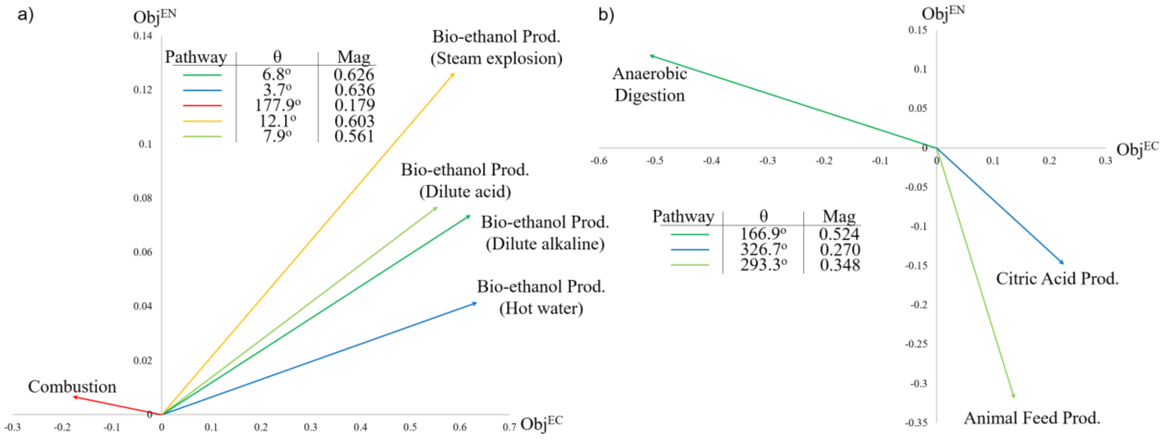

Figure 5: Sustainability vector of each conversion pathway for (a) sugarcane bagasse and (b) pineapple peel

The results show that most of the bioenergy products such as energy pack, bio-oil, bio-ethanol is more preferred (fall on the first quadrant). This suggests that these processes will provide substantial revenue and at the same time, unburden the environmental impacts. With the production of these bio-fuels, the requirement of fossil-based fuels is substantially reduced. However, biomass combustion and anaerobic digestion that generate electricity poses a different situation. These technologies fall on the second quadrant which indicates the presence of negative profit. This is probably due to the unattractive feed-in-tariff rate, unsupportive incentive policy and low boiler efficiency (Ahmad et al., 2011).

4. Conclusions

This work presents the development of sustainability vector which can be used to represent the sustainability performance of a given system graphically. The sustainability vector is easy to read and analyse since the tendency of the system toward each of the sustainability dimension is visualised in the quadrant diagram. On top of that, the misleading representation of sustainability vector has been resolved in the current model formulation. Keeping this in mind, the sustainability vector can now be used as an effective comparison tool to analyse the sustainability performance of various technologies (including green technologies and conventional technologies). In this work, it has been demonstrated by using a case study which incorporated multiple-biomass conversion pathways. This work can be further extended to consider the social dimension in the vector development. To achieve this, one additional quadrant diagram (e.g., economic dimension versus social dimension or environmental dimension versus economic) has to be constructed in order to visualise the tendency of the process towards all three sustainability dimensions.

Acknowledgments

The authors would like to acknowledge the financial support from the Ministry of Education (MOE), Malaysia, via LRGS Grant (Program code: LRGS/2013/UKM/PT).

References

Ahmad S., Ab Kadir M.Z.A., Shafie Ahmad S., 2011. Current perspective of the renewable energy development in Malaysia, Renewable and Sustainable Energy Reviews, 15(2), 897-904.

De Benedetto L., Klemeš J.J., 2009, The environmental performance strategy map: an integrated LCA approach to support the decision making process, Journal of Cleaner Production, 17, 900-906.

De Benedetto L., Klemeš J.J., 2015, The Environmental Performance Strategy Map: an integrated life cycle assessment approach to support the strategic decision-making process. In: Klemeš J.J. (Ed.), Assessing and Measuring Environmental Impact and Sustainability, Elsevier, Waltham, U.S., 367-408.

How B.S., Lam H.L., 2017a, Novel Evaluation Approach for Biomass Supply Chain: An Extended Application of PCA, Chemical Engineering Transactions, 61, 1591-1576.

How B.S., Lam H.L., 2017b, Integrated Palm Biomass Supply Chain toward Sustainable Management, Chemical Product and Process Modeling, 12(4), ISSN (Online) 1934-2659.

How B.S., Tan K.Y., Lam H.L., 2016, Transportation decision tool for optimisation of integrated biomass flow with vehicle capacity constraints, Journal of Cleaner Production, 136(Part B), 197-223.

Lam H.L., Chong K.H., Tan T.K., Ponniah G.D., Yeoh T.T., How B.S., 2017, Debottlenecking of the Integrated Biomass Network with Sustainability Index, Chemical Engineering Transaction, 61, 1615-1620.

Lim C.H., Lam H.L., 2014, Introduction of Novel Analysis Technique: Biomass Element Life Cycle Analysis (BELCA), Chemical Engineering Transaction, 39, 337-342.

Mota B., Gomes M.I., Carvalho A., Barbosa-Povoa A.P., 2015, Towards supply chain sustainability: economic, environmental and social design and planning, Journal of Cleaner Production, 105, 14-27.

Pavlou D., Orfanou A., Busato P., Berruto R., Sørensen C., Bochtis D., 2016, Functional modeling for green biomass supply chains, Computers and Electronics in Agriculture, 122, 29-40.

Raychaudhuri A., Ghost S.K., 2016, Biomass Supply Chain in Asian and European Countries, Procedia Environmental Sciences, 35, 914-924.

Tjan W., Tan R.R., Foo D.C.Y., 2010, A graphical representation of carbon footprint reduction for chemical processes, Journal of Cleaner Production, 18(9), 848-856.

Wan Y.K., Ng R.T.L., Ng D.K.S., Aviso K.B., Tan R.R., 2016, Fuzzy multi-footprint optimisation (FMFO) for synthesis of a sustainable value chain: Malaysian sago industry, Journal of Cleaner Production, 128, 62-76.

Wan Alwi S.R., Abdul Manan Z., Klemeš J.J., Huisingh D., 2014, Sustainability engineering for the future, Journal of Cleaner Production, 71, 1–10.