CHEMICAL ENGINEERING TRANSACTIONS

VOL. 88, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

ISBN 978-88-95608-86-0; **ISSN** 2283-9216

DOI: 10.3303/CET2188187

An Overview of Circular Economy-Life Cycle Assessment Framework

Seok Peng Ngan[a], Sue Lin Ngan[b], Hon Loong Lam[a,*]

[a]Department of Chemical Engineering, The University of Nottingham Malaysia Campus, 43500 Jalan Broga, Semenyih, Selangor, Malaysia

[b]UKM-Graduate School of Business, Universiti Kebangsaan Malaysia 43600 UKM, Bangi, Selangor, Malaysia
HonLoong.Lam@nottingham.edu.my

The increasing concern on the world waste issue has speed up the adoption of the circular economy model to replace the conventional “take, make, use, dispose” linear economy model. Life Cycle Assessment (LCA) has been widely used in the past to identify and evaluate the inputs and outputs of different activities carried out in a linear economy model. With more and more industry transition from linear economy model to Circular Economy (CE) model, especially in developed nations particularly Europe, United States and China, it is imperative for the LCA to consider the circularity relationship of resources in its framework to enhance the effectiveness of LCA. One of the fundamental principles of circular economy is that material waste is avoided by prioritizing the end-of-use capture of materials to create a positive value-driven closed loop. Nonetheless, the literature that include or integrate the circularity elements into the LCA framework remains limited. Anecdotal evidence has suggested that it is due to some limitations and barriers, including but not limited to industry acceptance level, high transition cost, lack of know-how expertise to enable the evaluation and others. In this work, the overview of the research and development towards the application of LCA to support CE strategies are reviewed. The limitations and challenges to apply LCA for a circular economy model are also identified to propose recommendations to extend the current application of LCA for a more robust strategy that capture the value of the reuse, recycle, remanufactured, repurposed resources and the potential upstream and downstream impacts for better decisions for sustainability. A case study in the palm oil industry is also presented to illustrate the possible development of CE-LCA framework in the context of developing countries.

1. Introduction

Linear Economy is also known as the economy that adapts the “take, make, use, dispose” model, where raw materials are extracted, manufactured into products, sold for consumption, and finally discarded when it reaches the end of its lifecycle. With the increasing concern for sustainable development, there have been more and more disputes and arguments on the linear economy model as an unsustainable practice due to its damage to the environment and its inability to promote global social equity (Milliar et al., 2019). Although linear economy model can indeed stimulate economic growth, it indirectly creates imbalance that focus solely on economic growth while neglecting the conversation and preservation of environment and the social well-being. Some examples of unnecessary resources losses using linear economy model includes waste in the production chain, end-of-life waste, energy use, and erosion of ecosystem services (Ellen MacArthur Foundation, 2013).
Life Cycle Assessment (LCA) is first introduced as a quantitative environmental performance tool that assess the potential environmental impacts and resources used throughout a product’s life cycle. It helps to quantify environmental impacts of a product during its life cycle from the stage of raw materials acquisition to manufacturing of products to the disposal and waste management process (Guinée et al., 1993). Since then, LCA has been gaining wider acceptance and being apply in many industries, including but not limited to building and constructions, manufacturing, oil and gas, life sciences and chemicals etc. However, LCA studies carried out often result in inconsistent outcomes due to the absence of a concrete methodology framework. The methodology framework of LCA studies was then developed and improved from time to time. Based on the most widely accepted standard finalized and determined by ISO 14040, LCA comprises four phases in sequence,

Paper Received: 26 April 2021; Revised: 28 July 2021; Accepted: 9 October 2021
Please cite this article as: Ngan S.P., Ngan S.L., Lam H.L., 2021, An Overview of Circular Economy-Life Cycle Assessment Framework, Chemical Engineering Transactions, 88, 1123-1128 DOI:10.3303/CET2188187

starting with the goal and scope definition, followed with Life Cycle Inventory Analysis (LCI), then Life Cycle Impact Assessment (LCIA), and finally the interpretation phase (Finkbeiner, 2006). By implementing LCA towards linear economy model, it helps to compare the full range of environmental effects assignable to products and services by quantifying all inputs and outputs of materials flows, which then evaluates how these material flows impact the environment within the system boundary. The life cycle in the system boundary includes the extraction and processing, necessary transportation, as well as reuse and recycling, that also described as cradle-to-grave analysis that ultimately helps decision maker to choose between alternative processes and processing routes (Azapagic and Clift, 1999).

Even with the International Organization for Standardization (ISO) documents, many academia and researchers remain doubtful towards LCA studies. Lee and Xu (2015) advocate that LCA investigates burdens on the environment instead of impacts due to the absence of universally acceptable method to evaluate impact on the environment. This can also lead to the explanation that LCA studies can only evaluate a single, but not multiple product life cycles at one time. Graedel (1998) proposed that some of the limitations and issues of LCA can be solved and the application of LCA can be more common considered it can be applied towards a region, country, or continent instead of just a single product or single corporation. These reasons illustrate the capability and appropriateness of applying LCA in linear economy model, rather than CE model. As linear economy model ultimately associated with challenges such as resource scarcity, high waste management cost and environmental degradation, more and more countries are interested to learn as well as transitioning to embrace the CE model (Panchal et al., 2021).

A circular economy is a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops (Schröder et al., 2019). CE turns products at the end of their life cycle into resources for other stakeholders by: i) reuse and recycle what is still functional; ii) remanufacture, refurbish, and repurpose the components that cannot be repaired; iii) regenerate and redistribute what is processed (Stahel, 2016). Circular economy replaces the linear take, make, use, dispose production model and gives the economy itself the ability to create a positive value-driven closed loop (Hishammuddin et al., 2018). Even though the economic growth might be showing positive sign over the short-term using the linear economy model, as raw material supply and resources getting rare and decreases in quantity, the consequences of overlook the importance of sustainability will rebound back to the stakeholder. With the increasing uptake of the concept of circular economy in different industries, the feasibility of applying LCA in the assessment and evaluation of the circular economy model on environment remains unknown. Thus, this work aims to examine the relationship between the LCA application towards linear economy and circular economy. The applications of LCA on linear economy model in the past are reviewed to serve as the basic of the development of the CE-LCA framework, to improve the current LCA to capture the circularity elements in the Circular Economy model. Furthermore, the limitations, research gaps, as well as barriers of utilizing LCA to support Circular Economy strategies are also identified. It is worth highlighting that the CE-LCA framework aims to take in consideration of the circularity in terms of the whole system environment. Conventional LCA applies cut off rules and establish a clear system boundary within the product system. Cut off points were meant for processes that have a negligible contribution to the total impact. The integration of the circular economy principles in an industry or process is often not restricted to a particular stage or process, but rather a systemic change that initiate in design out waste and pollution, maximize the resources lifespan as well as to improve the efficiency in regenerating natural ecosystem. The conventional LCA method that applies cutoff rules and establish a clear system boundary restricts the comprehensive assessment of the impacts of a circular economy project. CE-LCA offers an expansion to include the not only the “circular” resources within the product system through reduction, reuse, recycled, repurposed, and remanufactured, but also the interconnections between different system boundary that contributes in waste management, pollution reduction and regeneration of natural systems.

The rest of the paper is structured as follows: Section 2 –Circular Economy – Life Cycle Assessment (CE-LCA) Framework; Section 3 - Limitations and barriers to utilize CE-LCA Framework for sustainable development; Section 4 - Overall Industry Perspective and Reaction and Section 5 - Conclusion and future works.

2. Circular Economy – Life Cycle Assessment (CE-LCA) Framework

CE-LCA framework is a framework where it broadens the scope of the conventional LCA to integrate the circularity of the resources within the system boundary to evaluate the overall environmental performance. It refrains the LCA from solely focusing on the micro side of supply chain to pay more attention to the macro side of the supply chain. All stakeholders in the ecosystem were involved as a part of a bigger whole in CE-LCA as compared to the conventional LCA approach that only focus on the stakeholder at the upstream of the supply chain (Azapagic and Clift, 1999). For example, the system boundary of conventional LCA only focus on single upper stream stakeholder, usually producer or manufacturer in the supply chain. It will evaluate and analyze the

environmental impacts generated based on unit processes in the product system and come out with recommendations that can reduce the negative impacts. This is not entirely accurate as it neglects the importance and values that might be offered by the other stakeholders within the supply chain. CE-LCA includes all stakeholders in the system boundary itself, thus focusing more on cooperative effort as well as "waste to food" initiative among stakeholders in the supply chain. CE-LCA Framework generates a concrete idea on how to improve the well-being of the ecosystem. It also includes the creation of a positive value-driven closed loop where all the stakeholders in the economy cooperate with each other in utilizing their resources efficiently and channel the unused or unutilized resources to the respective stakeholders.
As shown in the Figure I the generic CE-LCA Framework for palm oil industry. CE-LCA Framework enlarge the system environment of LCA to includes four different system boundaries that each has different set of unit processes. The system environment of LCA is enlarged to allows a comprehensive evaluation of the environmental performances of the palm oil industry, that includes environmental impacts, cost, consumer safety, and other aspects. By able to capture all the values of the inputs, outputs, and the recycle, remanufactured, and reuse resources within the circular economy model, it enables the optimization and the improvement of the overall process to maximize positive outcomes and minimize the negative impacts. In order to capture the value that is hidden or cut off from the usual input-output method used in the conventional LCA studies, Artificial Neural Network (ANN) method is integrated to the existing LCI and LCIA to capture the complex nonlinear relationship and circularity components within the system. ANN is capable to capture the multilayer perceptions (MLPs), that includes input, hidden, and output associated within the system (Park and Lek, 2016). The neurons in MLP are then trained with the back propagation learning algorithm to reveal the hidden opportunities and positive values that are not captured in the direct causal-impact relationship.

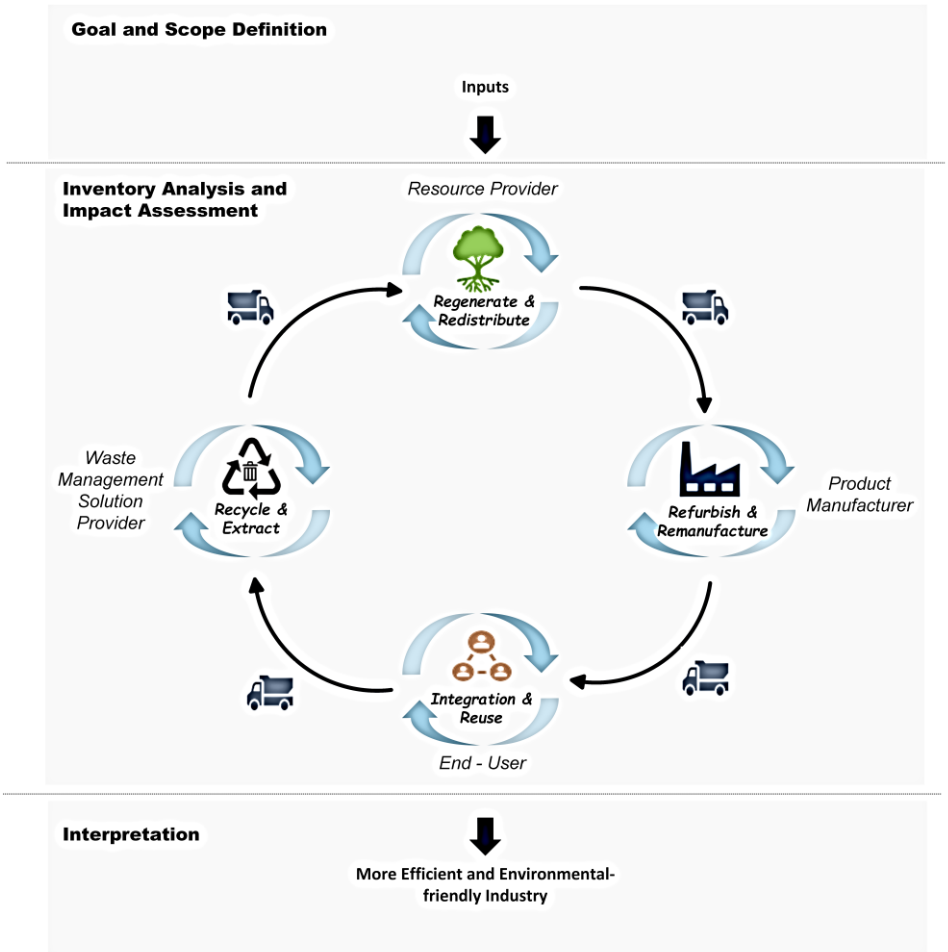

Figure 1: The generic CE-LCA Framework for Oil Palm Industry in Malaysia (own source)

Agriculture sector is one of the sectors that are less competitive in Malaysia. Most of the stakeholders in agriculture sector still prefers the linear economy model due to challenges in areas of cultural, structural, financial, and technical (Droege et al., 2021). Some examples will include low awareness of CE model, the absence of technical know-how knowledge to adapt changes, as well as unwillingness to invest huge capital into transforming their approach of doing business. Due to these reasons, the idea of CE is less popular, and negative impacts towards the ecosystem, especially environment and economic dimension had been accumulated for years. Malaysia is one of the world's leading producer of oil palm, and the palm oil industry is a notable contributor to the Malaysian agriculture sector. In 2019, the agriculture sector contributed 7.1 %, which totaled up to 101.5×10^9 RM to the Gross Domestic Product (GDP) in Malaysia and just the oil palm industry itself had contributed 37.7 % to the value added of agriculture sector (DOSM, 2020).

Oil palm industry generally comprised of several important stakeholders that includes Resource Provider (oil palm seedlings provider, agriculture landowner), Product Manufacturers (oil palm mills, fertilizer manufacturer), and End-user (manufactured product consumer). Most of the stakeholders are still using the linear economy approach, thus incurring negative impacts towards the industry itself over the long term. Waste had been accumulated for years within the supply chain and none of the stakeholders are taking initiatives to solve the issue. Some of the stakeholders play interchangeable role in the oil palm supply chain. For example, oil palm mills and fertilizer manufacturer, which both considered as Resource Provider and Product Manufacturer. Oil refineries produces a large amount of oily sludge during the process of crude oil refining, which the oily sludge is generally classified as hazardous waste (Yeo et al. 2020). Due to stricter regulation control, illegal dumping of such hazardous waste is no longer an option, and the method used by oil refinery currently is renting a huge area of land and dump all the oily sludge onto the ground, similar to landfill practice and certainly considered as unsustainable practice (Hou et al. 2013). This is where the idea of circularity mentioned in CE that includes the use of by-products from one production process as raw materials in another process. In this case, the waste of oil palm mills, which is the by-products of production process can be used as the food for fertilizer manufacturer. Fertilizer manufacturers had been using mineral deposits as well as fossil fuels, which is considered as non-renewable resource in fertilizer production in the past. It is proven that some of the raw materials can be replaced with residual biomass such as post-harvest residues as well as residues from production process (Chojnacka et al. 2019). As CE encourage renewable resources, it is possible to channel the waste of oil refinery as the food for fertilizer manufacturer, which in this case going through extensive process to remove the hazardous chemical residue in the oily sludge and add in some additional NPK (Nitrogen, Phosphorus, and Potassium) sources to create a sustainable source of fertilizers for crops. At the same time, it is possible that these fertilizers to be supplied back to the Resource Provider, which is the stakeholder that plants the oil palm trees that requires a constant supply of fertilizers to support the healthy growth of crops. CE-LCA offers a comprehensive evaluation in terms of cost, technology requirement, as well as the technical know-how knowledge to enhance the sustainability of the overall palm oil industry, through reduce the cost to manage the waste from the oil palm refinery and secure the sources for fertilizer manufacturer. It also shows a possibility in creating a positive value-driven closed loop in the oil palm supply chain. Further study can be conducted to understand the correlation and possible dependence between the stakeholders to apply the proposed CE-LCA framework to locate the best solution to achieve sustainability.

3. Limitations and barriers to utilize CE-LCA Framework for sustainable development

There are several limitations and barriers in order to utilize the CE-LCA Framework in supporting the circular economy initiatives and strategies. One of the biggest limitations would be how to address different sources and type of uncertainties that can lead to a better decision. Uncertainties, which also defined as the discrepancy between a measured or calculated quantity and the true value of the quantity, are often not considered critically in the conventional Life Cycle Assessment (LCA) studies, even though it is mentioned as a part of the Life Cycle Inventory analysis (LCI), Life Cycle Impact Assessment (LCIA), as well as Interpretation phase in ISO 14040 Framework (Finnveden et al., 2009). Since CE-LCA framework aims to illustrate the possibility of LCA application using a wider circular economy approach, it focuses on every stakeholder in the closed-loop circular supply chain. The closed loop supply chain works in a way that waste of the current stakeholder equals to food of the next stakeholder, which is one of the key concepts in Cradle-to-Cradle (C2C) design (De Pauw et al., 2013). As stakeholders involved in this cycle increases, information and data will increase, and automatically the uncertainties will increase. Therefore, it is very important to sort out effective methods to deal with the uncertainties.

Another barrier of CE-LCA framework will be that a closed-loop circular flow does not guarantee a sustainable outcome. For example, within the system boundary of the process known as "Recycle and Extract" stage, the increasing level of entropy that builds up during the process of recycling will certainly create waste and side-products that cannot be fully utilized or channeled back into the closed loop according to the second thermodynamics law (Georgescu-Roegen, 1971). It is also agreed that if the development of the physical scale of the total economic system is not checked, even the potential "positive value-driven close loop" can end up with unsustainable levels of resource depletion, pollution, and waste generation (Korhonen et al., 2018). It is very reasonable to avoid the situation above because if this situation happens, the negative environmental impact will be similar as that of the Linear Economy, and sustainable development cannot be achieved.

4. Overall Industry Perspective and Reaction

The awareness of the general public towards Circular Economy is considerably lower in developing countries compared developed countries. For example, in Malaysia, most of the stakeholders in agriculture industry chose to stick back to their former practice of linear economy model which is “take, make, use, dispose” model instead of embracing the circular economy as they think the additional capital investment in supporting circular economy initiatives is not worth the effort. These stakeholders usually put business profitability above all the other elements such as concern towards environment or social dimension in their decision-making process.

Bigger players in the economy such as big corporations and government linked companies were less likely willing to participate in circular economy initiatives especially in developing country because a modular governance approach at the level of policymaking is generally absent. Without clear direction as well the know-how knowledge, the ambiguity of facing the implementing actors on the ground will greatly increase. Corporation will be more likely to adapt to the change considered that a certain degree of modularity is built into the policy instruments that allows them to accommodate various implementing actors, encourage local experimentation, and at the same time ensure data collection for future use (Manning and Reinecked, 2016).

While that is the case for corporate players, the smaller players in general agriculture industry, the Small and Medium Enterprises (SMEs) thinks that their readiness in terms of capital as well as technology is both low compared to those of corporation. Given the government does not encourage and implement incentives to adapt to the new circular economy model and the forefront support of bigger corporate players, the SMEs are struggle and hesitant to adapt to a circular economy model that requires higher capital as well technology requirement, and certainly indicates higher risk for them. These stakeholders usually do not think out of the box of how circular economy model could generate more value and profit for them, over the long term.

Even though some of the SMEs realize that changes are inevitable and beneficial in the long term, SMEs tend to think that the role is too insignificant in supporting the changes and so remains the same. Due to this same reason, education as well as the awareness must be emphasized accordingly within the industry (Fan et al., 2021), particularly the government for being the forefront to embrace circular economy approach in their governing policy instruments.

5. Conclusions

The practicality and usefulness of Life Cycle Assessment (LCA) in understanding the inputs and outputs for different process or projects to enhance the overall performance is well recognized across the globe. Nonetheless, with the world transitioning to cleaner production and focus more on maximize the lifespan of resources to minimize the usage of virgin resources, it is imperative to expand the scopes of LCA to take in consideration of the circularity of the resources within the process as well. The proposed Circular Economy - Life Cycle Assessment (CE-LCA) framework expanded the existing LCA framework to include the circularity of resources in the inventory analysis and impact assessment stage. This can serve as a medium to ensure the application of LCA in support of circular economy initiatives and strategies, which is more and more popular nowadays. The potential challenges and limitations of CE-LCA are also addressed to prepare the respective stakeholders in enabling a successful transition toward circular economy. From this study, the possibilities to develop a more concrete CE-LCA Framework is feasible, considered that the limitations and barriers mentioned earlier can be solved.

Awareness among the general public in developing countries, especially in Malaysia is still considered low. Although there are quite a number of university seminars as well as industry talking and discussion over the years regarding the importance of circular economy as well as the application, it appears that there are still quite some research gaps between the actual industry action and implementation phase.

This work proposed a generic framework of CE-LCA to illustrate the potential and feasibility of applying LCA in circular economy model. By dwelling deeper into structuring the CE-LCA framework, there will be more challenges as well as opportunity to construct a more refined CE-LCA framework. The future work will be focused on customizing the CE-LCA for different industries, as different industries are associated with different system boundary to enhance the overall accuracy and effectiveness of the evaluation. Benchmarking studies can also be conducted to understand the current state of circular economy initiatives in developed nations and developing countries to educate and encourage more CE strategies and initiatives in developing countries. Software of CE-LCA can be developed to enhance the decision-making process of the different industry stakeholders in determining the resources used and process design for sustainable development.

Acknowledgements

The authors would like to thank Huachang Growmax (M) Sdn Bhd, and MPOB-UKM Endowment Chair [Grant number: EP-2020–027] for its partnership and funding of this research.

References

Azapagic A., Clift R., 1999. The application of life cycle assessment to process optimization. Computers of Chemical Engineering, 23, 1509-1526.

Chojnacka K., Moustakas K., Witek-Krowiak A., 2019. Bio-based fertilizers: a practical approach towards circular economy. Bioresource Technology, 122223.

De Pauw I., Karana E., Kandachar P., 2013. Cradle to Cradle in Product Development: A Case Study of Closed-Loop Design. In: Nee A., Song B., Ong S.K. (Eds), Re-Engineering Manufacturing for Sustainability, 47-52.

DOSM, 2020, Department of Statistics Malaysia, <www.dosm.gov.my >, assessed 30.05.2021.

Droege H., Raggi, A., Ramos, T.B., 2021. Overcoming Current Challenges for Circular Economy Assessment Implementation in Public Sector Organizations. Sustainability, 13, 1182.

Ellen MacArthur Foundation, 2013. Towards the Circular Economy, vol. 1. Cowes, Isle of Wight, UK.

Fan Y.V., Jiang P., Klemeš J.J., Liew P.Y., Lee C.T., 2021. Integrated regional waste management to minimise the environmental footprints in circular economy transition. Resources, Conservation and Recycling, 168, 105292.

Finkbeiner M., Inaba A., Tan R., Christiansen K., Klüppel H.-J., 2006. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. Int J Life Cycle Assessment, 11, 80–85.

Finnveden G., Hauschild M.Z., Ekvall T., Guinée J., Heijungs R., Hellweg S., Koehler A., Pennington D., Suh S., 2009. Recent developments in Life Cycle Assessment. Journal of Environmental Management, 91(1), 1-21.

Georgescu-Roegen N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge, MA, USA.

Graedel T.E., 1998. Streamlined Life-Cycle Assessment, Prentice Hall Inc., Upper Saddle River, New Jersey, USA, 310 p.

Guinée J.B., Udo de Haes H.A., Huppes G., 1993. Quantitative life cycle assessment of products. Journal of Cleaner Production, 1(1), 3-13.

Hishammuddin M.A.H., Ling G.H.T., Chao L.W., Ho C.S., Ho W.S., Idris A.M., 2018. Circular Economy (CE): A Framework towards Sustainable Low Carbon Development in Pengerang, Johor, Malaysia. Chemical Engineering Transactions, 63, 481-486.

Hou, B., Xie, S. X., Chen, M., Jin, Y., Hao, D., Wang, R. S., 2013. The Treatment of Refinery Heavy Oil Sludge, Petroleum Science and Technology, 31(5), 458-464.

Korhonen J., Honkasalo A., Seppälä J., 2018. Circular Economy: The Concept and its Limitations. Ecological Economics, 143, 37-46.

Lee S.G., Xu X., 2005. Design for the Environment: life cycle assessment and sustainable packaging issues. International Journal of Environmental Technology and Management, 5(1), 14-41.

Manning S., Reinecked J., 2016. A modular governance architecture in-the-making: How transnational standard-setters govern sustainability transitions. Research Policy, 45(3), 618-633.

Millar N., McLaughlin E., Börger T., 2019. The Circular Economy: Swings and Roundabouts? Ecological Economics, 158, 11-19.

Panchal R., Singh A., Diwan H., 2021. Does circular economy performance lead to sustainable development? – A systematic literature review. Journal of Environmental Management, 293, 112811.

Park Y.-S., Lek S., 2016. Artificial Neural Networks: Multilayer Perception for Ecological Modeling, In: Jorgensen S.E. (Ed.), Ecological Model Types. Elsevier, Amsterdam, Netherlands, 123-140.

Schröder P., Bengtsson M., Cohen M., Dewick P., Hoffstetter J., Sarkis J., 2019. Degrowth within – Aligning circular economy and strong sustainability narratives. Resources Conservation and Recycling, 146, 190-191.

Stahel W.R., 2016. The circular economy. Nature, 531, 435-438.

Yeo J.Y.J., How B.S., Teng S.Y., Leong W.D., Ng W.P.Q., Lim C.H., Ngan S.L., Sunarso J., Lam H.L., 2020. Synthesis of Sustainable Circular Economy in Palm Oil Industry Using Graph-Theoretic Method. Sustainability, 12, 8081.