Biofuel Research Journal 37 (2023) 1810-1815

Biofuel Research Journal

Journal homepage: www.biofueljournal.com

Perspective

Life cycle assessment for sustainability assessment of biofuels and bioproducts

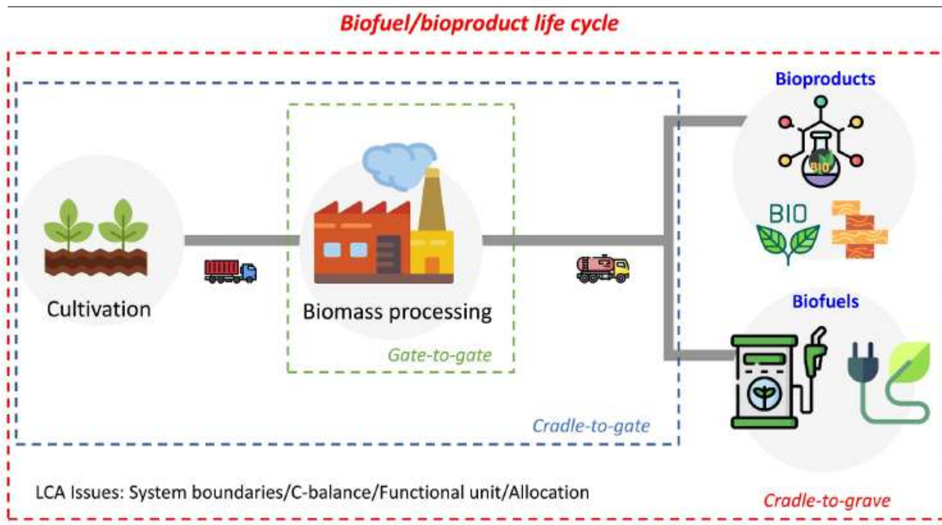
Shabbir H. Gheewala[1,2,3,4,*]

[1]*Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, 126 Prachauthit Rd., Bangmod, Tungkru, Bangkok 10140, Thailand.*
[2]*Center of Excellence on Energy Technology and Environment (CEE), Ministry of Higher Education, Science, Research and Innovation, Bangkok, Thailand.*
[3]*School of Postgraduate Studies, Diponegoro University, Semarang, Central Java 50241, Indonesia.*
[4]*Department of Environmental Sciences and Engineering, Gillings School of Global Public Health, University of North Carolina, Chapel Hill, NC 27514, USA.*

HIGHLIGHTS

- ➢Methodological challenges faced when applying life cycle assessment are critically discussed.
- ➢Life cycle assessment is essential to ensure the potential benefits of biofuels and bioproducts.
- ➢Biorefineries can enhance the environmental performance of biofuels and bioproducts.
- ➢Balancing carbon emissions from a life cycle perspective needs dynamic assessment.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 December 2022
Received in revised form 21 February 2023
Accepted 23 February 2023
Published 1 March 2023

Keywords:
Biofuel
Biomaterial
Biorefinery
Greenhouse gas
Life cycle assessment
Sustainable development

ABSTRACT

Bio-based materials have been used traditionally for millennia. Their use was overtaken in recent times by the discovery and utilization of fossil-based resources for materials and energy. However, concerns about the non-renewability of fossil resources and greenhouse gas and other emissions associated with their use have brought forth a renewed interest in using bio-based materials in recent years. The environmental advantages of bio-based materials cannot be taken for granted without a rigorous scientific assessment. Many tools based on energy, economics, and environmental impacts have been used. Life cycle assessment is one such tool developed and successfully utilized for the environmental assessment of biofuels and bioproducts. However, many methodological challenges, among other things related to system boundaries, functional units, allocation, and carbon accounting, still need further research and consideration. In this work, the related issues are summarized, and the directions for addressing them are discussed. Despite the methodological challenges in their assessment, biofuels and bioproducts show promise in terms of their environmental advantages compared to their fossil-oriented counterparts. These advantages can be further enhanced by utilizing all parts of the feedstock biomass, especially for value-added materials and chemicals *via* biorefineries.

* Corresponding author at: Tel.: +66 2470 8309-10 (ext.: 4139)
E-mail address: shabbir.ghe@kmutt.ac.th; shabbirg@hotmail.com

Please cite this article as: Gheewala S.H. Life cycle assessment for sustainability assessment of biofuels and bioproducts. Biofuel Research Journal 37 (2023) 1810-1815. DOI: 10.18331/BRJ2023.10.1.5

Contents

1. Introduction....1811
2. Why biofuels?....1811
3. Assessment tools for biofuels and bioproducts....1811
4. LCA of biofuels and bioproducts....1812
5. Quo vadis?....1812
6. Concluding remarks and future perspectives....1813
Acknowledgments....1813
References....1813

1. Introduction

Energy, along with food and shelter, is one of the necessities of life. Procuring food and shelter also requires energy for agriculture, infrastructure development, and comfort. Directly or indirectly, all energy on the planet is ultimately from the sun. Traditionally, energy has been provided by biomass but with inefficient transformation resulting in excessive use of natural resources and environmental pollution, particularly related to air quality. Fossil fuels, such as coal, oil, and natural gas, are high-quality energy carriers developed naturally over millennia in the Earth's crust from biomass (dead plants and animals). However, the increased use of fossil fuels following the industrial revolution has resulted in many environmental problems, the most prominent of which in recent times has been the accumulation of climate change-inducing greenhouse gases in the atmosphere to levels that, if unchecked, may lead to irreversibly disastrous consequences (IPCC, 2021).

Fossil fuels have contributed more to anthropogenic carbon dioxide emissions than all other sources combined; a recent report shows that fossil fuels contributed more than half the global carbon dioxide emissions in 2020 (UNDP, 2021). The small decrease in fossil fuel utilization in the last couple of years due to the pandemic has already been reversed. The unequal distribution of fossil energy resources has also been a cause of much concern in terms of national energy security, even at times leading to war. Conversely, wars have also disrupted the supply of energy resources leading to energy crises. *The limits to growth* report published in 1972 by the Club of Rome (Meadows et al., 1972) cautioned about the limited reserves of fossil fuels and the limits to the capacity of our planet to absorb the byproducts from burning them for energy. A revisit 30 years later confirmed the warnings with more updated data and modeling (Meadows et al., 2004). A more recent 50-year update has reconfirmed the main messages from the initial report (Bardi and Pereira, 2022).

Biomass has been used for energy since humans first learned to make fire. Using biomass for non-traditional uses beyond wood for cooking and heating is also not new. The early diesel engines in the late nineteenth and early twentieth centuries were tested with vegetable oils by the inventor of the diesel engines himself. However, the high production of low-cost petroleum-based fuels outcompeted the use of vegetable oils. Occasionally, there has been a comeback towards bio-based fuels in times such as the energy crisis of the 1970s. However, these periods have not lasted long enough for bio-based fuels to gain traction at a more sustained level. Once the crisis is over and fossil fuel prices become attractive again, the enthusiasm for promoting bio-based fuels is lost. A notable exception has been the National Alcohol Program (*Pró-Álcool*) of Brazil. Initiated in 1975 as a response to the 1973 oil crisis, Brazil started to partially replace gasoline in automobiles with ethanol from sugarcane. Subsidiaries of some carmakers in Brazil also developed the so-called flexible-fuel vehicles, which could run on high blends of ethanol with gasoline or even on 100% ethanol. Brazil has consistently supported the sugar and ethanol industry over the last 50 years and is currently the world's second-largest producer and largest exporter of ethanol. At a global level, there has been a resurgence in the use of biofuels since the early twenty-first century. This has been even more so for developing countries with agro-based economies. The current war in Ukraine brings to the forefront the dependence on oil and the need for energy independence (Shams Esfandabadi et al., 2022).

2. Why biofuels?

Biofuels, liquid transportation fuels made from biomass sources, have been attractive for various reasons. One is the use of locally-produced, renewable resources that can reduce dependence on oil which needs to be imported by most countries in the world. This helps both increase energy security by reducing dependence on imports and energy diversity, leading to improved resilience (Kruyt et al., 2009). There is also the idea of carbon neutrality since the carbon stored in the biomass, which is released as carbon dioxide when the biofuels are combusted, is balanced by the carbon dioxide taken up by the biomass from the atmosphere by photosynthesis during its growth. Promoting fuels based on biomass is also hoped to stabilize farmers' income, who are often the weakest players in the entire supply chain of agriculture and agro-based products. The perceived sustainability benefits of biofuels have made them attractive to policymakers in many countries, especially agriculture-based developing countries (Gheewala et al., 2013 and 2018).

The sustainability advantages of biofuels have also been challenged due to various conditions and constraints in practice, which may negate the desired benefits. The apparent carbon neutrality mentioned above is certainly not maintained when considering the entire life cycle of biofuel production and use (Gheewala, 2021). Nevertheless, that does not automatically mean there can be no advantage vis-à-vis greenhouse gas emissions reduction compared to fossil fuels. Many studies have shown that the greenhouse gas emissions from biofuels can be lower than their fossil fuel counterparts provided that there are not too many fossil fuels (especially coal) being used in the biofuel supply chain and high carbon stock land such as forests are not converted to agriculture for planting the biofuels feedstock (Silalertruksa and Gheewala, 2012). However, the issues of land use change (LUC) can get very complicated (Prapaspongsa and Gheewala, 2017), particularly when including indirect LUC in the accounting (Brandão et al., 2022).

3. Assessment tools for biofuels and bioproducts

Many tools have been used to assess the sustainability of biofuels and bioproducts. The most preliminary one is energy analysis based on the first law of thermodynamics; two commonly used indicators are net energy balance and net energy ratio (Gheewala, 2013). These can be used as a first check for biofuels; if the total energy obtained from them is lower than the input energy throughout their life cycle, producing them makes little sense. A more refined indicator is 'renewability', which considers only the life cycle input of fossil energy; in this case, if the energy output from the biofuels is lower than the fossil energy input, it indicates producing more renewable energy *via* the biofuel by investing a lower amount of fossil energy in the production chain. A more sophisticated tool is exergy analysis, which includes the second law of thermodynamics that considers energy quality and quantity. Exergy analysis has been successfully used to identify the thermodynamic inefficiencies of energy systems (Sciubba, 2001; Soltanian et al., 2020). It has also been combined with life cycle assessment (LCA) to provide exergoenvironmental and exergoeconomic assessment (Aghbashlo and Rosen, 2018a; Aghbashlo et al., 2021).

Another concept somewhat similar to the idea of exergy but also taking into account Earth's processes, such as wind, river flow, waves, etc., is emergy (Hau and Bakshi, 2004). This is an ecocentric valuation method based on thermodynamics that can account for non-market inputs in an objective manner. It includes the contribution of natural capital to the economy. However, calculating the emergy of stored natural resources such as minerals and fossil fuels is fraught with conceptual challenges; knowing all solar energy inputs over geological time scales is very difficult. Even the meaning of doing so is difficult to grasp in physical terms. Also, it does not directly include impacts due to environmental emissions. Recent attempts have combined this with LCA to perform exergoeconomic and exergoenvironmental analyses (Aghbashlo and Rosen, 2018b). An excellent summary of all these tools is provided by Aghbashlo et al. (2022).

The present paper focuses on LCA, which is an internationally standardized method for the assessment of environmental impacts throughout the life cycle of a product or service.

4. LCA of biofuels and bioproducts

LCA has often been used to assess the environmental implications of transportation fuels, particularly for comparing biofuels with their fossil counterparts. As it considers the entire life cycle of fuels, the tool avoids the issues of problem shifting between life cycle stages (Gheewala, 2021). Also, as it considers multiple impact categories, problem shifting between different impacts is resolved. As mentioned in *Section 2*, the apparent carbon neutrality based on the balance between the carbon dioxide uptake during photosynthesis and carbon dioxide released during biofuel combustion is questionable when the greenhouse gas emissions during agriculture, processing, and transportation of the fuels are considered. However, even the LCA application has challenges (Hosseinzadeh-Bandbafha et al., 2021). The setting of an appropriate framework, attributional or consequential, depending on the objective of the study is one of them (Zamagni et al., 2012; Prapaspongsa and Gheewala, 2017).

Attributional LCA is used for quantifying the current environmental burdens of biofuels and bioproducts across the entire life cycle with an aim to identify the hotspots and strategies to minimize the burdens. The results can be used for comparison with their fossil counterparts as well as to support decision-making for producers, consumers, and policymakers. Consequential LCA, on the other hand, evaluates the changes in environmental burdens occurring as a result of policies and decisions related to biofuels and bioproducts promotion. This often entails the inclusion of economic models to calculate the economy-wide effects of policy decisions (Panichelli and Gnansounou, 2017).

LUC, particularly indirect LUC, presents special challenges (Brandão et al., 2022). However, this is a very important issue with serious consequences on the sustainability of biofuels and bioproducts. Another challenge is the setting up of system boundaries, *viz.*, cradle-to-grave, cradle-to-gate, and gate-to-gate, which is, of course, dependent on the goal of the study. Cradle-to-grave studies include the entire life cycle starting from the cultivation of the biomass feedstock for biofuels or bioproducts, transformation of the biomass to the product, use, and final disposal in case of bioproducts. Cradle-to-gate studies are often used, for example, when comparing biofuels or bioproducts from different feedstocks. Gate-to-gate studies may be used when focusing on a particular novel transformation process.

The choice of a functional unit for comparing systems can also influence results, for example, leading to differences in results when bioenergy is compared based on the energy of outputs or a per-hectare basis (Choudhary et al., 2014). Functional units based on energy content or driving distance are used for cradle-to-grave studies, whereas cradle-to-gate studies are generally based on mass or volume. Where feedstock utilization is of primary concern, a land area-based functional unit may be used. As biomass systems are most often associated with co-products both at the cultivation and processing stages, allocation of environmental burdens also poses a challenge. ISO 14044 recommends avoiding allocation through sub-division of the unit process or system expansion; both can present difficulties in practice. Sub-division of the unit process is often not possible, and system expansion to include alternative products requires the identification of the alternative products for substituting the co-products, which is not always practically possible. Partitioning *via* mass, energy, and/or economic allocation can lead to many variations in results, making comparing systems or different studies difficult (Bezergianni and Chrysikou, 2020; Hosseinzadeh-Bandbafha et al., 2021). The issues related to the LCA of biofuels and bioproducts are summarized in **Figure 1**. Collecting accurate and representative data is a challenge in LCA in general, leading to uncertainties; in particular for bio-based energy and materials, the issue of including carbon storage and accounting for the time lag between carbon dioxide update and emissions must be addressed (Levasseur et al., 2010; Martin-Gamboa et al., 2020). Temporal representativeness and uncertainty can significantly affect the results, with the amortization period of LUC being a case in point (Maciel et al., 2022).

Apart from the issue of greenhouse gas emissions, which is currently at the forefront of any discussion, especially for biofuels, is the issue of water, which is quite critical. Although we have enough freshwater resources in the world to fulfill all our current needs, the distribution of these resources, both spatially and temporally, is a major concern for agriculture (Gheewala et al., 2011). Climate change is anticipated to further exacerbate this issue (OECD, 2014). Not including this in the consideration can lead to unintended negative effects. Food-energy-water nexus studies are proposed, including land use and biodiversity considerations for accounting for the interactions among related issues, which should be looked at together rather than in isolation (FAO, 2014; Jaroenkietkajorn and Gheewala, 2021; Gazal et al., 2022). Although positive impacts have been reported for the employment generation in the agriculture sector and rural livelihoods (Silalertruksa et al., 2012; Chaya and Gheewala, 2022), there have also been several issues associated with negative impacts on the land tenure of farmers (Cotula et al., 2008; Cudlínová et al., 2020).

The sustainability assessment of biofuels has thus yielded mixed results. The important lesson, though, is to be aware of the potential pitfalls so that the intended sustainability benefits of biofuels can be maintained. First is the use of life cycle-based tools for assessing the sustainability of biofuels (Sala, 2020; Stamford, 2020; Gheewala, 2021). The generic options for improvement at every stage of the biofuel lifecycle include using green chemistry at the research and development stage, good agricultural practices at the cultivation stage, and efficient production and logistics (Sala, 2020). Proper and coherent policy frameworks need to be developed, which will give confidence to the stakeholders, particularly the industry, in pursuing long-term commitments towards biofuel production. If policies frequently change with changes in government or world markets, then the industry is not confident in making investments. The example of Brazil mentioned earlier is a good case to follow. Vulnerable groups need to be protected both in terms of food and energy security. Agricultural productivity needs to be focused on to avoid food *vs.* fuel conflicts and for the efficient and sustainable utilization of natural resources such as land and water. This will also reduce feedstock costs, the major contributor to biofuel prices. Good practices in agriculture to avoid deterioration of soil quality and protect biodiversity are also important. Forest and other high carbon stock lands should not be converted directly or indirectly for biofuel feedstock production. Innovation in biofuel production (for example, advanced biofuels) need to be continually promoted. The optimal utilization of biomass residues via the so-called biorefineries is also important for resource and energy-efficient biofuel and bioproducts production (Gheewala, 2019). Thailand, for example, has been promoting the so-called Bio-Circular-Green Economy (BCG) model, which emphasizes the utilization of biomass for energy and materials, particularly value-added products, to help transition to a circular economy and address some of the United Nations' Sustainable Development Goals (SDGs).

5. Quo vadis?

Promoting a bio-based economy is being pursued as a way forward to address many of the societal challenges, such as food security, natural resource scarcity, fossil resource dependence, and climate change while achieving sustainable economic growth. The United Nations' SDGs also target all these issues. The directly concerned SDG is Goal 7, which concerns affordable and clean energy for all; however, each of the 17 SDGs is also linked (Sala, 2020). Biofuels will also play a key role in the transition to net zero carbon dioxide emissions by 2050, as energy contributes almost three-fourths of the total greenhouse gas emissions (IEA, 2021). The production of biofuels could be quadrupled in the next decade and, combined with carbon capture and storage (BECCS), would substantially contribute to the efforts towards next zero carbon dioxide emissions. The Conference of the Parties (COP) set up by the United Nations Framework Convention on Climate Change (UNFCCC) has been grappling with this issue. The COP26 in Glasgow last year finalized the Paris Agreement from the year before to accelerate action on climate change through mitigation of greenhouse gas emissions to keep alive the goal of limiting the global temperature increase within 1.5°C. Phasing down coal power was one of the major thrusts. The recently concluded COP27 in Sharm El-Sheikh highlighted climate finance and adaptation as key strategies moving forward. Recent regional assessments, for example, in Southeast Asia, have also underlined the contribution of biofuels in the energy transition (IRENA, 2022; ACE, 2020; ACE, 2022). All this will require sustained effort and political will to transform aspirations into action. We should not wait for wars or energy crises to seek what is clearly within reach and sensible action toward a sustainable future. Handled properly, biofuels, though not a silver bullet or the major energy carriers, can still play an

Please cite this article as: Gheewala S.H. Life cycle assessment for sustainability assessment of biofuels and bioproducts. Biofuel Research Journal 37 (2023) 1810-1815. DOI: 10.18331/BRJ2023.10.1.5

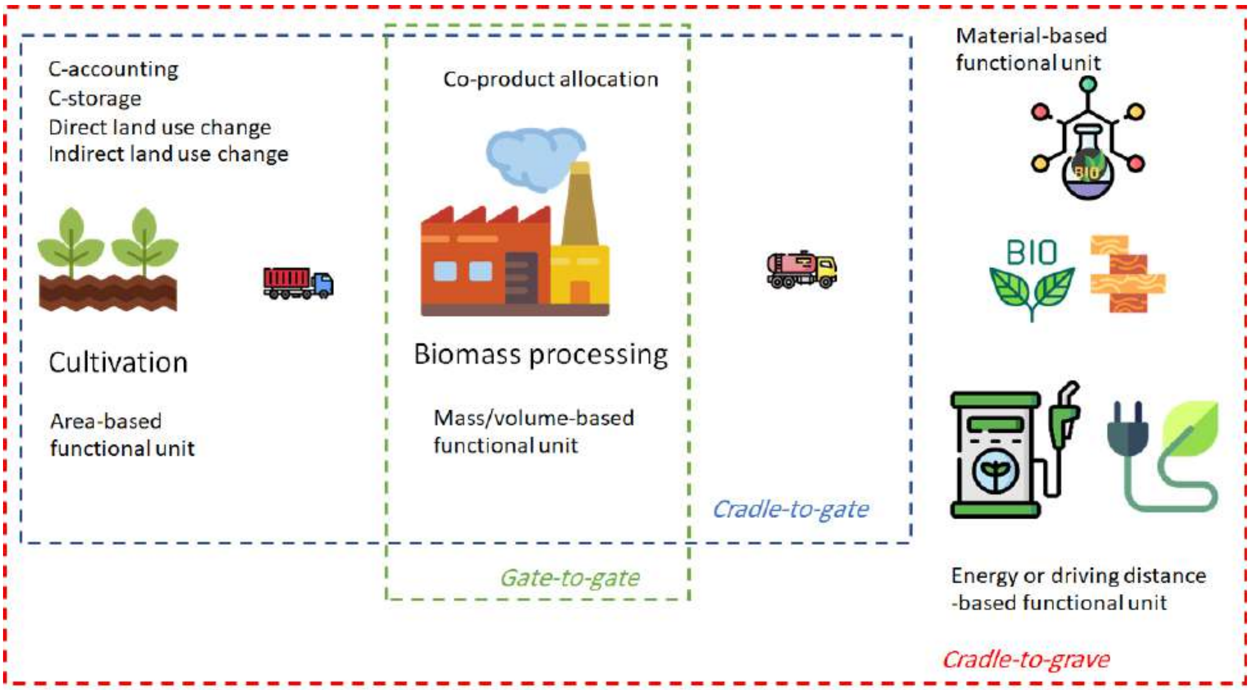


Fig. 1. Methodological issues in life cycle assessment of biofuels and bioproducts.

important role in a sustainable energy transition towards net zero. Also, combining value-added biomaterials with biofuels in biorefineries would make the production profitable and more environmentally friendly and stabilize the security of both bio-based energy and materials (Gheewala, 2019; Gheewala et al., 2022).

In assessing biofuels and bioproducts, LCA has been seen to be very useful though some methodological issues need to be resolved. Proper accounting of carbon/greenhouse gas emissions using a standardized framework and product category rules could at least help to harmonize the results, ensuring consistency in comparison. A more accurate representation of the actual situation could be obtained using regionalized data and assessment methods (O'Keeffe et al., 2016). Including uncertainty analysis would make the assessment results more meaningful, as uncertainties are inherent in all real systems (Mahmood et al., 2022). The temporal considerations in dealing with the carbon calculations for biofuels and bioproducts could be addressed *via* dynamic LCA (Levasseur et al., 2013; Beloin-Saint-Pierre et al., 2020). Tools for doing so have also been recently developed (Pigné et al., 2020).

6. Concluding remarks and future perspectives

Biofuels and bioproducts, especially *via* biorefineries, can offer many environmental advantages compared to their fossil counterparts, provided certain conditions are maintained. These favorable conditions can be identified by using assessment tools based on energy, exergy, emergy, LCA, or a combination of these, which also help improve the systems in the future. LCAs are particularly useful as they highlight and thus help avoid problem-shifting between the various production stages and environmental impact categories. However, as with all real-world systems, assessing bio-based systems is also complicated, with many methodological challenges. In LCAs of biofuels and bioproducts, there are challenges with system boundary definition, functional units, allocation methods, carbon accounting and storage, inventory data collection, and impact assessment methods. Despite these challenges, LCA provides a useful tool for the environmental assessment of biofuels and bioproducts. Its wide use for various products allows for comparison between product systems within a study and also from the literature, though care must be taken to ensure methodological consistency when making comparisons with studies from the literature, which may have been done with a different goal and scope. There have continually been methodological developments to address the issues, such as dynamic carbon accounting and life cycle impact assessment, with methods getting increasingly sophisticated and accurate. As more environmental impacts are identified, methods for the assessment are also being developed and updated. Tools such as sensitivity analysis and uncertainty analysis add to the robustness of the assessment so that decisions can be better supported.

Acknowledgements

The author would like to acknowledge the financial support from the National Research Council of Thailand *via* the Research Team Promotion Grant "Moving towards carbon neutrality and sustainability of food, feed, fuel through BCG using life cycle thinking".

References

[1] ACE, 2020. The 6th ASEAN Energy Outlook (AEO6), ASEAN Centre for Energy (ACE). Jakarta.

[2] ACE, 2022. The 7th ASEAN Energy Outlook (AEO7), ASEAN Centre for Energy (ACE). Jakarta.

[3] Aghbashlo, M., Hosseinzadeh-Bandbafha, Shahbeik, H., Tabatabaei, M., 2022. The role of sustainability assessment tools in realizing bioenergy and bioproduct systems. Biofuel Res. J. 35, 1697-1706.

[4] Aghbashlo, M., Khounani, Z., Hosseinzadeh-Bandbafha, H., Gupta, V.K., Amiri, H., Lam, S.S., Morosuk, T., Tabatabaei, M., 2021. Exergoenvironmental analysis of bioenergy systems: a comprehensive review. Renew. Sust. Energy Rev. 149, 111399.

[5] Aghbashlo, M., Rosen, M.A., 2018a. Exergoeconoenvironmental analysis as a new concept for developing thermodynamically, economically, and environmentally sound energy conversion systems. J. Clean. Prod. 187, 190-204.

[6] Aghbashlo, M., Rosen, M.A., 2018b. Consolidating exergoeconomic and exergoenvironmental analyses using the emergy concept for better understanding energy conversion systems. J. Clean. Prod. 172, 696-708.

[7] Bardi, U., Pereira, C.A. (Eds.), 2022. Limits and Beyond: 50 years on from The Limits to Growth, what did we learn and what's next?.A Report to the Club of Rome. Exapt Press.

Please cite this article as: Gheewala S.H. Life cycle assessment for sustainability assessment of biofuels and bioproducts. Biofuel Research Journal 37 (2023) 1810-1815. DOI: 10.18331/BRJ2023.10.1.5

[8] Beloin-Saint-Pierre, D., Albers, A., Hélias, A., Tiruta-Barna, L., Fantke, P., Levasseur, A., Benetto, E., Benoist, A., Collet, P., 2020. Addressing temporal considerations in life cycle assessment. Sci. Total Environ. 743, 140700.
[9] Bezergianni, S., Chrysikou, L.P., 2020. Chapter 17-Application of life-cycle assessment in biorefineries. Waste Biorefin. Elsevier. 455-480.
[10] Brandão, M., Heijungs, R., Cowie, A.R., 2022. On quantifying sources of uncertainty in the carbon footprint of biofuels: crop/feedstock, LCA modelling approach, land-use change, and GHG metrics. Biofuel Res. J. 9(2), 1608-1616.
[11] Chaya, W., Gheewala, S.H., 2022. Sustainable livelihood outcomes, causal mechanisms and indicators self-determined by Thai farmers producing bioethanol feedstocks. Sustainable Prod. Consumption. 29, 447-466.
[12] Choudhary, S., Liang, S., Cai, H., Keoleian, G. A., Miller, S.A., Kelly, J., Xu, M., 2014. Reference and functional unit can change bioenergy pathway choices. Int. J. Life Cycle Assess. 19, 796-805.
[13] Cotula, L., Dyer, N., Vermeulen, S., 2008. Fuelling exclusion?.the biofuels boom and poor people's access to land. London: LIED.
[14] Cudlínová, E., Sobrinho, V.G., Lapka, M., Salvati, L., 2020. New forms of land grabbing due to the bioeconomy: the case of Brazil. Sustainability. 12(8), 3395.
[15] FAO, 2014. The water-energy-food nexus: a new approach in support of food security and sustainable agriculture. United Nations Food and Agriculture Organization, Rome.
[16] Gazal, A.A., Jakrawatana, N., Silalertruksa, T., Gheewala, S.H., 2022. Water-energy-food nexus review for biofuels assessment. Int. J. Renewable Energy Dev (IJRED). 11(1), 193-205.
[17] Gheewala, S.H., 2021. Life cycle thinking in sustainability assessment of bioenergy systems. E3S Web Conf. 277, 01001.
[18] Gheewala, S.H., 2019. Biorefineries for sustainable food-fuel-fibre production: towards a circular economy. E3S Web Conf. 125, 01002.
[19] Gheewala, S.H., 2013. Environmental sustainability assessment of ethanol from cassava and sugarcane molasses in a life cycle perspective, in: Singh, A., Olsen, S.L., Pant, D. (Eds.), Life Cycle Assess. Renewable Energy Sources. Springer. 131-143.
[20] Gheewala, S.H., Berndes, G., Jewitt, G., 2011. The bioenergy and water nexus. Biofuels, Bioprod. Biorefin. 5(4), 353-360.
[21] Gheewala, S.H., Jaroenkietkajorn, U., Nilsalab, N., Silalertruksa, T., Somkerd, T., Laosiripojana, N., 2022. Sustainability assessment of palm oil-based refinery systems for food, fuel and chemicals. Biofuel Res. J. 36, 1750-1763.
[22] Gheewala, S.H., Kittner, N., Shi, X., 2018. Costs and benefits of biofuels in Asia, in: Bhattacharyya, S.C. (Ed.), Routledge handbook of energy in Asia. Taylor and Francis, pp. 363-376.
[23] Gheewala, S.H., Damen, B., Shi, X., 2013. Biofuels: economic, environmental and social benefits and costs for developing countries in Asia. Wiley Interdiscip. Rev. Clim. Change. 4(6), 497-511.
[24] Hau, J.L., Bakshi, B.R., 2004. Promise and problems of emergy analysis. Ecol. Modell. 178(1-2), 215-225.
[25] Hosseinzadeh-Bandbafha, H., Aghbashlo, M., Tabatabaei, M., 2021. Life cycle assessment of bioenergy product systems: a critical review. e-Prime Adv. Electr. Eng. Electron. 1, 100015.
[26] IEA (2021), Global Energy Review 2021, IEA, Paris.
[27] IPCC, 2021. Summary for policymakers. In climate change 2021: the physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (Eds.). Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.
[28] IRENA, 2022. Scaling up biomass for the energy transition: Untapped opportunities in Southeast Asia, International Renewable Energy Agency, Abu Dhabi.
[29] Jaroenkietkajorn U., Gheewala, S.H., 2021. Understanding the impacts on land use through GHG-Water-Land-Biodiversity nexus: the case of oil palm plantations in Thailand. Sci. Total Environ. 800, 149425.
[30] Kruyt, B., van Vuuren, D.P., de Vries, H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Policy. 37(6), 2166-2181.
[31] Levasseur, A., Lesage, P., Margni, M., Deschenes, L., Samson, R., 2010. Considering time in LCA: dynamic LCA and its application to global warming impact assessments. Environ. Sci. Technol. 44(8), 3169-3174.
[32] Levasseur, A., Lesage, P., Margni, M., Samson, R., 2013. Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. J. Ind. Ecol. 17(1), 117-128.
[33] Maciel, V.G., Novaes, R.M.L., Brandão, M., Cavalett, O., Pazianotto, R.A.A., Garofalo, D.T., Folegatti-Matsuura, M.I., 2022. Towards a non-ambiguous view of the amortization period for quantifying direct land-use change in LCA. Int. J. Life Cycle Assess. 27(12), 1299-1315.
[34] Mahmood, A., Varabuntoonvit, V., Mungkalasiri, J., Silalertruksa, T., Gheewala, S.H., 2022. A tier-wise method for evaluating uncertainty in life cycle assessment. Sustainability. 14(20), 13400.
[35] Martin-Gamboa, M., Marques, P., Freire, F., Arroja, L., Dias, A.C., 2020. Life cycle assessment of biomass pellets: a review of methodological choices and results. Renew. Sust. Energy Rev. 133, 110278.
[36] Meadows, D., Randers, J., Meadows, D., Behrens III, W.W., 1972. The Limits to Growth; A Report for the Club of Rome's Project on the Predicament of Mankind, New York: Universe Books.
[37] Meadows, D., Randers, J., 2012. Limits to growth: the 30-year update. Routledge.
[38] OECD, 2014. Climate Change, Water and Agriculture: Towards Resilient Systems, OECD Studies on Water, OECD Publishing.
[39] O'Keeffe, S., Wochele-Marx, S., Thrän, D., 2016. RELCA: a REgional life cycle inventory for assessing bioenergy systems within a region. Energy Sustainability Soc. 6(1), 1-19.
[40] Panichelli, L., Gnansounou, E., 2017. Modeling land-use change effects of biofuels policies: coupling economic models and LCA. Elsevier. 233-258.
[41] Pigné, Y., Gutiérrez, T.N., Gibon, T., Schaubroeck, T., Popovici, E., Shimako, A.H., Benetto, E., Tiruta-Barna, L., 2020. A tool to operationalize dynamic LCA, including time differentiation on the complete background database. Int. J. Life Cycle Assess. 25, 267-279.
[42] Prapaspongsa, T., Gheewala, S.H., 2017. Consequential and attributional environmental assessment of biofuels: Implications of modelling choices on climate change mitigation strategies. Int. J. Life Cycle Assess. 22, 1644-1657.
[43] Sala, S., 2020. Chapter 3-Triple bottom line, sustainability and sustainability assessment, an overview. Biofuels for a More Sustainable Future. Elsevier. 44-72.
[44] Sciubba, E., 2001. Beyond thermoeconomics? The concept of extended exergy accounting and its application to the analysis and design of thermal systems. Exergy, Int. J. 1, 68-84.
[45] Shams Esfandabadi, Z., Ranjbari, M., Scagnelli, S.D., 2022. The imbalance of food and biofuel markets amid Ukraine-Russia crisis: a systems thinking perspective. Biofuel Res. J. 9(2), 1640-1647.
[46] Silalertruksa, T., Gheewala, S.H., 2012. Food, fuel and climate change: is palm-based biodiesel a sustainable option for Thailand?. J. Ind. Ecol. 16(4), 541-551.
[47] Silalertruksa, T., Gheewala, S.H., Hünecke, K. Fritsche, U.R., 2012. Biofuels and employment effects: implications for socio-economic development in Thailand. Biomass Bioenergy. 46, 409-418.
[48] Stamford, L., 2020. Chapter5-Life cycle sustainability assessment in the energy sector. Biofuels for a More Sustainable Future. Elsevier. 115-163.
[49] Soltanian, S., Aghbashlo, M., Almasi, F., Hosseinzadeh-Bandbafha, H., Nizami, A.S., Ok, Y.S., Lam, S.S., Tabatabaei, M., 2020. A critical review of the effects of pretreatment methods on the exergetic aspects of lignocellulosic biofuels. Energy Convers. Manage. 212, 112792.
[50] United Nations Environment Programme, 2021. Emissions gap report 2021: the heat is on-a world of climate promises not yet delivered. Nairobi.
[51] Zamagni, A., Guinée, J., Heijungs, R., Masoni, P., Raggi, A., 2012. Lights and shadows in consequential LCA. Int. J. Life Cycle Assess. 17, 904-918.

Please cite this article as: Gheewala S.H. Life cycle assessment for sustainability assessment of biofuels and bioproducts. Biofuel Research Journal 37 (2023) 1810-1815. DOI: 10.18331/BRJ2023.10.1.5

Shabbir H. Gheewala is a full Professor and Head of the Life Cycle Sustainability Assessment Laboratory (LCSAL) at the Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology Thonburi (KMUTT), Thailand, where he teaches Life Cycle Assessment and heads the Life Cycle Sustainability Assessment Lab for over 20 years. He is also an adjunct professor at the University of North Carolina, Chapel Hill, USA and Diponegoro University, Indonesia. His research focuses on the sustainability assessment of energy systems; sustainability indicators; circular economy; and certification issues in biofuels and agro-industry. He has co-authored over 300 peer-reviewed journal papers and is listed in the top 1% of highly cited academics worldwide in the field of earth and environmental sciences. Shabbir H. Gheewala`s research profile can be found at the following link: https://scholar.google.com/citations?user=Tdv7AxIAAAAJ&hl=en

Please cite this article as: Gheewala S.H. Life cycle assessment for sustainability assessment of biofuels and bioproducts. Biofuel Research Journal 37 (2023) 1810-1815. DOI: 10.18331/BRJ2023.10.1.5