



Review Paper

# The role of sustainability assessment tools in realizing bioenergy and bioproduct systems

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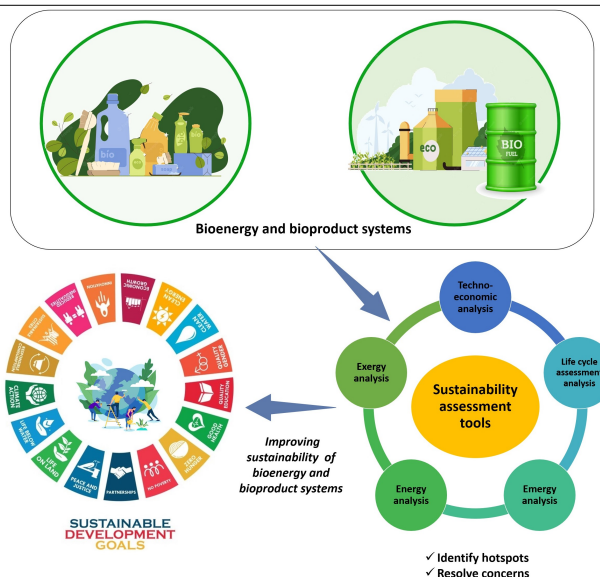
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## HIGHLIGHTS

- Sustainability assessment tools in the context of bioenergy and bioproduct are critically reviewed.
- The pros and cons of various sustainability assessment tools are highlighted to guide future research.
- There is no perfect tool that address all the sustainability issues of bioenergy and bioproduct systems.
- Integration of sustainability tools can provide more reliable and accurate results than single approaches.
- Exergy-based analyses can outperform other sustainability tools in providing more informative indicators.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The pressing global challenges, including global warming and climate change, the Russia-Ukraine war, and the Covid-19 pandemic, all are indicative of the necessity of a transition from fossil-based systems toward bioenergy and bioproduct to ensure our plans for sustainable development. Such a transition, however, should be thoroughly engineered, considering the sustainability of the different elements of these systems. Advanced sustainability tools are instrumental in realizing this important objective. The present work critically reviews these tools, including techno-economic, life cycle assessment, energy, energy, and exergy analyses, within the context of the bioenergy and bioproduct systems. The principles behind these methods are briefly explained, and then their pros and cons in designing, analyzing, and optimizing bioenergy and bioproduct systems are highlighted. Overall, it can be concluded that despite the promises held by these tools, they cannot be regarded as perfect solutions to address all the issues involved in realizing bioenergy and bioproduct systems, and integration of these tools can provide more reliable and accurate results than single approaches.

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1. Introduction

The dire consequences of over two centuries of unsustainable development primarily based on fossil resources could become existential threats to the human community globally. This highly carbon-intensive growth has led to an increasing concentration of carbon dioxide in the atmosphere, resulting in global warming and climate change. These threats are diverse, compromising every aspect of human life, ranging from increased vulnerability to the extremes of heat, especially in more vulnerable populations, i.e., people younger than 1 year and those older than 65 years (Fig. 1), to heat-related deaths and reduced labour capacity.

In 2020 alone, 295 billion h of potential work were lost owing to extreme heat exposure (Fig. 2). It is important to note that more than three-quarters of these losses took place in countries with a low human development index and the agricultural sector (Romanello et al., 2021). It is needless to underline the significance of this phenomenon on already fragile global food security and inequity.

The latest evidence also supports the idea that biodiversity loss and climate change are behind the rise in zoonotic diseases, including Coronavirus, also known as COVID-19, in recent decades (HT Correspondent, 2022). All these

findings highlight the urgency of taking the necessary actions to decarbonize the global economy and limiting global temperature increases to well below 2°C. An urgent but effective transition from fossil-based systems of producing energy and products to bioenergy and bioproduct systems is widely believed to present an opportunity to realize the abovementioned objectives.

Bioenergy and bioproduct systems could be based on various biogenic feedstocks, including food and feed resources, rendering them unsustainable due to their unfavourable impacts on food and feed security, including increases in the prices of food and feed commodities by boosting demands. Such systems can also contribute to land use change (deforestation) and loss of biodiversity. The negative aspects of bioenergy and bioproduct systems driven by edible resources have become more evident in light of the latest global developments, particularly the Russia-Ukraine war and its adverse impacts on the food and biofuel markets (Shams Esfandabadi et al., 2022). Hence, to achieve the core objectives of these systems, they must be based on various biomass sources, ranging from agricultural and forest (woody) biomass to municipal solid wastes, including food wastes and energy crops grown on marginal lands. The

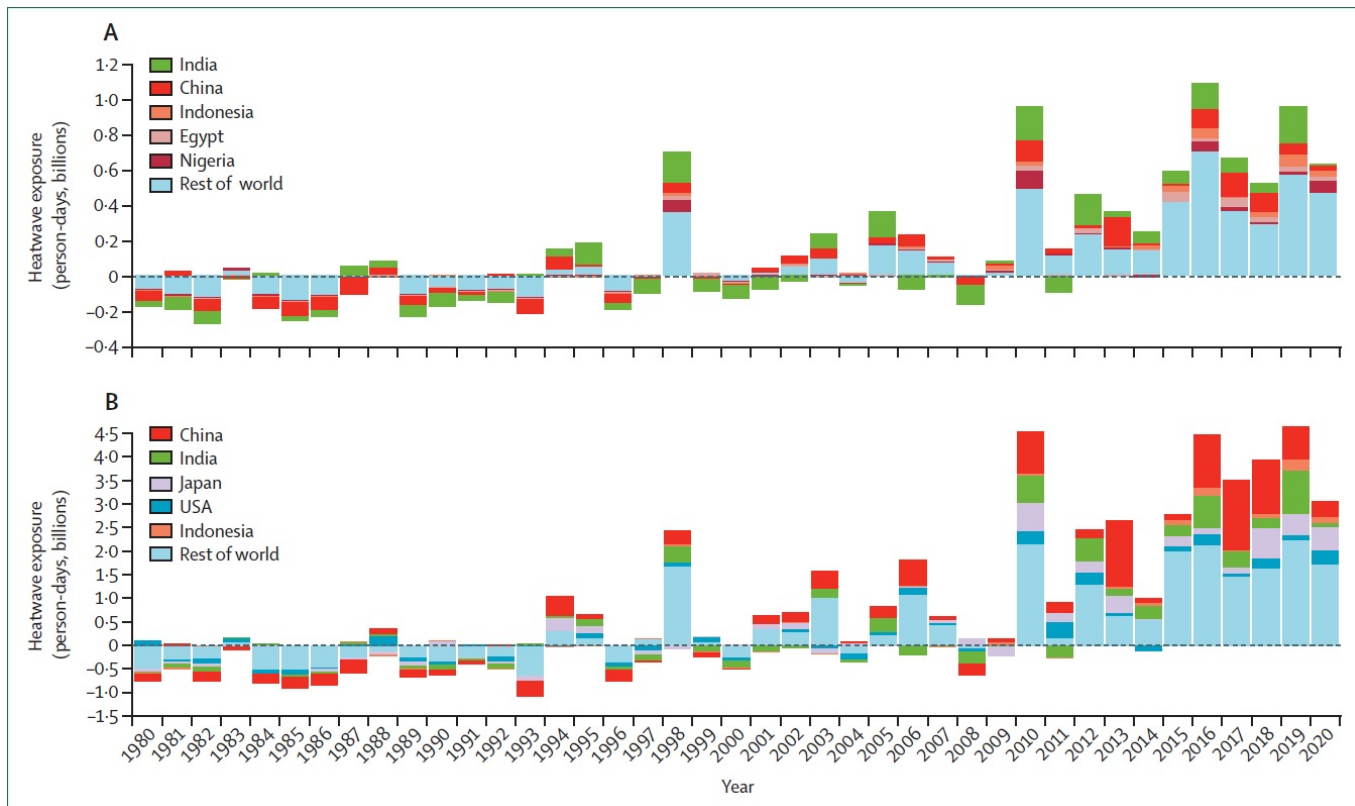
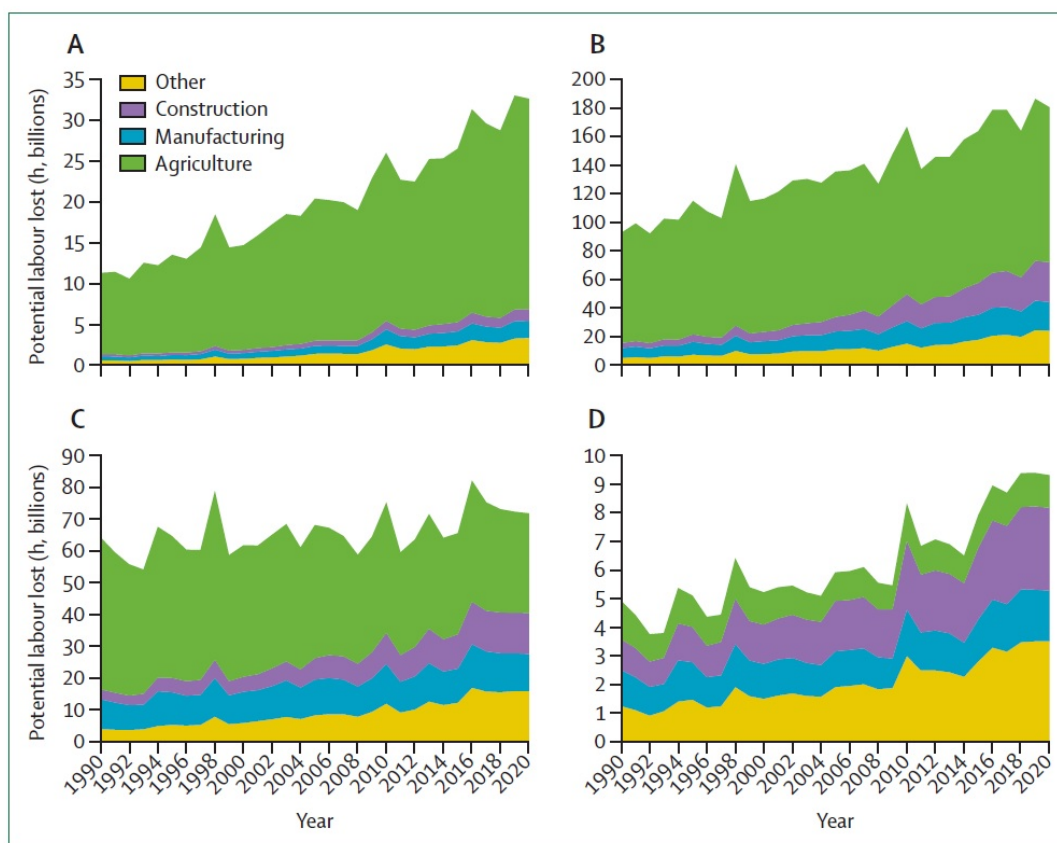


Fig. 1. Change in person-days of heatwave exposure against the 1986–2005 baseline (dotted line at 0). (A) People younger than 1 year and (B) People older than 65 years (Romanello et al., 2021). With permission from Elsevier. Copyright©2021. License Number: 5379191052369.

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**Fig. 2.** Potential labour lost owing to heat-related factors in each sector and countries with different human development indexes (HDI) (1990–2000). (A) Low HDI, (B) medium HDI, (C) high HDI, and (D) very high HDI groups (based on the 2019 HDI country group) (Romanello et al., 2021). With permission from Elsevier. Copyright©2021. License Number: 5379191052369.

former involves transitioning from lower generation bioenergy and bioproduct systems (also known as the first generation) to higher generations, requiring more advanced technologies, such as pyrolysis, gasification, and hydrothermal liquefaction.

Exploiting marginal and agriculturally degraded lands for biomass production is another promising solution to achieving a sustainable biomass supply for operating advanced bioenergy and bioproduct systems that could meet the very objectives of the United Nations' Sustainable Development Goals (SDGs). For instance, biofuel produced from low-input high-diversity grassland biomass obtained from native grassland perennials was reported to contribute more usable energy, larger greenhouse gas reductions, and less agrichemical pollution per hectare compared to corn ethanol or soybean biodiesel. Such a biofuel system can also be considered carbon negative as the net ecosystem CO<sub>2</sub> sequestration in soil and roots exceeds fossil CO<sub>2</sub> release during biofuel production (4.4 vs 0.32 mega g/ha/yr, respectively) (Tilman et al., 2006). It has also been experimentally shown that the main benefits of using bioenergy produced from energy crops lie in the carbon sequestration in soil rather than the emission reductions achieved through the consumption of the generated bioenergy (e.g., bioethanol or biodiesel) (Yang and Tilman, 2020).

Biomass can be exploited beyond its conventional valorization pathways leading to the generation of a wide spectrum of bioproducts to replace their fossil-based counterparts. For instance, plant biomass, in addition to fermentable sugars derived through bioconversion of lignocelluloses, also contains a considerable amount of acetate. In a study on switchgrass biomass, the co-consumption of acetate and xylose by engineered *Saccharomyces cerevisiae* resulted in the synthesis of acetyl-CoA derived bioproducts, including triacetic acid lactone and vitamin A (Sun et al., 2021). Acid condensate, also known as wood vinegar, obtained from microwave-assisted pyrolysis of palm kernel shells, was recently evaluated for its potential

biomedical applications (Mohd Hamzah et al., 2022). The phenolic-rich acid condensate was demonstrated to enhance the wound healing activity on human skin fibroblast cells. This enhanced wound healing activity was attributed to the increase in protein activation of Phosphatidylinositol 3-kinase and Protein kinase B, which are related to the common wound healing signaling pathway. These findings are just some examples highlighting the great promises held by biomass in developing more sophisticated bioproduct systems.

Overall, the magnitude of the potential benefits of bioenergy and bioproducts depends on the environmental sustainability of biomass production. Hence, it is important to employ advanced sustainability assessment tools, including techno-economic analysis, life cycle assessment (LCA), energy analysis, emergy analysis, exergy analysis, and the combination of these techniques such as exergoenvironmental and exergoeconomic analyses, to establish the overall sustainability of these systems and offer solutions to mitigate the environmental hot spots and energy sinks. The present work critically discusses these techniques and elaborates on their role in realizing the core objectives of bioenergy and bioproduct systems.

## 2. Sustainability assessment tools

### 2.1. Techno-economic analysis

Techno-economic analysis is a methodology widely employed to evaluate the technical feasibility and economic viability of a process (performance indices, costs, and revenues). This promising framework can be used for cost-benefit comparison and real-world implementation of bioenergy and bioproduct systems. Techno-economic analysis attempts to

link technological parameters of bioenergy and bioproduct systems with economic indicators (Thomassen et al., 2019). Generally, three economic methods, i.e., payback period, return on investment, and cash flow analysis, are used in techno-economic studies of energy and material conversion systems. The cash flow analysis providing different metrics (i.e., net present value, internal rate of return, and minimum selling price) is the widely used approach to assess the economic performance of bioenergy and bioproduct processes (Mahmud et al., 2021). The net present value and internal rate of return approaches are used when the selling price of the products is known or can be estimated. In the minimum selling price approach, the selling price of the products is systematically computed. In general, the methodology for cost estimation relies on two major items: capital expenditure (CAPEX), i.e., equipment cost, piping, warehouse, and service facility, and operational expenditures (OPEX), i.e., transportation cost, raw material cost, utilities, maintenance costs, labor and overhead, and taxes. The total production costs (summation of CAPEX and OPEX), and the revenues of the project (e.g., yearly product sales) are taken into account during the project lifetime (typically 20–30 yr) in a yearly cash flow. The important challenge is to reduce the CAPEX and OPEX while increasing the production volume of bioenergy carriers and bioproduct streams to increase the project profitability. Figure 3 shows different phases of conducting techno-economic analysis for bioenergy and bioproduct processing systems.

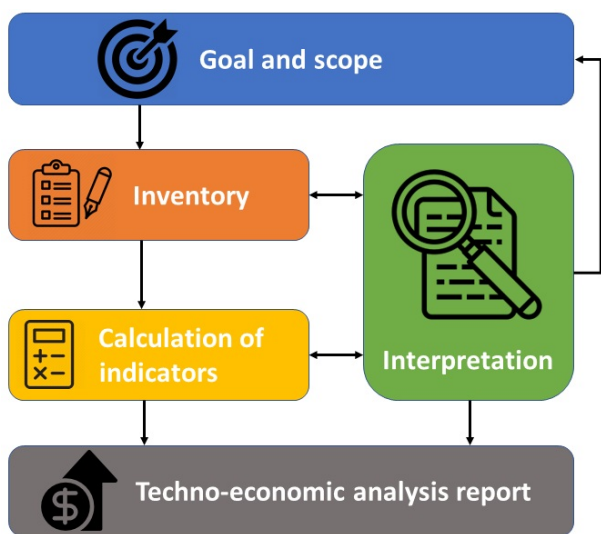


Fig. 3. Different phases of conducting a techno-economic analysis for bioenergy and bioproduct processing systems. Reproduced from Zimmermann et al. (2020).

Techno-economic analysis has become an attractive tool for researchers to weigh the sustainability performance of bioenergy and bioproduct systems because of its capability to assess them from technological and economic perspectives (Shahbeig and Nosrati, 2020). In addition, this promising approach could systematically evaluate the benefits, risks, and uncertainties attributed to the process. Unlike LCA and energy analysis, this analysis can effectively identify the economic feasibility and specify the short- and long-term economic success of energy projects (Soltanian et al., 2020). Despite the promising capability of techno-economic analysis, this sustainability assessment approach has some limitations. For example, the results of techno-economic analysis might be misleading because of various assumptions, simplifications, and approximations frequently made in the simulation of the processes (Gutiérrez Ortiz, 2020; Amid et al., 2021). The accuracy and reliability of techno-economic analysis can be enhanced by detailed modelling of thermodynamics, kinetics, and transport phenomena of processing units. This method does not account for the thermodynamic and environmental aspects of bioenergy and bioproduct systems. This issue can be addressed by coupling techno-economic analysis with LCA and exergy approaches. The profitability assessment through techno-economic analysis is significantly

dependent on the scale of the project. Therefore, sensitivity and uncertainty analyses should be conducted to increase the transparency and credibility of techno-economic results. Overall, techno-economic analysis is not a perfect tool for the sustainability assessment of bioenergy and bioproduct processing systems. Accordingly, it should be used in combination with other sustainability assessment tools like LCA, exergy, and energy.

## 2.2. Life cycle assessment analysis

As mentioned earlier, one of the most significant motives for developing bioenergy and bioproduct systems is their critical role in reducing unfavourable environmental impacts such as global warming and climate change (Liu et al., 2017). This claim is attributed to the theory that the carbon contained in bioenergy and bioproducts is mainly from biogenic carbon dioxide that is considered "carbon neutral" (Cherubini et al., 2009). However, bioenergy and bioproduct systems depend on major amounts of materials, chemicals, and fossil energy resources, and their production is not carbon-free. Most importantly, because of the time lag between carbon dioxide removals and emissions, products produced by bio-based systems are not completely carbon neutral (Hosseinzadeh-Bandbafha et al., 2021). Accordingly, it can be deduced that bioenergy and bioproduct systems are still faced with challenges, questioning their environmental sustainability. Hence, these systems should be assessed from an environmental point of view to identify the environmental hotspots and provide strategies that could lead to minimal environmental damage.

LCA is a promising approach to quantifying the environmental burdens of various products and systems (Aghbashlo et al., 2021). LCA is a unique technique since it focuses on products and systems from a life-cycle perspective and avoids problem-shifting (Ubando et al., 2019). With a step-by-step approach, this technique calculates the potential environmental burdens of materials and energies used throughout a product's life cycle, from raw material extraction to waste management/disposal (Liu et al., 2018). Therefore, it can easily identify sources of unsustainability at each stage of a product's life cycle. LCA is a standardized method based on the International Organization for Standardization (ISO, 2006) that assesses a product or a system in four steps, including goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results. Overall, goal definition can follow two pathways in bioenergy and bioproduct systems: attributional LCA (ALCA) and consequential LCA (CLCA). Generally, ALCA describes the environmental burdens of flows to/from a system; so, in bioenergy and bioproduct systems based on ALCA, the goal can be defined such that it leads to quantifying the environmental burdens caused by the production of materials and energy carriers to the system and all substances associated with their application from the system (Lee et al., 2020). This pathway helps to identify environmental hotspots and the origin of the environmental unsustainability of bioenergy and bioproduct systems (Brandao et al., 2022). This path can also make it possible to compare bio-based with fossil systems facilitating policy- and decision-making processes. However, this pathway cannot describe how environmental burdens associated with products or systems change in response to various policies and decisions (Hosseinzadeh-Bandbafha et al., 2022).

In comparison, CLCA can reflect changes in environmental burdens in response to policies and decisions related to the bioenergy and bioproduct systems. So, CLCA presents an opportunity for bio-based systems by easily showing the environmental consequences of bioenergy and bioproduct production and consumption compared to their fossil counterparts. However, its calculations are relatively complicated and are faced with double counting of emissions and substantial uncertainties (Zamagni et al., 2012). Moreover, many negative consequences are usually ignored in bioenergy and bioproduct studies based on CLCA. In better words, environmental consequences caused by the replacement of fossil-based energy and products with bio-based energy and products are limited to favourable consequences such as eliminating harmful emissions of fossil fuel combustion; while many negative consequences such as environmental burdens associated with fertilizers and chemicals application in feedstock production are ignored. In addition, the environmental consequences of land-use change in bio-based systems are less frequently considered in CLCA studies. Ignoring this issue can be highly effective in highlighting the sustainability of bioenergy and bioproduct production, while the reality

could be the opposite. Hence, future studies should focus more on these limitations.

It should be noted that bioenergy and bioproduct systems usually have more than one product, so, in these systems, environmental burdens associated with the system should be allocated between co-products. According to ISO (2006), the allocation of the environmental burdens can be done based on partitioning and system expansion. The former allocates the environmental burdens among co-products based on the physical parameter, e.g., mass, energy, or economic value (Finnveden et al., 2009). However, in bio-based systems, not all co-products have mass or energy value; for example, bio-based heat has no mass value, or biochemicals are not regarded as energy products (Hosseinzadeh-Bandbafha et al., 2021). Accordingly, mass or energy allocation in bio-based systems with various outputs might not be logical. Economic allocation can solve this issue, but due to the large variations in prices announced by manufacturers, wholesalers, and consumers, this method may also face concerns and uncertainties (Cherubini et al., 2011). While ISO (2006) generally emphasizes partitioning, when partitioning is not possible, system expansion can solve the concerns about the allocation of environmental burdens of multi-product systems. However, system expansion needs data related to marginal production that might not be easily available. Therefore, it can be deduced that allocation in the system is one of the most important points that, if not chosen correctly, may lead to directed and unrealistic results.

In both ALCA and CLCA pathways in bio-based systems, inputs and outputs should be quantified based on a specific functional unit (FU), which can be input- or output-oriented according to stakeholder interests. Briefly, input-oriented FU in bioenergy and bioproduct systems can be the amount of feedstock used based on mass, volume, or land needed for feedstock production. While out-oriented FU can be the amount of bioenergy or bioproduct produced based on mass, volume, energy content, power produced, or vehicle distance travelled by bioenergy. Accordingly, various FU is used in bioenergy and bioproduct systems, and their uniformity leads to the inability to compare the results reported by different studies.

System boundary definition is another important decision when applying an LCA in bioenergy and bioproduct systems. System boundaries can be limited to cradle-to-grave, cradle-to-gate, or gate-to-gate approaches. The cradle-to-grave approach should be used if the goal is to estimate the environmental burdens associated with feedstock production to the end of consumption/disposal of bioenergy or bioproducts. If environmental burdens associated with the consumption stage are not desired, system boundaries can be limited to cradle-to-gate (Hosseinzadeh-Bandbafha et al., 2020).

The second step of an LCA study in bioenergy and bioproduct systems is LCI, collecting all input and output to/from bio-based systems. In this step, two data groups should be carefully collected, including foreground data and background data associated with the life cycle of bioenergy and bioproducts. Foreground data are the data related to the type and quantity of materials and energies used in the life cycle of a product. In bioenergy and bioproduct systems, these data are the type and quantity of materials and energies used in feedstock production, feedstock treatment, feedstock processing, bioenergy/bioproduct production, transportation, consumption, and waste management, which are collected directly. It also includes data related to environmental burdens of applying materials and energies in a system which are mainly estimated using the existing literature, such as emissions from fertilizer application in feedstock production or emissions from fossil combustion in agriculture machinery. Background data related to environmental burdens of production of materials and energies used in bioenergy and bioproduct systems are generally extracted from databases such as EcoInvent (Ecoinvent Database, 2016). It should be noted that if LCI is not done correctly, it leads to overestimation or underestimation of environmental burdens, and the results of the studies face significant uncertainty. In bioenergy and bioproduct systems, especially in feedstock production, important data are generally neglected, such as the data related to land use change. Also, the data extracted from the databases are usually not presented at the local and regional levels, which can affect the uncertainty of the results. Finally, LCI leads to a long list of substances with very different potentials to cause environmental damage, rendering LCI-based decision-making illogical, and hence in the third step of an LCA study, i.e., LCIA, LCI is converted to a certain number of impact/damage categories.

LCIA is based on various methods, such as CML 2001, Eco-indicator 99, EDIP 2003, IMPACT 2002+, IMPACT world+, and ReCiPe, according to the

project goal. If the goal is only about conventional environmental problems such as climate change, methods that define the environmental impacts based on the midpoint impact categories, such as CML 2001, can be employed. In comparison, when the goal is to present environmental damages to human health and ecosystem quality, methods defining the environmental impacts based on the midpoint and endpoint impact categories, such as IMPACT 2002+, IMPACT world+, and ReCiPe, are suggested.

Overall, it can be concluded that LCA can help to promote and improve the sustainability of bioenergy and bioproduct systems since it can identify the environmental hotspots. However, there are still concerning limitations. For example, diversity in system boundary, FU, allocation methods, database, and LCIA method cannot only make the comparison of the results of various studies impractical but also lead to over or underestimation of environmental burdens of bioenergy and bioproduct systems and thus biased results. Ignoring some data, for example, data related to land-use change in feedstock production or data related to waste collection in waste-based bioenergy and bioproduct systems can also lead to uncertainty of results and, hence, making wrong decisions and policies. In the interpretation step of LCA, studies conducted on bioenergy and bioproduct systems seek to justify the production and utilization of these products, which might lead to incorrect recommendations and strategies. Future studies should focus on these limitations to help achieve more tangible sustainability in producing bioenergy and bioproducts. Figure 4 schematically shows the opportunities and limitations of using LCA in bioenergy and bioproduct systems.

### 2.3. Energy analysis

The energy concept was first elaborated by the American system ecologist H.T. Odum in the 1980s based on a consolidation of energy analysis and system ecology (Ulgiati and Brown, 2002). The main hypothesis behind this concept is that the sun provides energy for everything on earth (Li et al., 2022). The value energy represents the total historical energy embodied in a product or service (energy memory) (Wang et al., 2022). In other words, energy represents all types of energy and resources used to create a product or service in terms of solar energy, facilitating comparative assessment and contribution analysis of various input resources. More specifically, a conversion factor called "transformity value" is applied in this approach to translate all process or service inputs (i.e., energy resources, material streams, human labor, and economic services) into solar energy joule equivalent. The intensive quantity transformity can be presented in various dimensions, i.e., energy per unit energy (sej/J), energy per unit material (sej/g), energy-to-GDP ratio (sej/currency), energy per labor working hours (sej/time), and energy per unit area (sej/m<sup>2</sup>). One of the most challenging issues of energy analysis is to choose the most appropriate transformity values. Once the appropriate transformity values are chosen, all the energy resources, material streams, human labor, and economic services involved in producing a product or service can be presented based on a consolidated term, i.e., solar energy joule (sej). The energy calculation procedure is schematically shown in Figure 5. The obtained energy values are energy-based. These values can be converted into exergy-based energy values by multiplying them by a scale factor ( $\beta \approx 0.93$ ) (Bastianoni et al., 2007).

By translating different energy, material, and economic flows into solar energy joule (sej), energy analysis can systematically establish the relationships between human systems and their supporting environment (Aghbashlo et al., 2021). Unlike LCA and techno-economic approaches, energy can effectively build a bridge between human health, ecology, environment, and economy (Li et al., 2022). In better words, the combined impacts of various mass-energy-resource nexus between input-output balances can be reliably evaluated using energy analysis (Li et al., 2022). Energy analysis has been widely used in the published literature to assess the sustainability performance of bioenergy and bioproduct systems because it provides an ecocentric view of ecological and human activities (Hau and Bakshi, 2004). Despite the promising capability of energy analysis in jointly analyzing ecological and economic systems, energy analysis has its methodological inaccuracy and inconsistency like the other existing environmental impact assessment approaches. For example, accurate calculation of transformity values is one of the most challenging

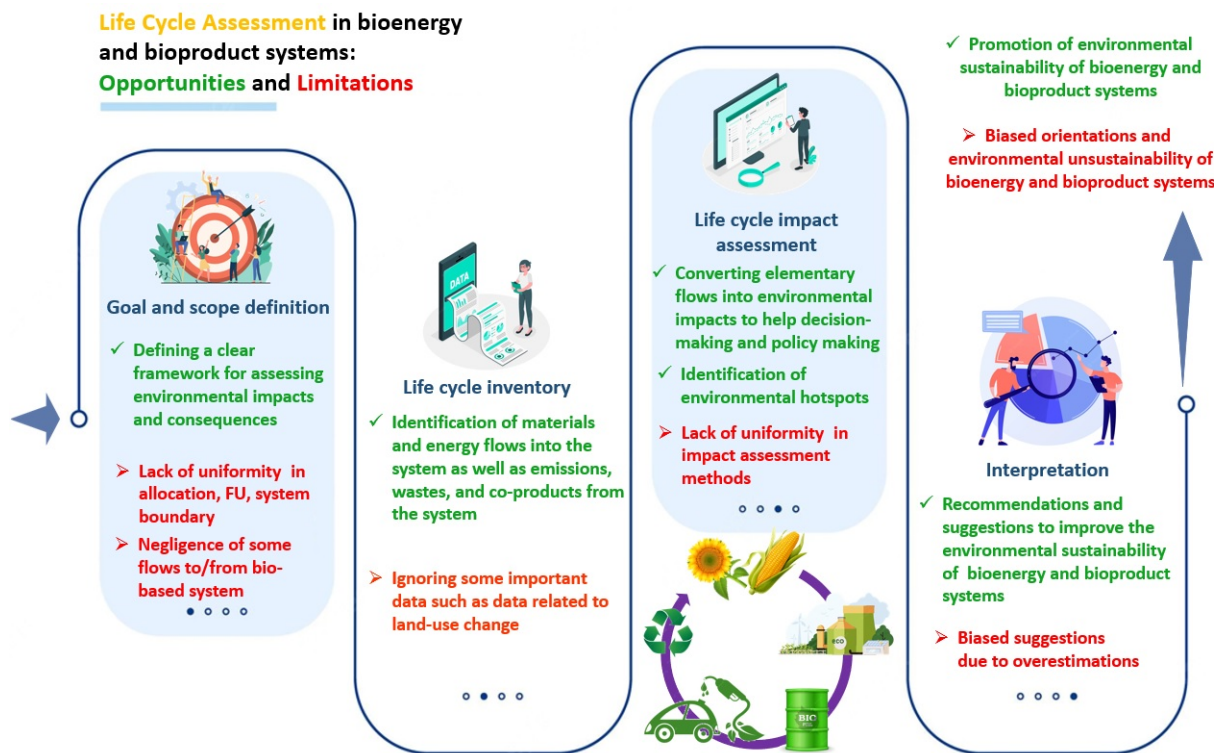


Fig. 4. Opportunities and limitations of using LCA in bioenergy and bioproduct systems.

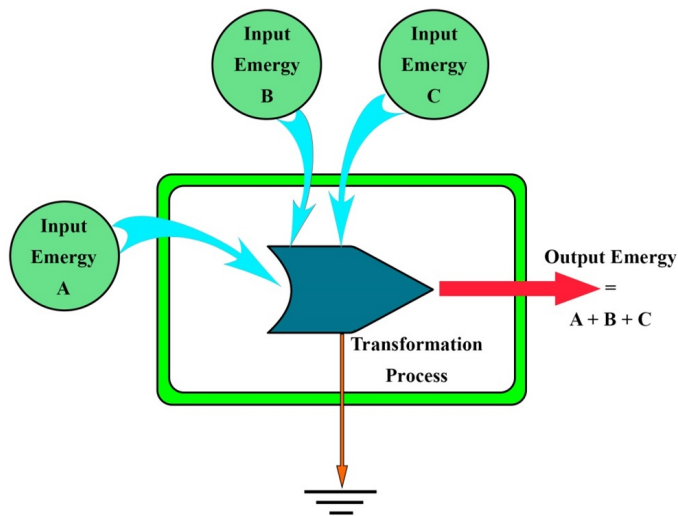


Fig. 5. Computing the emergy value of a given product.

issues in emergy analysis. Inventory modelling principles of the LCA approach can be adopted to address this drawback in a reliable and systematic manner (Raugei et al., 2014). In addition, the transparency and credibility of emergy analysis can be further enhanced by carrying out uncertainty and sensitivity analyses. The uncertainty associated with dispersed and inappropriate transformity values might negatively affect the quality of the conclusions obtained from emergy analysis. This analysis also requires some allocation decisions, which is a challenging issue in the sustainability assessment of bioenergy and bioproduct systems. Readers are referred to Hau and Bakshi (2004), where the pros and cons of emergy analysis have been comprehensively

scrutinized. Overall, this concept still needs some improvements and amendments before being used as a powerful tool for the sustainability assessment of bioenergy and bioproduct systems.

2.4. Energy analysis

Energy analysis based on the first law of thermodynamics is the most widely used method to make decisions regarding resource utilization efficiency (sustainability) of bioenergy and bioproduct systems. This analysis can also be used to reduce energy consumption in energy and material conversion systems and to optimize their design solutions (Song et al., 2014). Energy analysis can avoid potentially misleading conclusions that might be derived from conventional economic feasibility and environmental impact assessment methods (Mortimer, 1991). This analysis considers all energetic flows and material streams (input energy/material, output energy/material, and energy/material production) involved in producing a product or service. It should be noted that material streams are translated into energetic terms by using appropriate conversion factors. This analysis often entails performing energy balances to determine waste energy streams and find a way to recover them. Some dimensionless (i.e., energy efficiency) or dimensioned (i.e., specific energy consumption) indicators are also determined to compare different bioenergy and bioproduct systems from the sustainability perspective. The simplicity and ease of implementation of energy analysis have allowed a wide range of researchers to use energetic indices to assess the sustainability of bioenergy and bioproduct systems.

Despite the extensive use of energy analysis in the published literature for the sustainability assessment of bioenergy and bioproduct processes, this method suffers from serious drawbacks, hindering its real-world applications. Based on the first law of thermodynamics, energy can be neither destroyed nor produced (conserved for all processes). Accordingly, energy analysis cannot provide insights into energy degradation (irreversibility) in a process. The energy value does not include the usefulness or quality of various energy flows and material streams supplying to a system and leaving as product/waste streams. The property

energy depends only on the properties of energy flows or material streams (independent of environmental properties). Accordingly, it cannot effectively link bioenergy/bioproduct systems with their surrounding environment (Dincer and Rosen, 2013). The efficiency values determined based on energy analysis do not account for true ideality and, therefore, can not provide more meaningful information on the performance assessment of bioenergy/bioproduct systems (Rosen, 2002). Energy analysis does not include economic, environmental, and social factors, thus providing potentially misleading information on the sustainability of bioenergy and bioproduct systems. Given the obvious shortcomings of energy analysis, energy-based indicators appear to be unsuitable measures to evaluate the sustainability and efficiency of energy and material conversion processes.

### 2.5. Exergy analysis

Exergy is the maximum useful work that can theoretically be obtained from a system when it is brought to an equilibrium state through reversible processes (Song et al., 2021). Unlike energy value, the property exergy accounts for both the quality and quantity of energy flows and material streams. Indeed, the exergy concept systematically consolidates the first and second laws of thermodynamics to resolve the drawbacks of energy analysis (Soltanian et al., 2020). This thermodynamic property can fairly weigh all energy flows and material streams based on the unit of energy without needing subjective evaluation by expert evaluators. The main outcome of exergy analysis, i.e., irreversibility or exergy destruction, can present invaluable information concerning the locations, causes, and sources of deviations from ideality in a system (Rosen, 2002). Notably, there is a direct association between exergy destruction and economic loss/resource depletion (Fig. 6). Interestingly, exergy destruction correlates meaningfully with greenhouse gas emissions (Portha et al., 2008 and 2010). Thanks to its unique conceptual features, exergy analysis has recently been widely applied to understand and improve bioenergy and bioproduct processing systems from sustainability, efficiency, and productivity perspectives.

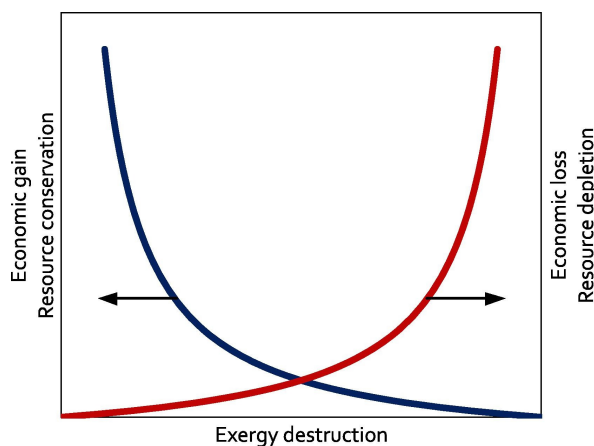


Fig. 6. Association between exergy destruction and economic loss/resource depletion (Soltanian et al., 2020). With permission from Elsevier. Copyright©2020. License Number: 5379190794464.

One of the most important features of the exergy concept is its capability to be integrated with economic and environmental constraints (Aghbashlo and Rosen, 2018a). These integrated methods, called “exergoeconomic and exergoenvironmental” approaches, are powerful tools to identify, quantify, and interpret economic losses and environmental burdens of bioenergy and bioproduct systems at the component level. More specifically, the exergoeconomic method can effectively address the shortcomings of techno-economic analysis by accounting for thermodynamic losses. In addition, the exergoenvironmental method can reliably cope with the drawbacks of LCA analysis in the sustainability assessment of bioenergy and bioproduct systems by allocating the environmental burdens at the component level and measuring the environmental burdens of intermediate products. It is interesting to note that

exergy, economy, and environment can be presented in a single framework (exergoenvironmental analysis) such as that proposed by elaborated by Aghbashlo and Rosen (2018a). This unique combination of exergy, economy, and environment can reliably assess the thermodynamic productivity, economic viability, environmental safety, and overall sustainability of energy and material conversion processes (Fig. 7). Exergoeconomic and exergoenvironmental methods can also be bridged using the emergy concept, as proposed by Aghbashlo and Rosen (2018b). Such a combination not only can facilitate understanding and interpretation of the results derived from exergoeconomic and exergoenvironmental analyses but also make finding a global optimal point possible.

The quality of conclusions obtained from exergy-based methods can be further enhanced by implementing advanced analysis. Such an advanced analysis can reveal the interactions among the bioenergy and bioproduct processing units and measure the avoidable part of thermodynamic inefficiencies, economic losses, and environmental burdens (Tsatsaronis and Morosuk, 2008). Advanced exergy-based analyses can split exergy destruction and its costs and environmental impacts as well as component-related costs and environmental impacts into avoidable/unavoidable endogenous/exogenous parts. Another appealing extension of exergy analysis is the extended exergy accounting approach presented by Sciubba (2001). Like the emergy concept, extended exergy accounting can translate all energy flows, material streams, labor fees, economic inputs, and environmental remediation costs into a unified exergy scale. Even though this exergy-based method cannot provide information at the component level, its results are easier to understand than exergoeconomic, exergoenvironmental, and exergoeconomic analyses. Moreover, the extended exergy accounting approach can conceptually and systemically link bioenergy and bioproduct systems with the economy, environment, and society. It is worth mentioning that there are various combinations of exergy with economic and ecological concepts, such as cumulative exergy consumption (Szargut, 1978), ecological cost and thermo-ecological cost (Szargut et al., 2002), exergoecological (Valero et al., 1986), environomics (Frangopoulos and Caralis, 1997), exergetic life cycle analysis (Cornelissen, 1997), and life cycle exergy analysis (Gong and Wall, 1997). Throughout this review article, the most widely used extensions of exergy analysis have been presented and discussed.

Despite the promising features of the exergy concept, it has some limitations like the other sustainability assessment methods. For example, reference environment conditions (temperature, pressure, and chemical composition) can, to some extent, affect the outcomes of exergy-based analyses (Soltanian et al., 2022). The accuracy of the results of exergy-based analyses is influenced by the cut-off criteria defined for the boundaries of energy and material conversion systems (Aghbashlo et al., 2017). The exergetic indicators defined in the published literature are different paper by paper, making the comparison of results of different studies difficult or even impossible (Soltanian et al., 2022). Unlike other exergy types (i.e., physical, potential, and kinetic exergies), there is significant uncertainty in determining the chemical exergy values of bio-based products. In fact, the chemical exergy values of bio-based products are computed based on several empirical and semi-theoretical models. The uncertainty associated with chemical exergy calculation might substantially affect the exergetic results since its contribution to the overall exergy values of the involved streams are higher than other exergy types. Despite many advances in using exergy-based analyses for the sustainability assessment of bioenergy and bioproduct systems, there is still room to further enhance these unique tools. Overall, exergy-based analyses, particularly those enhanced by economic and environmental constraints, can outperform other sustainability assessment tools in providing accurate and reliable results.

### 3. Concluding remarks and future directions

Various tools, including techno-economic, LCA, emergy, energy, and exergy analyses, used for the sustainability assessment of bioenergy and bioproduct systems are comprehensively reviewed and critically discussed in this communication. After briefly explaining the principles behind sustainability assessment methods, their effectiveness and weakness in designing, analyzing, and optimizing bioenergy and bioproduct systems are highlighted. Even though the reviewed sustainability assessment

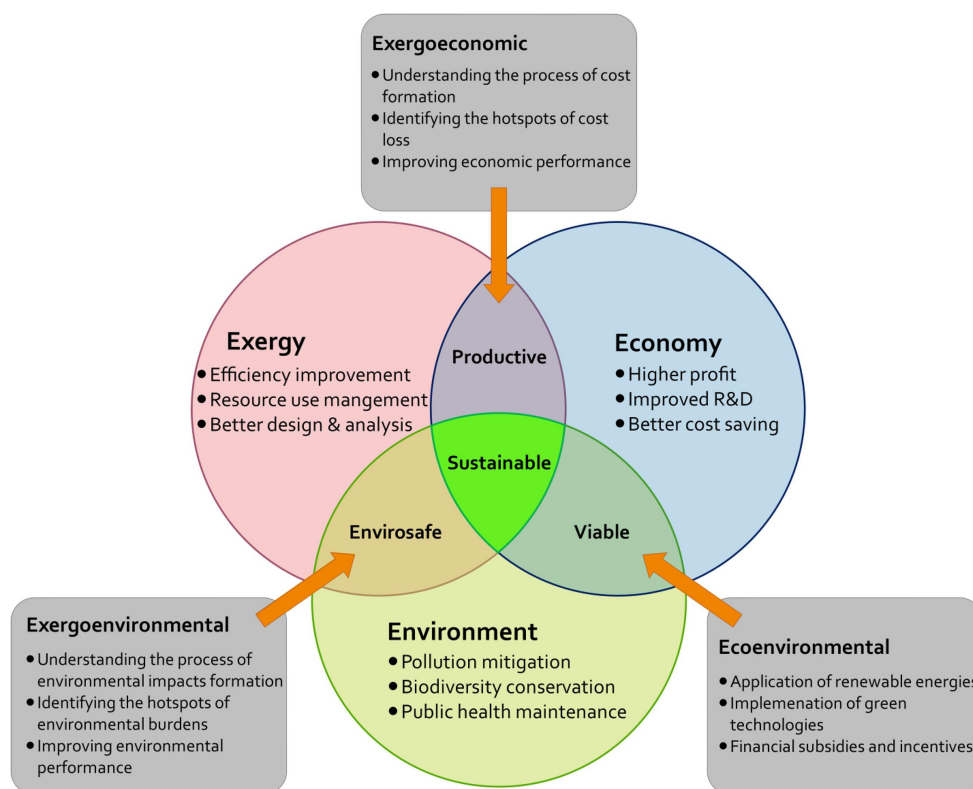


Fig. 7. Opportunity interactions among exergy, economy, and environment (Soltanian et al., 2020). With permission from Elsevier. Copyright©2020. License Number: 5379190794464.

approaches are powerful tools for realizing bioenergy and bioproduct processing systems, but they cannot be regarded as perfect solutions to address all the issues involved. Each sustainability assessment method has its own merits and demerits, so the optimum method depends on the study objective, process complexity, and desired level of precision. Overall, integrated sustainability assessment methods can provide more reliable and accurate results than single approaches. It is interesting to note that integrated methods can also eliminate the majority of drawbacks of lonely-used approaches. Among the sustainability assessment methods reviewed, exergy-based approaches have attracted significant attention from the scientific community due to the scientific rigour of the exergy concept. Exergy-based analyses, particularly those enhanced by economic and environmental indicators, can outperform other sustainability assessment tools in providing more informative indicators. The integrated exergy-based approaches (i.e., exergoeconomic, exergoenvironmental, and exergoeconomico-environmental) can provide decision-makers with information not achievable by exergy, techno-economic, and LCA analyses. These approaches can aid researchers and engineers in implementing bioenergy and bioproduct systems with improved thermodynamic, economic, and environmental performance. Nevertheless, most published research papers have mainly focused on determining the irreversibility rate and exergy efficiency of bioenergy and bioproduct systems, while a few studies have applied integrated exergy-based approaches. Therefore, there is still room to introduce more efficient, viable, and sustainable bioenergy and bioproduct technologies using advanced exergy-based methods. The methodologies used in integrated exergy-based approaches for identifying and quantifying economic and environmental parameters suffer from arbitrariness, inaccuracies, and uncertainties. The accuracy and reliability of these methods should be improved by evolving economic accounting and environmental impact assessment methods. The exergy concept has its own drawbacks, negatively affecting the quality of conclusions derived from integrated exergy-based methods. In addition, some theoretical assumptions and simplifications in integrated exergy-based approaches might affect the reliability and

accuracy of their results. Future work should focus on dealing with these issues by employing advanced scientific techniques.

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