CHAPTER ELEVEN

Lifecycle assessment and techno-economic analysis of biofuel production from lignocellulosic biomass

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11.1 Introduction

The growing demand for renewable and sustainable energy sources has prompted increased interest in biofuels derived from lignocellulosic biomass. As a promising alternative to fossil fuels, biofuels offer the potential to mitigate greenhouse gas emissions, reduce dependence on non-renewable resources and promote rural development (Makepa et al., 2023). However, the sustainability of biofuel production systems must be carefully evaluated to ensure their environmental and economic viability (Aghbashlo et al., 2022).

Lifecycle assessment (LCA) and techno-economic analysis (TEA) have emerged as essential tools for assessing the environmental impacts and economic feasibility of biofuel production from lignocellulosic biomass (Mousavi-Avval et al., 2023). LCA provides a comprehensive evaluation of the entire lifecycle of biofuel production, including biomass cultivation, harvesting, conversion processes and fuel distribution (Gheewala, 2023). On the other hand, TEA assesses the economic viability of biofuel production by considering factors such as capital costs, operating expenses and revenue streams (Zuorro et al., 2020).

This chapter aims to provide a comprehensive perspective on the application of LCA and TEA in the context of biofuel production from lignocellulosic biomass. It explores the challenges faced, the progress achieved and the opportunities and future perspectives in these analytical approaches. By examining the environmental and economic aspects of biofuel

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production, this chapter seeks to contribute to the development of sustainable and economically viable bioenergy systems.

Throughout the chapter, the challenges associated with conducting LCA and TEA, including data availability, system boundaries, uncertainty and trade-offs are discussed. The chapter also highlight the progress made in methodological advancements and technological improvements that have enhanced the accuracy and reliability of these analyses. Moreover, the opportunities arising from policy support and circular economy approaches, as well as the role of technological innovation in shaping the future of biofuel production are explored.

By integrating LCA and TEA, stakeholders can gain valuable insights into the environmental performance, economic feasibility and overall sustainability of biofuel production from lignocellulosic biomass. This knowledge will facilitate informed decision-making, policy formulation and technological advancements, ultimately driving the transition towards a more sustainable and renewable energy future (Makepa et al., 2023).

11.2 Lifecycle assessment

11.2.1 Lifecycle assessment and sustainable development

Sustainable development is defined as 'the development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (Brundtland, 1987). The United Nations established 17 sustainable development goals in 2015 as part of the 2030 agenda, aligning with the aforementioned definition (Spencer, 2021). The sustainability approach can be broadly categorized into three key aspects: the environmental aspect, the economic aspect and the social aspect (Rafiaani et al., 2018).

In order to facilitate the transition from conventional fossil fuels to biofuels, it is important to enhance the environmental and socioeconomic value of biofuels. Additionally, the biofuel market needs to become cost-competitive with the fossil fuel market (Paris et al., 2021). To establish biofuels as a sustainable alternative to fossil fuels, it is crucial for them to demonstrate advantages in terms of environmental, economic and social aspects (Fig. 11.1). However, developing a robust framework that can effectively assess the environmental, economic and social impacts poses significant challenges. Conducting various LCA studies is essential to enhance biofuel production and establish a solid foundation for long-term

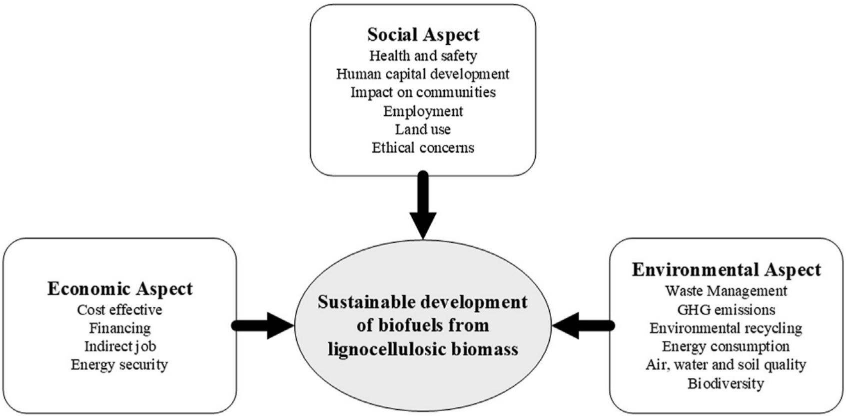

Figure 11.1 Environmental, social and economic aspects for sustainable development of biofuels.

objectives. Given that LCA studies for biofuels involve complex considerations encompassing market dynamics and technological factors, it is imperative to form a multidisciplinary team comprising economists, social scientists and systems engineers. This collaborative approach is necessary to effectively manage the transitional phase and facilitate large-scale changes in the biofuel industry (Rafiaani et al., 2018; Paris et al., 2021).

The environmental aspect of biofuels encompasses considerations such as greenhouse gas (GHG) emissions, impacts on environmental cycles, climate forcing, water and soil quality, conservation of biodiversity and natural resources and the use of toxic chemicals. On the other hand, the socioeconomic dimensions involve aspects such as contributing to social welfare, ethical concerns in resource procurement (especially for resources used as food and feed), impacts on human and ecological life, effects on the public and the quality of working conditions. Achieving sustainable development in the long term requires a well-balanced approach where all these factors are carefully considered and harmonized throughout the biofuel lifecycle. It is essential to ensure that the environmental and socioeconomic aspects of biofuels are mutually supportive, promoting positive outcomes for both. This balanced approach is crucial for fostering sustainable development and realizing the potential of biofuels as a viable alternative to conventional fuels (Paris et al., 2021). If the focus is solely on GHG emissions while neglecting other socioeconomic and environmental impacts, it can lead to incorrect incentives and decision-making (Rafiaani et al., 2018).

McKone et al. (2011) have identified and summarized seven major challenges for effectively evaluating the ecological footprint of bio-based fuels based on their studies on LCA of crop/plant-based biofuel production. These challenges are as follows:

1. Understanding farmers' expectations and comparing various feedstocks and land use.
2. Improving and determining advanced biofuel production processes.
3. Investigating exhaust emissions and assessing their impacts on human health.
4. Considering both inventories and assessments due to spatial heterogeneity.
5. Incorporating the element of time during impact assessment.
6. Evaluating not only end states but also transition states in the biofuel lifecycle.
7. Managing uncertainties and variabilities associated with the assessment.

These challenges highlight the need for comprehensive and systematic approaches in conducting LCAs for biofuel production, taking into account various factors and ensuring that both environmental and socioeconomic aspects are adequately addressed (McKone et al., 2011).

The International Standard Organization (ISO) established the ISO 14040-series to standardize LCA for biofuels. These standards serve to define the benefits of biofuels and aid in determining the most advantageous alternative from various perspectives. Recent studies have utilized these standards to quantitatively assess the ecological balance of biofuel production chains, moving beyond qualitative assessments (Rebolledo-Leiva et al., 2023). However, it is worth noting that the application of LCA to biofuels has often been limited to assessing energy and gas emissions balances, as highlighted by (Gheewala, 2023). Thus, there is a need to expand the scope of LCA studies to encompass a broader range of environmental and socioeconomic factors in order to comprehensively evaluate the sustainability and overall impacts of biofuels.

11.2.2 Methodology

The entire journey of a product or process, starting from the extraction of feedstock, continuing through production, distribution, utilization and ending with disposal, encompasses the lifecycle (McKone et al., 2011). LCA is utilized to effectively assess and measure the environmental sustainability and utility of products. This tool is particularly valuable for policymakers as it aids in selecting the most suitable product. By determining environmental performance, evaluating alternatives and identifying critical points within a lifecycle approach, LCA supports informed decision-making (Golberg et al., 2021).

The LCA methodology offers a comprehensive analysis and assessment of a product, process or pathway, considering each step from extraction, production, pre-consumption chain, consumption, disposal, to process development. It can be applied to the entire lifecycle or a specific lifetime, typically adopting a cradle-to-grave perspective. This perspective takes into consideration the consumption of resources and the emissions of materials (Gheewala, 2023; Rebolledo-Leiva et al., 2023; Golberg et al., 2021).

The objective of LCA is to compare various products using a functional unit, with the goal of identifying environmentally friendly and sustainable goods and services through ecological means (Furberg et al., 2022). Through this comparison, a deeper understanding of the environmental impacts of products or processes can be achieved. These products or processes may include biofuels or bio-based products, which are often associated with the concept of biorefinery (Hosseinzadeh-Bandbafha et al., 2022).

Traditionally, LCA has been employed to address specific inquiries that directly pertain to a product's lifecycle within the current economic and technological context. This approach is referred to as attributional LCA (aLCA). However, a more recent and arguably crucial objective of LCA is to facilitate the prediction of future impacts, thereby influencing policy decisions and assessing sustainability in energy, resources and emerging technologies. This approach is known as consequential LCA (cLCA), which considers impacts within a broader and more global context (Schaubroeck et al., 2021).

Within this methodology, various aspects such as climate change, ecosystem quality and human health can be addressed. In addition to its environmental focus, LCA, when combined with waste valorization, can provide an advantage in promoting sustainability. The methodology of LCA consists of four stages: goal and scope definition, lifecycle inventory (LCI), lifecycle impact assessment (LCIA) and interpretation of results, as outlined in Fig. 11.2 (Hosseinzadeh-Bandbafha et al., 2022).

11.2.2.1 Goal and scope definition

The initial stage of LCA involves clearly defining the goal, scope and key elements such as boundaries, functional unit, allocation and cut-off criteria. Although often underestimated, this step is critically important as it involves

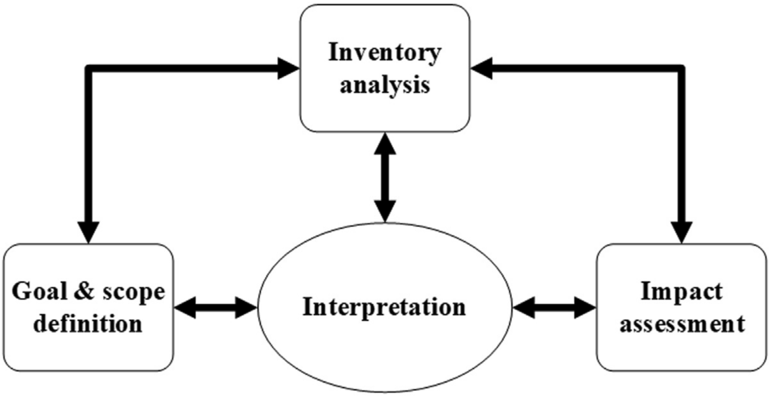

Figure 11.2 Key elements of the LCA methodology.

conceptualization, understanding, simplification and consideration of the potential measurements in LCA. The lifecycle can be categorized into different perspectives, including cradle-to-cradle, gate-to-gate, cradle-to-gate, cradle-to-wheel and cradle-to-grave approaches (Hosseinzadeh-Bandbafha et al., 2022; Dahiya et al., 2020).

The initial step holds significant importance in LCA as it entails defining the precise goal, which in turn affects subsequent phases and study outcomes. This step involves addressing specific questions, such as the intended use of LCA outputs, making decisions regarding the scope and basis of the study and determining the extent and qualifications of these decisions. The primary objective should be centred on enhancing product performance through the evaluation of alternative options. The outputs of the LCA study can play a crucial role in optimizing production development (Golberg et al., 2021). These goals and objectives can be related to various aspects, such as process design, operation or policy. They may be focused on improving the design of processes, optimizing operational efficiency or informing policy decisions. The specific orientation of the goals depends on the intended application and desired outcomes of the LCA study (Gheewala, 2023).

The scope of an LCA study is closely tied to its main characteristics and should be clearly defined. However, it's important to note that the scope can be subject to change if additional information is obtained during the course of the study. LCA is an iterative method, meaning that as new data or insights emerge, adjustments to the scope may be necessary to ensure the study remains comprehensive and accurate. This iterative approach allows for ongoing refinement and improvement of the LCA process (Golberg et al., 2021).

The boundaries of an LCA study establish the framework and define the limits of the intended investigation. They encompass the materials and energy involved, extending from the initial stages of production to the final treatment of wastewater. These boundaries are determined by factors such as temporal considerations, spatial aspects and the production chains involved, which dictate the starting and ending points of the system. For instance, when examining a product system, the boundaries can be defined based on spatial and temporal parameters (Hosseinzadeh-Bandbafha et al., 2022; Dahiya et al., 2020; El Joumri et al., 2022).

The functional unit serves as a measure that enables the quantification of performance within the product system and acts as a reference for the flows. When comparing different product systems that provide the same service, it is crucial to express the results based on a consistent functional unit. The choice of functional unit can vary depending on the objectives of the disciplines or research, and it plays a significant role in facilitating comparisons between LCAs. In accordance with ISO 14040, the functional unit should be determined as a quantity, such as per kilogram of a product. Various types of functional units are described in the literature. Service-oriented functional units, for instance, are based on a specific transport distance (e.g., 1 km), while energy-oriented functional units are based on a specific amount of energy (e.g., 1 MJ). Mass-oriented functional units may be based on the amount of fuel (e.g., 1 kg of fuel), and land-area oriented functional units use a specified area of farmland (e.g., 1 ha) as reference (Rafiaani et al., 2018; Dahiya et al., 2020; Huang et al., 2022).

To establish cut-off criteria, practitioners of LCA need to exclude certain material or energy flows or levels of environmental importance from the study. This exclusion ensures that effects below the cut-off score are not considered in the final results. By setting a cut-off point, the practitioner can focus on the most significant aspects and prioritize the assessment of impacts that exceed the established threshold. This allows for a more efficient and manageable LCA process, enabling practitioners to concentrate on the most relevant areas of analysis (Dahiya et al., 2020).

11.2.2.2 Lifecycle inventory analysis

The lifecycle inventory analysis (LCI) analysis assesses the product systems by considering all relevant flows of materials and energy. This includes examining various stages such as feedstock production, pretreatment, extraction, processing, production, transportation, storage, distribution and product utilization. During this step, flow diagrams are designed by determining system boundaries and unit processes (Rafiaani et al., 2018). Essential data related to the process, materials, energy flows, wastes and emissions are collected. Allocation steps are implemented, and calculations are performed to achieve the specific goals of the study. The LCI analysis plays a crucial role in defining the framework of the LCA (Lopes Silva et al., 2019). However, it's important to note that the framework can be adjusted based on the goals and objectives of the study. The LCI serves as a foundation for subsequent assessments and provides a comprehensive understanding of the relevant inputs and outputs associated with the product system under evaluation (Dahiya et al., 2020).

The LCI analysis is typically the most time-consuming part of the methodology and involves several components. It entails identifying processes and their connections within the product system through a flow model. LCA is employed to model the interdependencies among individual processes within the product system and determine the energy and material flows into the system. Additionally, emissions to soil, water and air must be calculated for the system. During this stage, various aspects such as material and energy flows, measured emissions and energy constraints are documented. Primary and secondary data sources are selected, sorted or modified in accordance with the goals and scope of the study to define the lifecycle of the product or process. To facilitate analysis, the system may be divided into subsystems and unit processes. All relevant data, including input and output flows for each unit process, must be gathered, along with other pertinent information about the processes themselves (Hosseinzadeh-Bandbafha et al., 2022; Dahiya et al., 2020).

During the LCI phase, allocation becomes necessary when one or more processes generate coproducts, such as in the case of biofuel production. Allocation involves distributing environmental burdens among the various products within a multifunctional system's LCA. In addition to quantifying material and energy requirements, LCI analysis identifies the relevant environmental impacts, including waste emissions, associated with a product, process or activity throughout its entire lifecycle. To collect data on the physical inputs and outputs of the product system, various databases are commonly utilized in LCI, such as the Ecoinvent database (widely used), ETH database and ELCD database. The outcome of the LCI analysis is an inventory table, which serves as input for the subsequent impact assessment phase. The success of the study hinges on obtaining high-quality and detailed datasets that are comprehensive in nature (Gheewala, 2023; Golberg et al., 2021; Ortiz et al., 2020). The outcome of the LCI assessment is the quantification of the fundamental flows that arise from the delivery of the functional unit, which represents the product or service being evaluated. However, it is important to note that variations in the calculation of input and output components, as well as uncertainties associated with these factors, can lead to different results in the overall LCA analysis. These variations and uncertainties can stem from factors such as data quality, methodological choices, boundary definitions and assumptions made during the assessment (Khang et al., 2017). As a result, the LCA results may vary depending on these considerations.

11.2.2.3 Lifecycle impact assessment

A key objective of LCA is to identify and assess the lifecycle impacts, including hotspots, associated with the component processes. This helps to characterize the environmental impacts of these processes (McKone et al., 2011; Golberg et al., 2021). Lifecycle impact assessment (LCIA) is the phase of LCA that quantifies the potential environmental harm based on the results obtained from the inventory analysis. ISO 14042 provides a standard framework for conducting impact assessment within LCA (Rebolledo-Leiva et al., 2023). It serves as a guideline for performing impact assessment, ensuring consistency and comparability in the evaluation of environmental impacts across different LCA studies.

The lifecycle impact assessment (LCIA) method enables the determination of environmental loads associated with different stages of a process or product. This step involves grouping resources and emissions based on impact categories and converting them into comparable impact units. LCIA encompasses categorization, characterization, normalization and weighting. The selection, description, classification and characterization of impact categories are crucial steps that address various environmental concerns, including ozone depletion, global warming, human toxicity, loss of biodiversity, acidification and eutrophication. Normalization and weighting, on the other hand, are optional steps (Gheewala, 2023; Rebolledo-Leiva et al., 2023; Dahiya et al., 2020). It is important to note that certain impact categories may vary at the local or regional level, such as water quality (McManus et al., 2015).

Characterization involves categorizing inventory data into different impact categories based on their environmental impacts. Reference systems are used to facilitate comparisons and guide decision-makers, typically based on the selected functional unit. When studying products, processes or pathways, it is essential to compare them with a baseline called a reference system (Rafiaani et al., 2018; Paris et al., 2021). In the characterization step, the impact of each element is calculated based on its specific activity and quantitatively expressed in terms of reference component equivalents. For example, eutrophication impact category may be expressed in kilograms of phosphate equivalents for each raw material. Inventory data within the impact categories are multiplied by a characterization factor to evaluate the relative contribution of each product's impacts to the overall impacts through normalization. The normalized impact categories are then multiplied by weighting factors to obtain the final weighted calculation (Golberg et al., 2021; Dahiya et al., 2020).

Popular software tools commonly used for lifecycle impact assessment include SimaPro software, openLCA, GaBi and IMPACT 2002+. As an illustration, IMPACT 2002+ was developed by the Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland, and focuses on four damage categories: human health, climate change, quality of ecosystems and resource categories. These software tools provide researchers and practitioners with computational capabilities and databases to analyse and assess the environmental impacts associated with various lifecycle stages and processes. They facilitate the quantification and evaluation of impacts in terms of these specific damage categories, aiding in decision-making and providing insights for sustainable product and process development (Hosseinzadeh-Bandbafha et al., 2022; Dahiya et al., 2020).

11.2.2.4 Interpretation of results

The interpretation of LCA results involves obtaining comprehensive outputs of options, analyses and assumptions to support decision-making. It includes evaluating and reviewing formulations, limitations, recommendations and conclusions derived from the study. As per ISO 14043 guidelines, interpretation is a systematic procedure for identifying, qualifying, verifying and evaluating the consequences of LCI/LCIA and presenting these results in relation to the study's goals and scope. This process typically involves several steps, including contribution analysis, completeness assessment, consistency checks and sensitivity analysis (Paris et al., 2021; McKone et al., 2011; Dahiya et al., 2020).

The interpretation phase aims to ensure and enhance the credibility of the LCA results by focusing on result reliability and clear presentation of outputs. The entire lifecycle is evaluated, and any constraints or limitations are addressed systematically. Opportunities for improvement are also identified and incorporated into the interpretation phase. Outputs of LCA evaluation can include variables such as electricity, heat and metabolites, which are commonly used in economic and engineering applications (Golberg et al., 2021; Dahiya et al., 2020). The aim is to provide a clear and comprehensive understanding of the study findings, enabling informed decision-making and supporting the integration of sustainability considerations into various processes and systems.

11.2.3 LCA studies of biofuel production from lignocellulosic biomass

Environmental impacts of microalgal and lignocellulosic biomass feedstocks are assessed through lifecycle assessment (LCA) studies. These studies typically employ different system boundaries, such as cradle-to-grave, cradle-to-gate or gate-to-grave.

In a cradle-to-grave boundary, the assessment covers all processes involved, starting from biomass cultivation, harvesting, transportation, pretreatment, thermochemical conversion, consumption and disposal. Cradle-to-gate focuses on the cultivation and production of the product, omitting the consumption and disposal stages. Gate-to-grave begins with biomass transportation and extends to the product gate, excluding cultivation, consumption and disposal stages.

Fig. 11.3 illustrates the LCA system boundaries for torrefaction, pyrolysis, gasification and hydrothermal liquefaction of different lignocellulosic biomass feedstocks. Table 11.1 provides a summary of various LCA studies conducted on both lignocellulosic and microalgal biomass, highlighting their key findings and results. These studies play a crucial role in assessing the environmental impacts associated with different biomass feedstocks and conversion processes, aiding in the development of sustainable bioenergy systems.

11.2.3.1 Torrefaction

In a comparative LCA research on wood pellets, Adams et al. (2015) and McNamee et al. (2016) found that the torrefied wood pellet had a lower GWP effect than the raw biomass. McNamee et al. (2016) emphasized that the biggest GWP impact was caused by drying, followed by torrefaction and transportation. Christoforou and Fokaides (2016) examined the torrefied olive husk's environmental effects and discovered that torrefaction and drying had a relatively larger GWP impact than transportation.

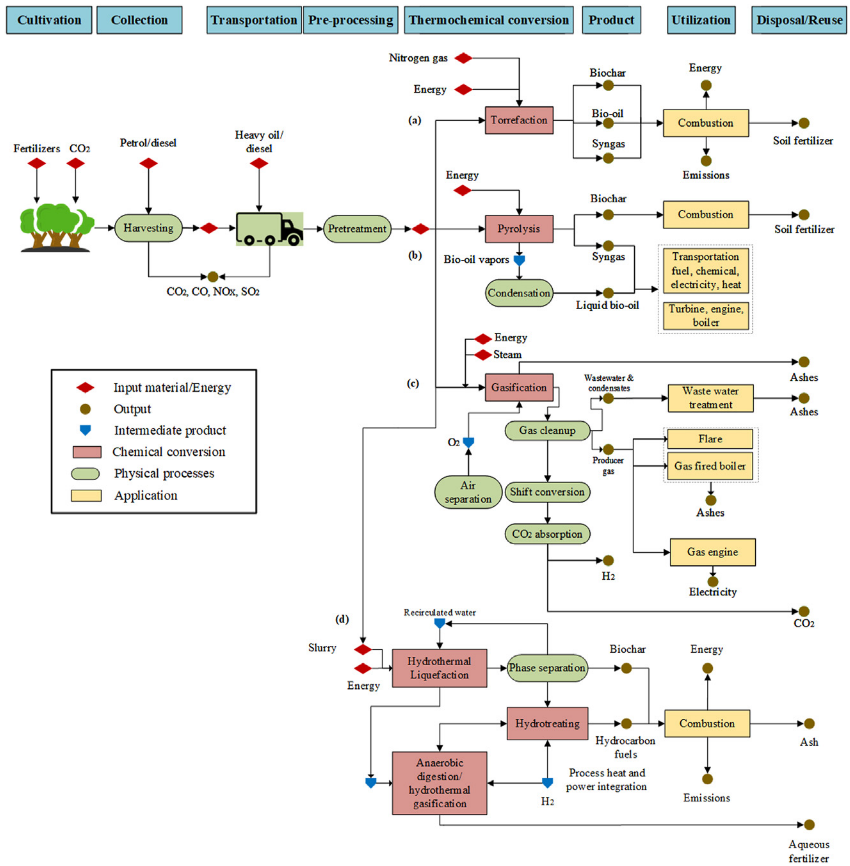

Figure 11.3 The system boundary for the (a) torrefaction, (b) pyrolysis, (c) gasification, (d) hydrothermal liquefaction technologies.

Torrefied biomass made of bamboo, teak and acacia wood was subjected to a comparative LCA by Partey et al. (2017). The results showed that bamboo, acacia wood and teak had the lowest to highest GWP effect degrees.

The following environmental advantages of cofiring torrefied lignocellulosic biomass and coal with traditional coal power generation were compared using the LCA technique. Tsalidis et al. (2014) examined the various effect categories of coal-fired, conventional coal-fired and co-fired torrefied wood biomass electricity. In comparison to coal, co-firing reduced the GWP by 12%, acidification by 7% and photochemical oxidation potential by 5%. Huang et al. (2013) assessed the advantages of

Table 11.1 The summary of the LCA studies using the various thermochemical processes.

Biomass	Process	Product	Functional unit	System boundary	Software	Impact categories	Refs.
Jatropha curcas seedcake	Gasification + Fischer Tropsch synthesis	Bio-methanol	1 kg of bio-methanol produced	Cradle to gate	Waste reduction algorithm (WAR)	HTP, TEP, AP, GWP, OLDP, POFP	Makepa et al. (2023)
Acacia (*Acacia auriculiformis*)	Torrefaction	Biochar	1 MJ energy produced	Cradle-to-gate	SimaPro	EP, HTP, RD	(Partey et al., 2017)
Bamboo (*Bambusa balcooa*)	Torrefaction	Biochar	1 MJ energy produced	Cradle-to-gate	SimaPro	EP, GWP, HTP, RD	Partey et al. (2017)
Coen stover	Torrefaction	Biochar	1 MJ electricity	Gate-to-grave	GREET	GWP	Kaliyan et al. (2014)
Olive husk	Torrefaction	Biochar	1 ton torrefied olive husk	Gate-to-grave	GaBi CML 2001	AD, AP, EP, GWP, OLDP	Christoforou and Fokaides (2016)
Pine pellet	Torrefaction	Biochar	1 MJ energy content and 1 kWh electricity produced	Cradle-to-gate	SimaPro	AD, AP, EP, FWEP, HTP, MAEP, POFP, TEP	Arteaga-Pérez et al. (2015)
Rice straw	Torrefaction	Biochar	1 kW-hr electricity	Cradle-to-grave	SimaPro	AEP, GWP, LO, TEP	Huang et al. (2013)
Teak (*tectona grandis*)	Torrefaction	Biochar	1 MJ energy produced	Cradle-to-gate	SimaPro	EP, GWP, HTP, RD	Partey et al. (2017)

(*Continued*)

Table 11.1 The summary of the LCA studies using the various thermochemical processes.—cont'd

Biomass	Process	Product	Functional unit	System boundary	Software	Impact categories	Refs.
Pine wood	Torrefaction	Biochar	1 ton torrefied wood pellet	Cradle-to-gate	SimaPro	EP, FFD, GWP, LO, PMF	Adams et al. (2015)
Pine wood	Torrefaction	Biochar	1 MJ electricity produced	Cradle-to-grave	—	GWP	McNamee and et al. (2016)
Woody biomass	Torrefaction	Biochar	1 kWh electricity produced	Cradle-to-gate	CMLCA	AP, GWP, POFP	Tsalidis et al. (2014)
Corn stover	Pyrolysis	Biochar	1 ton dry biomass	Cradle-to-gate	GREET	GWP	Roberts et al. (2010)
Short rotation coppice willow	Pyrolysis	Biochar	1 GJ energy content	Cradle-to-grave	Ecoinvent database v3.3	GWP	Ahmadi Moghaddam et al. (2019)
Switchgrass	Pyrolysis	Biochar	1 ton dry biomass	Cradle-to-gate	GREET	GWP	Ahmadi Moghaddam et al. (2019)
Yard waste (brush, leaves, grass clippings)	Pyrolysis	Biochar	1 ton dry biomass	Cradle-to-gate	GREET	GWP	Roberts et al. (2010)
Logging residue	Pyrolysis	Bio-oil	1 kWh electricity generated	Cradle-to-gate	SimaPro	GWP	Fan et al. (2011)
Oil palm empty fruit bunch	Pyrolysis	Bio-oil	1 kg bio-oil	Cradle-to-gate	GREET	AP, EP, GWP, HTP, POFP	Chan et al. (2016)

Short-rotation poplar	Pyrolysis	Bio-oil	1 ton bio-oil	Cradle-to-gate	SimaPro	AP, EP, GWP, LO, OLDP, POFP,	Iribarren et al. (2012)
SRF poplar	Pyrolysis	Bio-oil	1 kWh electricity generated	Cradle-to-gate	SimaPro	GWP	Fan et al. (2011)
Short rotation forestry (SRF) willow	Pyrolysis	Bio-oil	1 kWh electricity generated	Cradle-to-gate	SimaPro	GWP	Fan et al. (2011)
Wood waste (sawmill)	Pyrolysis	Bio-oil	1 kWh electricity generated	Cradle-to-gate	SimaPro	GWP	Fan et al. (2011)
Oil palm empty fruit bunch	Liquefaction	Bio-oil	1 kg bio-oil	Gate-to-grave	GREET	AP, EP, GWP, HTP, POFP	Chan et al. (2016)
Palm kernel shell	Liquefaction	Bio-oil	1 kg bio-oil	Cradle-to-gate	GaBi	AP, GWP, HTP, POFP	Chan et al. (2018)
Sugarcane residue	Liquefaction	Bio-oil	1 MJ bio-jet fuel	Cradle-to-grave	CCaLC2 software	GWP	Michailos (2018)
Almond	Gasification	Synthesis gas	1 Nm^3 hydrogen	Cradle-to-gate	GaBi	AP, EP, GWP	Moreno and Dufour (2013)
Eucalyptus	Gasification	Synthesis gas	1 Nm^3 hydrogen	Cradle-to-gate	GaBi	AP, EP, GWP	Moreno and Dufour (2013)
Vine	Gasification	Synthesis gas	1 Nm^3 hydrogen	Cradle-to-gate	GaBi	AP, EP, GWP	Moreno and Dufour (2013)

(Continued)

Table 11.1 The summary of the LCA studies using the various thermochemical processes.—cont'd

Biomass	Process	Product	Functional unit	System boundary	Software	Impact categories	Refs.
Pinewood	Gasification	Synthesis gas	1 Nm^3 hydrogen	Cradle-to-gate	GaBi	AP, EP, GWP	Moreno and Dufour (2013)
Pine wood	Gasification	Synthesis gas	1 MJ/s produced hydrogen	Cradle-to-gate	—	AP, AEP, EP, FFD, HTP, LO, OLDP,	Kalinci et al. (2012)
Poplar	Gasification	Synthesis gas	1 MJ energy produced	Cradle-to-gate	SimaPro	AP, EP, GWP, OLDP	Carpentieri et al. (2005)
Sugarcane	Gasification	Synthesis gas	1 kg produced methanol	Cradle-to-gate	SimaPro	AD, AP, EP, FWEP, GWP, HTP, LO, MAEP, OLDP, POFP, TEP	Renó et al. (2011)
Willow	Gasification	Synthesis gas	1 MWh electricity generated	Cradle-to-gate	TEAM	GWP	Heller et al. (2004)
Willow chip (*Salix* spp.)	Gasification	Synthesis gas	200-Ton willow chip	Cradle-to-gate	SimaPro	AD, AP, EP, GWP, LO, OLDP, POFP,	González-García et al. (2012)
Wood	Gasification	Synthesis gas	1 MJ energy produced	Cradle-to-gate	Eco-indicator 99, Eco-scarcity	GWP	Luterbacher et al. (2009)

Wood	Gasification	Synthesis gas	1 kWh electricity produced	Cradle-to-gate	SimaPro	AP, EP, FFD, GWP, PMF	Nuss et al. (2013)
Wood waste	Gasification	Synthesis gas	1 ton wood pellet	Cradle-to-grave	SimaPro	GWP, HTP	Pa et al. (2011)
Wood pellet	Gasification	Synthesis gas	1 ton wood pellet	Cradle-to-grave	SimaPro	GWP, HTP	Pa et al. (2011)

AD, Abiotic depletion; *AEP*, Aquatic Ecotoxicity Potential; *AP*, Acidification Potential; *EP*, Eutrophication Potential; *FFD*, Fossil Fuel Depletion; *FWEP*, Fresh Water Ecotoxicity Potential; *GWP*, Global Warming Potential; *HTP*, Human Toxicity Potential; *LO*, Land Occupation; *MAEP*, Marine Aquatic Ecotoxicity Potential; *OLDP*, Ozone Layer Depletion Potential; *PMF*, Particulate matter formation; *POFP*, Photochemical Oxidation Formation Potential; *RD*, Resource Depletion; *TEP*, Terrestrial Ecotoxicity Potential.

co-firing coal at a ratio of 10% and 20% with torrefied biomass made from rice straw. In order to compare the consequences of utilizing coal alone versus coal with torrefied pine pellets for power generation, Arteaga-Pérez et al. (2015) performed a comparative research. In comparison to a plant using just coal, a 20:80 ratio of torrefied wood biomass to coal reduced abiotic depletion by 11%, acidification potential by 20%, human toxicity by 20%, eutrophication potential by 15% and GWP by 16%. Kaliyan et al. (2014) investigated the GHG emissions of torrefied corn stover co-fired with coal and corn stover co-fired with coal for the purpose of producing electricity. When torrefied maize stover was mixed with coal at a higher ratio than regular coal, the findings showed a decreasing trend in GHG emissions.

11.2.3.2 Pyrolysis

The majority of recent research is on the characterization of pyrolysis of various lignocellulosic biomass feedstocks to yield pyrolysed bioenergy products such biochar, bio-oil and combustible gases. However, there are just three LCA studies that were discovered on the LCA of pyrolysed lignocellulosic biomass.

Fan et al. (2011) studied the GWP of pyrolysed bio-oil derived from various forest resources, including logging residue, willow and poplar, and found that their GWP impacts were relatively lower than oil derived from fossil fuels. Roberts et al. (2010) evaluated the energy, economic and climate change potential of switchgrass, maize stover and yard trash and found that the uptake of CO_2 during the biomass growth phase had a negative influence on GWP. Chan et al. (2016) assessed the environmental effects of pyrolysing empty fruit bunches to produce bio-oil, contrasting the effects with hydrothermal liquefaction.

11.2.3.3 Liquefaction

The majority of HTL investigations are devoted to characterizing various lignocellulosic biomass (Haarlemmer et al., 2016; Yim et al., 2017). A limited number of studies, however, have attempted to accurately assess the sustainable production of bioenergy products using the HTL pathway. The following is a discussion of these LCA works. Chan et al. (2016) assessed the liquefaction-produced empty fruit bunch oil's effects on the environment. Later, Chan et al. (2018) broadened the evaluation to include the effects of palm kernel shell oil. A 50% GWP decrease was obtained for bio-jet fuel when compared with fossil jet fuel.

11.2.3.4 Gasification

The following is a discussion of several research studies on the LCA of gasification of lignocellulosic biomass. Renó et al. (2011) investigated the manufacture of methanol from sugarcane biomass, which produced a negative carbon emission (2.28 $kgCO_{2e}$/kg methanol) because of the significant CO_2 uptake during cultivation. Moreno and Dufour (2013) assessed the gasification of a variety of biomass feedstocks, including eucalyptus, pine, almond and vine. Given its high rate of carbon fixing during growth, eucalyptus had the lowest carbon output of all the feedstocks tested. González-García et al. (2012) looked at the gasification of wood to make ethanol, which had a negative carbon emission of 78.5 tCO_{2e} since CO_2 was absorbed during the development of the biomass. However, Carpentieri et al. (2005) and Luterbacher et al. (2009) examined the gasification of wood to produce natural gas and syngas, respectively. Their findings showed a decrease in carbon emissions for the same reason as González-García et al. (2012). In the meanwhile, Nuss et al. (2013) investigated the gasification of wood to create electricity and found emissions ranging from 0.325 to 0.653 kgCO2e/kWh of energy produced. Additionally, Heller et al. (Kalinci et al., 2012) conducted an investigation of the hydrogen generation from pine wood, yielding a GWP of 6.72 gCO_{2e}/MW of hydrogen.

The LCA was conducted without taking the emissions from the burning of the bioenergy product into account based on the aforementioned research. There were net negative CO_2 emissions as a result of a comparatively strong CO_2 fixing during the biomass growth outpacing the produced CO_2 emissions from the processing of the biomass (González-García et al., 2012).

11.3 Techno-economic assessment of biofuels from lignocellulosic biomass

The broad methodological framework for the techno-economic evaluation and earlier techno-economic studies conducted for various feedstocks for producing various biofuels are discussed in this section.

11.3.1 Methodological framework of techno-economic assessment

TEA is a method used to assess the financial viability of an industrial process. It involves using models to estimate the costs involved in setting up and operating the process, as well as evaluating its economic feasibility based on various technical and financial factors. By considering factors such as capital costs, operating costs and potential profitability, TEA provides both qualitative and quantitative evaluations of the process's financial feasibility (Makepa et al., 2023).

TEA is a commonly used approach for conducting cost–benefit analysis and exploring the economic viability of different technologies. It helps estimate cash flow, compare different technologies based on factors such as scale, efficiency and yield and assess their suitability for specific applications. Moreover, TEA is also employed to evaluate existing technologies and future prospects on a consistent analytical basis (Buchner et al., 2018).

To effectively design a process, it is crucial to screen the research status of available technologies and determine their potential for commercial viability. This involves making assumptions based on relevant and consistent data, while considering the level of detail required for the process design. When evaluating emerging technology pathways to produce various products, the production costs are estimated by considering both capital and operating expenses. Additionally, any credits or benefits resulting from by-products of the process should be taken into account (Makepa et al., 2023). Fig. 11.4 presents a typical framework for analysing the techno-economic feasibility of emerging technologies. It serves as a guide to carry out a comprehensive assessment of the financial aspects associated with the technology under consideration.

The TEA process involves several key steps. First, a conceptual design configuration is developed for the proposed process or product. This includes exploring potential options for existing commercial production processes. Reliable data are then gathered from laboratory-scale experiments and relevant literature to inform the envisioned process options. Next, a conceptual process design is created, incorporating material and energy balance data. This is achieved through the use of process simulation software such as Aspen, HYSIS or CHEMCAD. These software models are developed based on research and development results obtained at bench and pilot scales. The simulation takes into account various factors such as mass and energy flows, temperature, pressure, yield and efficiency. In order to accurately represent the current state of technology, appropriate assumptions are made where necessary. These assumptions are based on industrial-scale knowledge and are informed by data obtained from the relevant literature (Do et al., 2020).

The subsequent stage involves estimating the capital and operating expenses by utilizing data obtained from material and energy balances for

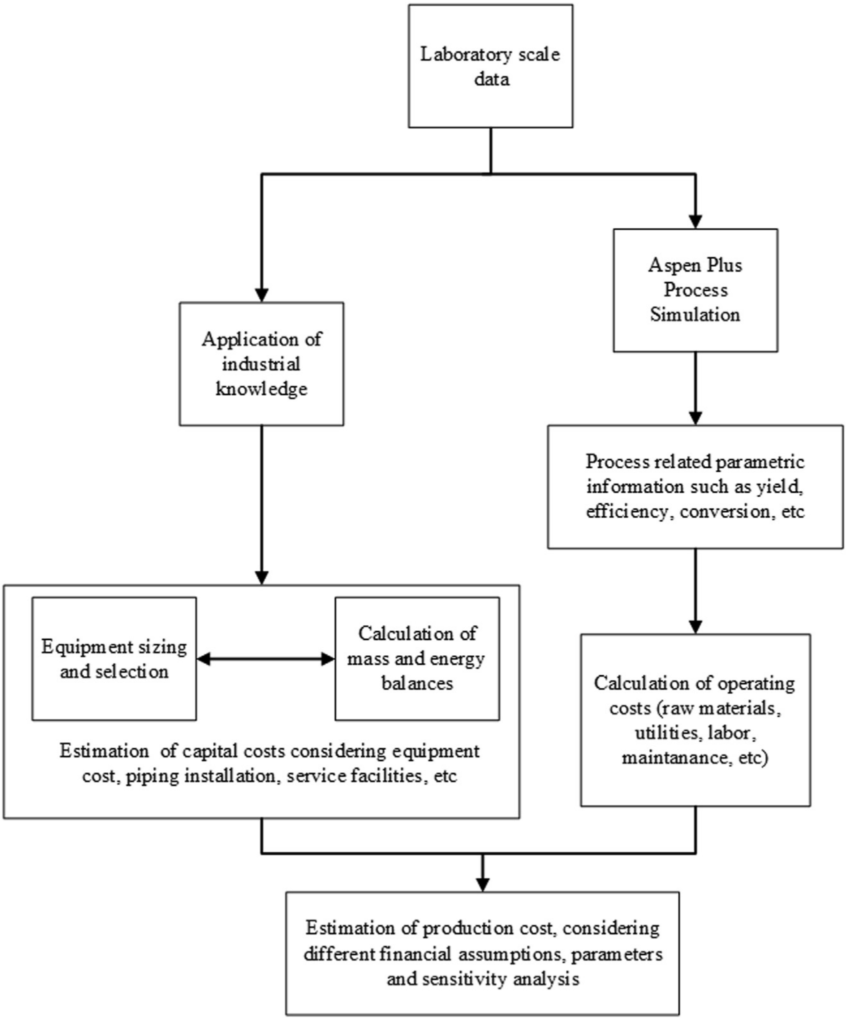

Figure 11.4 A broad conceptual framework outlining the methodology for conducting techno-economic assessments of emerging technologies.

various processes through simulations. Capital costs typically encompass the total financial investment required for constructing an industrial plant. Working capital, which refers to the initial investment needed to start the plant, is recovered over the project's lifespan. The capital costs for the proposed plant primarily consist of expenses related to significant components such as equipment procurement, land acquisition, building construction and overall construction costs. The sizing of equipment is determined based on the data from material and energy balances, with considerations made for each process and the proposed capacity for scaling up (Arena et al., 2010). The costs associated with equipment, instrumentation and control can be estimated by referencing published literature and obtaining quotes from manufacturers, taking into account the specified reference year. The total capital investment (TCI) for a plant comprises several components: the fixed capital investment (FCI), start-up costs (equivalent to 10% of FCI), working capital (equivalent to 5% of FCI) and interest during the construction phase. A portion of the fixed operating costs, including maintenance labour, maintenance materials, overheads and insurance, is determined based on percentages of the FCI, which can be obtained from relevant literature. These percentages serve as the basis for calculating the variable operating costs, which encompass expenses such as feedstock, electricity, heat, catalyst costs and other related factors. The capital charges, along with the fixed and variable operating costs, are combined to determine the overall production cost for the specific product (Zuorro et al., 2020).

When conducting a techno-economic analysis, it is possible to examine the total time and recurring costs incurred throughout the project's lifespan using various financial metrics. Continuous improvement of the process in TEA involves incorporating data from previous assessments and updated information regarding the process and other system variables. As the process or technology progresses towards commercialization, the level of uncertainty associated with TEA tends to decrease. To address uncertainty, sensitivity analysis is performed by altering different input parameters in the model and observing their impact on the output parameters. This analysis helps determine the contribution of various factors such as feedstock costs, plant capacity, yields, to the variability of the final results and understand their corresponding effects. TEAs are valuable in assessing the potential success of conceptual designs and economic parameters in the short, medium and long term for the process or technology under consideration. Additionally, TEA can be used to compare different process or technology pathways by utilizing technical and economic outcomes derived from the techno-economic models. Through this comparison, the most promising route for further commercialization can be identified (Makepa et al., 2023; Albrecht et al., 2017).

The production cost of a product is significantly influenced by factors such as the feedstock supply chain, location, scale of operation and the selection of technology. To analyse the economic aspect of technologies, various techniques and metrics are employed, often based on certain assumptions.

However, these assumptions can vary significantly across different studies, making it challenging to compare different techno-economic evaluations. Techno-economic assessment offers valuable insights for various stakeholders. For engineering research, it provides potential areas of improvement that can lead to significant cost reductions. For other stakeholders, such as biomass suppliers, investors, governments and energy consumers, it offers additional insights to aid decision-making at different stages. These insights can inform choices related to investment, policy-making and energy consumption strategies (Mousavi-Avval et al., 2023; Makepa et al., 2023; Zuberi et al., 2023).

11.3.2 Overview of the techno-economic assessment studies of biofuel production from lignocellulosic biomass

Recent advancements in thermochemical processing pathways for biomass have demonstrated their potential for commercialization. However, conducting techno-economic assessments (TEAs) is crucial to accurately evaluate the economic competitiveness of these emerging fuel production pathways, using petroleum alternatives as benchmarks for comparison. The choice of technologies heavily depends on factors such as the type of feedstock, desired end products and geographical location. Assessing the technical and economic performance of each process route is essential for formulating long-term strategies and making informed investment decisions for the future. TEAs provide valuable insights into the economic feasibility and viability of different thermochemical pathways, enabling stakeholders to make well-informed choices in the context of biofuel production (Table 11.2) (Patel et al., 2016).

In the preceding section, an overview of several TEA studies that explore various advanced biofuel production pathways was provided. These studies encompass a wide range of feedstocks and products, and they shed light on the cost of production based on the growing body of literature on TEA. The table presented earlier summarizes comprehensive techno-economic analyses of diverse biomass raw materials utilized for the production of bio-based fuels and products through thermochemical processing routes. The production cost of biofuels is significantly influenced by factors such as the scale of operation, choice of technology, location and the maturity level of the technology (Do et al., 2014; Atsonios et al., 2015; García-Velásquez and Cardona, 2019; Brigagão et al., 2019; Ramirez and Rainey, 2019; Winjobi et al., 2017). However, despite notable advancements in recent years, only a limited number of thermochemical pathways have achieved

Table 11.2 Overview of the different techno-economic assessment studies for different lignocellulosic biomass feedstocks.

Biomass feedstock	Conversion technology	Product	Capacity (tonnes/day)	Production cost ($/kg or $/L)	Refs.
Pine sawdust	Microwave-assisted pyrolysis	Bio-oil	4.8	1.14	Makepa et al. (2023)
Palm empty fruit branches	Fast pyrolysis using fluidized bed	Bio-oil	60	0.47	Do et al. (2014)
Wood chips	Fluidized bed gasification	Ethanol	2140	0.75	Reyes Valle et al. (2013)
Lignocellulosic biomass	Gasification + upgradation	Ethanol	2100	0.39	He and Zhang (2011)
Woody biomass	Hydrothermal liquefaction (HTL) and upgrading	Bio-oil	2000	1.29	Zhu et al. (2014)
Wood chips	Gasification + upgrading of alcohols to aviation fuel	Jet fuel	864	1.52	Atsonios et al. (2015)
Forest biomass	Pyrolysis + upgradation	Liquid biofuel + biochar	220	1.09	Campbell et al. (2018)
Wood chips	Entrained flow gasification	Ethanol	2000	0.90−1.25	Uslu et al. (2008)
Poplar chips	Gasification + (dimethyl ether) hydro carbonylation	Ethanol	2140	0.55−0.59	Haro et al. (2012)
Rice husk	Pyrolysis	Bio-oil and biochar	300	0.043 ($/MJ)	Unrean et al. (2018)
Rice husk	Hydrothermal carbonization (HTC)	Pelletized solid fuel	300	0.013 ($/MJ)	Unrean et al. (2018)
Pinus patula (PP)	Gasification	Electricity	1000	0.025($/MJ)	García-Velásquez and Cardona (2019)
Corn cob	Gasification	Methanol	1400	0.238−0.369	Brigagão et al. (2019)
Corn cob	Pyrolysis	Bio oil	1990	0.0763−0.167 ($/MJ)	Brigagão et al. (2019)

Willow	Fast pyrolysis	Bio oil	65	0.42	Kuppens et al. (2015)
Willow	Fast pyrolysis	Char	65	0.15	Kuppens and et al. (2015)
Sugarcane bagasse	Gasification	Syngas	240	1.94	Ramirez and Rainey (2019)
Sugarcane bagasse	Liquefaction	Biocrude	240	0.98	Ramirez and Rainey (2019)
Sugarcane bagasse	Pyrolysis	Biooil	240	1.19	Ramirez and Rainey (2019)
Corn stover	Fast pyrolysis integrated bio-oil gasification	Advanced biofuel	2000	1.47	Li et al. (2015)
Corn stover	Gasification	Biohydrogen	2000	2.33−4.33	Zhang et al. (2013)
Napier grass	Pyrolysis + upgradation	Pyrolytic oil	1.2	1.45	Mohammed et al. (2019)
Pine	Torrefaction and fast pyrolysis	Liquid biofuel	1000	0.83	Winjobi et al. (2017)
Woody biomass	Gasification + upgradation	Butanol	1000	1.60−1.69	Okoli and Adams (2014)

commercial viability at an industrial scale. This highlights the challenges that still need to be addressed. Continued research and development efforts are necessary to enhance the competitiveness of thermochemical pathways and enable them to effectively compete with non-renewable energy resources.

11.4 Challenges, progress, opportunities and future perspectives

LCA and TEA are two important tools used to evaluate the environmental and economic aspects of biofuel production from lignocellulosic biomass. However, there challenges and opportunities associated with these analyses.

LCA and TEA heavily rely on accurate and reliable data. Obtaining comprehensive and up-to-date data for all stages of the biofuel production process, including biomass cultivation, harvesting, conversion and distribution, can be challenging. Setting appropriate system boundaries for LCA and TEA is crucial. Determining which processes and inputs to include or exclude can be complex and may impact the results and comparability of different studies. LCA and TEA involve numerous assumptions and uncertainties that can influence the results. Variability in biomass composition, conversion technologies and regional-specific factors adds complexity to the analysis. Assessing indirect effects, such as land-use change or displacement effects and trade-offs between environmental and economic aspects can be challenging, as they often require complex modeling and data integration.

Significant progress has been made in LCA and TEA methodologies for biofuel production from lignocellulosic biomass. Researchers have developed standardized frameworks and databases, such as the GWP and Ecoinvent, which facilitate more consistent and comparable assessments. Advances in lignocellulosic biomass conversion technologies, such as biochemical and thermochemical processes, have improved the efficiency and environmental performance of biofuel production. These advancements have led to more accurate input data and reduced uncertainties in LCA and TEA. LCA and TEA are increasingly considering broader sustainability metrics, including social and economic indicators, to provide a more comprehensive assessment of biofuel production systems.

Governments and regulatory bodies worldwide are recognizing the importance of biofuels in mitigating climate change and reducing dependence on fossil fuels. This support creates opportunities for conducting LCA and TEA to inform policy decisions and incentivize sustainable biofuel production. Lignocellulosic biomass can be derived from various waste and by-product streams, promoting the concept of a circular economy. LCA and TEA can help identify the most sustainable pathways for utilizing these biomass resources and minimizing waste generation. Ongoing research and development efforts are focused on improving lignocellulosic biomass conversion technologies, such as pretreatment methods, enzymatic hydrolysis and fermentation. LCA and TEA can guide the optimization and scale-up of these technologies by identifying their environmental and economic impacts.

Future LCA and TEA studies should aim to incorporate a more comprehensive and holistic approach, considering not only environmental and economic aspects but also social dimensions, such as employment generation and community impacts. Dynamic LCA and TEA models that account for changes in technology, feedstock availability and market conditions over time can provide more accurate predictions and support long-term decision-making. The increasing availability of big data and advanced analytics techniques can enhance LCA and TEA by improving data quality, identifying patterns and correlations and reducing uncertainties. LCA and TEA can be integrated into optimization models to identify the most sustainable and economically viable biofuel production pathways, considering various constraints and objectives simultaneously.

11.5 Conclusion

This chapter provided an overview of LCA and TEA approaches and their application to evaluating the environmental and economic impacts of biofuel production from lignocellulosic biomass. LCA methodologies were described in detail, outlining crucial steps such as goal and scope definition, lifecycle inventory analysis, impact assessment and interpretation of results. Numerous case studies applying LCA to thermochemical and biochemical conversion pathways for various biomass feedstocks were reviewed. TEA frameworks and methodologies were also discussed, highlighting important components such as process modeling, capital and operating cost estimation and economic metrics. Key techno-economic studies assessing different biofuel production routes were summarized.

While LCA and TEA are useful analytical tools, their application to emerging biomass technologies still faces challenges related to data availability and quality, boundary setting, modeling complexity and uncertainty. However, standardized methods and databases are helping to address these issues and facilitate more consistent and accurate assessments. Advances in conversion processes are also improving the sustainability and economic feasibility of biofuel pathways. Looking ahead, integrated LCA-TEA modeling and the incorporation of broader sustainability metrics can provide deeper insights. With continued progress in technologies and analytical methods, as well as supportive policies, LCA and TEA will play an important role in optimizing biofuel production systems and guiding their transition towards commercial viability and widespread adoption. Overall, assessing environmental impacts and costs throughout the entire lifecycle is essential to realizing the sustainable and large-scale potential of lignocellulosic biomass as a bioenergy feedstock.

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