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Review

A Critical Review of Life Cycle Assessments on Bioenergy Technologies: Methodological Choices, Limitations, and Suggestions for Future Studies

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Abstract: Bioenergy is one of the renewable energy sources with high expectations in terms of its potential for greenhouse gas (GHG) emissions mitigation, and thus has been included in most global warming limiting strategies and pathways. However, within this context, a state-of-the-art and comprehensive understanding of the environmental performance of currently available bioenergy technologies is still missing. Hence, we conduct this critical review on life cycle assessment (LCA) studies regarding a wide portfolio of bioenergy technologies to deal with this lack of knowledge. Our critical review of exhaustively searched literature identified commonly existing limitations and difficulties in the selected LCAs in terms of essential aspects of LCA, i.e., system boundaries, functional unit (FU), multifunctionality, and impact categories. Key findings of our review are as follows: inconsistency of system boundary definitions, incomparability of LCA results due to various FU definitions, incomprehensiveness of impact categories, as well as a lack of uncertainty and sensitivity analysis. Finally, in view of the above findings, we present a generic guideline for future studies with the purpose of overcoming the identified shortcomings.

Keywords: biomass; biopower; biofuel; life cycle assessment

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1. Introduction

Limiting global warming depends on reducing greenhouse gases (GHGs) to net zero, and carbon emissions from energy use are the largest source of GHG emissions [1]. The projected carbon-neutral energy systems in the global warming mitigation pathways all share a substantial reliance on bioenergy [2]. IPCC pointed out that the share of energy from renewable sources is supposed to reach 38–88% in 2050 in all mitigation pathways, and bioenergy specifically will reach more than 20%. Bioenergy in the global primary energy supply accounted for only 4.7% of the commercially traded shares in 2018, and totally fractioned 10.17% in 2020 [1,2].

Biofuel technologies have evolved from the first to the fourth generation, i.e., biofuels from food crops (e.g., corn and wheat), lignocellulosic crops (e.g., herbaceous and wood plants, agricultural, and forestry residues, etc.), algae, and genetically modified algae [3].

Currently, first- and second-generation biofuels are the most commercially available technologies; however, numerous studies have shown that their application is environmentally debatable. For instance, first-generation biofuels cause energy vs. food competition, and second-generation biofuels also result in a land use transformation from agricultural use to cultivating dedicated energy crops. As for the third generation, the associated technologies are still not widely commercially available. Fourth-generation biofuels are still at the laboratory scale. Thus, global-warming mitigation pathways raise complexity trade-offs between these environmental aspects for bioenergy utilization and future large-scale promotion.

Life cycle assessment (LCA) has been applied as a policymaking supporting instrument to assess energy systems' environmental implications. There have been a large number of reviews reported regarding LCA on bioenergy systems, from various perspectives such as methodological choices, LCA practice in specific regional areas, impact categories, specific technologies, and challenges of LCA. Below, we briefly summarize some of the reviews.

Review of LCA methodologies. Marvuglia et al. conducted a critical review of consequential life cycle inventory (LCI) modelling approaches and proposed a methodology to integrate economic modelling and LCA of biogas production [4]. Liu et al. presented a critical review regarding the carbon-neutrality assumption in LCA models for bioenergy usage [5]. Homa et al. reviewed the advancements in LCA within bioenergy systems, critically analyzing the advantages and limitations of LCA in bioenergy product systems and identifying the key sources of uncertainty [6]. Salim et al. discussed various LCA methodologies and tools, emphasizing the need for standardized approaches to ensure consistency and comparability of results [7]. Roos and Ahlgren conducted a review of consequential LCA (CLCA) studies on the use of bioenergy and found that most of the LCA literature emphasized European countries [8].

Review of LCA in specific regional areas. Hijazi et al. presented a review of LCA for biogas production in Europe, and their study indicates that feedstock types determine the systems' environmental impacts [9]. Lazarevic and Martin reviewed Swedish biofuel LCAs and concluded that the carbon footprint is dominantly focused on other impact categories [10]. Liu et al. reviewed China's biofuels LCAs and pointed out that impact indicators other than energy and GHG are barely investigated [11]. O'Keeffe et al. conducted an overview of important considerations when assessing bioenergy systems in a regional and LCA context and how these two contexts intersect [12]. Hoyoung et al. conducted a life cycle analysis of five offshore macroalgae production systems in the United States and evaluated their potential environmental impacts using publicly available LCA tools [13].

Review of LCA impact categories. Menten et al. reviewed LCAs of advanced biofuels and highlighted a hierarchy between third-generation and second-generation biofuels; the life cycle GHG emissions of the former are higher [14]. Gaudreault et al. presented an overview regarding land use (LU) related biodiversity impact in forestry biomass harvesting and stated that it is difficult to quantitatively assess biodiversity in LCA practice [15]. Souza et al. presented a review of the ecosystem services (ES) in the LCA of biofuels and proposed a framework for the integration of ES into LCA [16]. Li et al. presented an LCA review for bioenergy and identified that "GHG" attracted more attention; moreover, the environmental performance of "biogas" and "LU" began to receive attention in 2015 [17]. Neha et al. conducted an LCA of bioethanol production from various generations of biofuel feedstocks and waste materials, concluding that waste-based feedstocks exhibit the lowest environmental impact [18]. Andreas et al. employed the LCA method to comprehensively evaluate the greenhouse gas emission reduction potential of utilizing forestry residues in various bioenergy technologies, addressing the uncertainty and assumption issues in LCA modelling through scenario analysis [19].

Review of LCAs regarding specific technologies. Reviews of LCA on specific bioproducts and bioenergy technologies are also reported, e.g., LCAs on microalgae-based bioenergy [20], algae-based biofuels [21], lignocellulosic biomass thermochemical conversion technologies [22], and biomass densification systems [23], and the current status of bioplastic production in terms of LCA [24].

Review of bioenergy LCA challenges. McManus et al. reviewed bioenergy LCAs and identified the main challenges are overarching issues, application and practice, and ethical judgments [25]. Czyrnek-Deletre et al. presented a review of LCA on biofuel systems and aimed to illustrate the challenge in setting guidelines for biofuel LCA beyond carbon and energy [26]. Agostini et al. presented a review of the 100 most cited articles of biofuel LCAs and summarized the flaws in the interpretation phase of these LCAs [27]. Angelos et al. conducted a critical review of previous research employing LCAs to evaluate various pathways for macroalgae utilization; however, many development pathways have not yet been implemented on a large scale [28].

This paper pioneers a cross-technology systematic diagnosis of bioenergy LCA, synthesizing 233 studies on biomass combustion, biopower, and all four generations of biofuels. In contrast to previous reviews, we situate controversies such as food versus fuel within the broader LCA deficit, exposing widespread methodological flaws; compare environmental trade-offs across technologies: for example, while first-generation biofuels face greenhouse gas emission penalties driven by land use change, third-generation systems ignore the impacts of water scarcity, and biomass combustion tends to ignore ash disposal; and compare the environmental impacts of biofuels and biomass combustion across technologies by examining different geographic studies, integrating temporal and spatial scales. By bridging these divides, our analysis not only resolves isolated debates but also establishes a unifying framework to improve the rigour and policy relevance of LCA.

Overall, the following research gaps are identified: Although the first generation of biofuels has been widely adopted globally, there is still significant controversy surrounding biofuels produced from food crops such as corn, sugarcane, and oilseeds. These controversies mainly focus on their impact on environmental and social sustainability, especially when considering factors such as fertilizer use, irrigation demand, and process emissions. Many studies have found that excessive use of fertilizers in the production of first-generation biofuels not only increases soil and water pollution but also leads to an increase in greenhouse gas emissions. During the irrigation process, the consumption of water resources, especially in arid areas, exacerbates the local water shortage problem. At the same time, the cultivation of these crops may also lead to soil degradation and loss of biodiversity. In addition, the intensive agricultural production mode, especially in areas with scarce water resources, significantly exacerbates the tension and pollution problems of water resources. Policies promoting the production of first-generation biofuels often focus too much on energy security and overlook broader social and ecological trade-offs. These controversies highlight methodological challenges in the practice of life-cycle assessment, particularly in the definition of system boundaries, allocation methods, and the exclusion of indirect impacts, and resolving these discrepancies is critical to the development of equitable and effective bioenergy policies [25–27].

In addition, the existing review studies normally focus on specific technologies, rather than considering the bioenergy technologies as a whole; the existing literature usually reviews some aspects of the bioenergy LCAs and lacks a holistic sense of their implications; an up-to-date comprehensive critical review of LCAs including a wider portfolio of bioenergy technologies is missing. Thus, this study aims to critically review bioenergy LCAs on a broader bioenergy portfolio, i.e., biomass combustion, biopower, and biofuels. Essential aspects of LCA, e.g., system boundary, FU, multifunctionality, and impact

category [29] will be examined. We also synthesize the key findings and draw a generic guideline for future LCA practices of bioenergy systems in order to increase understanding of the environmental performance of bioenergy systems from a holistic point of view.

2. Materials and Methods

2.1. Life Cycle Assessment

For bioenergy systems, a typical life cycle usually includes biomass production, pre-treatment, conversion, and usage. A simplified cradle-to-grave life cycle scheme of a combined heat and power (CHP) system using woody biomass is shown in Figure 1. The life cycle encompasses the following stages: forestry biomass cultivation; energy acquisition from the sun through photosynthesis and stored as chemical energy; forestry biomass collection and the log transportation; log processing; wood biomass transportation to chipping (pelleting) plant; residue collection and transportation; the processed chip (pellet) transportation; electricity and heat generation in the CHP; electricity and heat delivery; and ash collection and disposal.

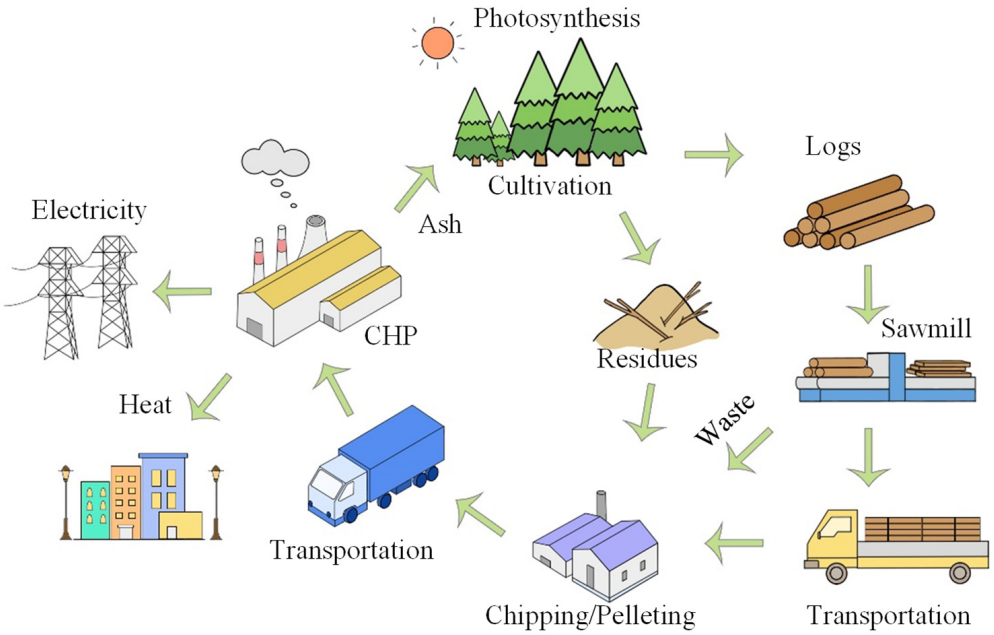


Figure 1. Schematic of simplified life cycle for a combined heat and power (CHP) plant using forestry biomass. Common LCA practices usually exclude the usage phase of the product (bio-electricity and heat) from the system boundary, yet here it is included for illustration of the integrity of life cycle stages.

2.2. Literature Search Strategy and Refining

The LCA review is conducted by searching Google Scholar and Scopus database with the following keywords: (1) "biomass", or "biopower", or "bioenergy", or "biofuel", or "bioproduct"; and (2) "life cycle assessment", or "LCA", or "life cycle analysis", or "environmental assessment". The identified 3617 studies were then screened with 4 criteria: (1) papers published in peer-reviewed journals, conference proceedings, or official technical reports; (2) focus on environmental aspects; (3) environmental analyses using tools other than LCA are excluded; and (4) secondary studies are excluded. This finally left 233 studies, amongst which 24 cases are about biomass combustion, 64 are about biopower, and 145 are about biofuels.

2.3. Structure of This Review

Our review is structured according to the portfolio, including biomass combustion, biofuels of four generations (including biogas), biopower, and bioproducts. We adopted the essential LCA aspects suggested by Terlouw et al. in their critical review study for carbon dioxide removal technologies, i.e., system boundaries, FU, multi-functionality, and impact categories [29], for this critical review.

3. Review

Each bioenergy technology is briefly introduced, and then the current state and essential aspects for related LCAs are quantitatively analyzed. The synthesis of the review results, open issues, and limitations of current LCA practice, and the suggestions for future LCAs on bioenergy systems are presented in Section 4.

3.1. Biomass Combustion for Heat Supply

Biomass combustion refers to the direct burning of biomass for energy supply, specifically heat supply for domestic heating and industrial processing. The studied feedstocks include dedicated energy crops such as woody and herbaceous plants, residues from forestry and agriculture, municipal solid waste, etc. The feedstocks vary in form, e.g., woody plant biomass could be prepared in the form of logs, chips, or briquettes. The appliances for the burning of biomass include a fireplace, stove, and boiler.

LCAs. Our literature search found 24 studies. These studies cover the heat supply end users from small to large scales, e.g., from buildings, residential areas, districts, and the nation. The most common finding is that biomass combustion is favourable in comparison with conventional fossil fuels in terms of global warming potential (GWP).

System boundaries. Our review found that the cradle-to-grave approach is applied by most (22/24) of the selected LCAs on biomass combustion. The system boundaries normally (21/24) include biomass-chain orientated processes, i.e., biomass material production, feedstock (e.g., wood logs, chips, and pellets) production, transportation, thermal energy conversion, and ash disposal. Life cycles of thermal energy production infrastructure (i.e., heat plant, furnace, stove, and boiler) are only considered in 4 studies [30–33]. When feedstock is produced from agricultural or forestry residues, the resource production stage is excluded, as it is argued that the biomass is not dedicatedly cultivated for thermal energy production [30,34,35].

Approaches other than cradle-to-grave are also used in some studies. For example, Supasri et al. conducted a cradle-to-gate LCA and focused on the environmental burdens for maize cultivation and cob pellet production [36]. Kylili et al. performed an LCA of the pelleting process and defined the system boundary starting from the collection of olive husks from olive mills and ending at the distribution of pellets to sale points [37]. Saba et al. performed a gate-to-gate LCA when comparing olive pruning residue made briquette with light fossil fuels [38].

The reviewed LCAs on biomass combustion are normally conducted through the attributional method with unit-process data included. As for the consequential method, Styles et al. investigated the indirect consequences of land use change (LUC), such as water purification delivered by perennial energy crops [39]. Andreas et al. evaluated the GHG reduction potential of utilizing forestry residue in different bioenergy technologies, while considering carbon capture and storage (CCS) or carbon capture and utilization (CCU) [19].

Functional Unit. The main function of the studied systems is to generate heat, and, therefore, most of the LCAs (19/24) defined the production and delivery of one unit (e.g., 1 MJ, GJ, or kWh) of thermal energy as the FU. Some studies also defined one unit (e.g., 1 kg or ton) of biomass as the FU when comparisons are made between different heat-generating

systems [34,37,40]. In some cases, both the above FU-defining approaches are adopted for the convenience of assessing different environmental indicators [36,41]. When considering LU shifts from arable land to energy crop cultivation, one unit area (1 hectare) of land is also used as the FU [42]. It is rare for LCAs on biomass combustion to use the system itself as the FU, except for one example [31], wherein two heat generation systems, a heat pump and biomass boiler, are compared. We also noticed that kW was misused as the FU [33], which is inaccurate as kW is a unit of energy generation rate instead of energy.

Multi-functionality. Most of the studied systems do not involve multi-functions. However, some systems encounter functions other than purely the generation of thermal energy, e.g., electricity generation, grain production, etc. As these functions are beyond the scope of the LCAs; therefore, they are less discussed. System expansion could be applied to further investigate the processes outside the defined system boundary if they are affected by the inside processes, e.g., using a consequential LCA approach to avoid allocation procedures.

Impact categories. GHG abatement through biomass combustion is the most important driver for its utilization to replace fossil fuels. Thus, it is reasonable that almost all the reviewed LCAs investigated the life cycle GHG emissions. Energy balance is another important indicator to evaluate the overall environmental performance of biomass combustion systems, considered in 13 studies. Taking advantage of LCA software, such as SimaPro and GaBi, other midpoint environmental impacts could be assessed, for instance, acidification, eutrophication, etc. [30,31,35,43–46]. Land occupation is of special interest for LCAs on biomass, especially when the feedstock is acquired from agricultural grains or dedicated energy crops. Styles et al. demonstrated whether excluding indirect LUC may provide significantly different results [39]. Although LUC is included in the midpoint impact categories of the software, we should realize that it is site-specific and should be treated with site-specific data rather than just data from the software database.

3.2. Biomass Power Generation

Biomass power generation refers to the conversion of biomass energy to electric power (heat) through biomass monocombustion or co-firing with fossil fuels. The feedstocks for combustion vary in states of solid (e.g., woody biomass logs, chips, and pellets), liquid, and gas (e.g., syngas from gasification). The raw biomass materials are usually acquired from dedicated energy crops, forestry, agricultural residues, construction, or sewage waste.

LCAs. There are also studies comparing the environmental performance of different bio-electricity technologies. Bioenergy is often considered superior to fossil fuels in reducing greenhouse gas emissions by considering the multiple life-cycle impacts of different technologies, including greenhouse gas emissions, water and land use, and air pollution, especially when the production, transport, and use of the fuel are considered together. Compared to fossil fuels, biomass can significantly reduce carbon dioxide emissions through carbon neutrality. In addition, many biomass sources, such as agricultural waste and forestry by-products, are renewable resources, and their utilization not only helps to reduce greenhouse gas emissions but also reduces the overexploitation of land resources. The environmental advantages of biopower technologies are also affected by factors such as land use change, crop cultivation, and transport of biomass fuels, which may result in additional environmental burdens. Therefore, further studies usually emphasize how to optimize resource use and reduce environmental burdens when implementing biomass power generation and select the best technology pathway, taking into account the resource endowment of a specific region [47–49].

System boundaries. The cradle-to-grave approach is used by most of the LCAs (44/64), followed by cradle-to-gate (19/64). The difference between cradle-to-grave and

cradle-to-gate approaches is whether to include the end-of-life process of biomass, e.g., ash disposal [50–52] or not [53–55]. The cradle-to-grave approach is used by most of the LCAs (44/64), followed by cradle-to-gate (19/64), and a small proportion were gate-to-gate (1/64). Cradle-to-grave encompasses all stages from raw material extraction to the end of the life cycle, and it provides a complete picture of the environmental impacts of a product throughout its life cycle (e.g., ash disposal, biofuel combustion). This approach is widely used in LCA because it ensures that no significant environmental impacts are overlooked. Assessing the entire life cycle enables more informed decision-making on sustainability and waste management. This is particularly important when the end-of-life-cycle phase (e.g., waste disposal or recycling) has a significant impact on the overall environmental impact. Cradle-to-gate covers the process from raw material extraction to the 'gate' of the production facility (e.g., pellet production, biofuel refining). The cradle-to-gate approach is often used when the focus is on the production phase of a product, especially in industries where the use or end-of-life phases are highly variable or of low relevance for analysis. It allows for a more focused and less resource-intensive LCA, although it may overlook important effects of use and disposal. In contrast, gate-to-gate focuses on specific processes in the supply chain (e.g., granulation, gasification). A gate-to-gate approach is often used when a detailed assessment of a specific manufacturing process is required. This approach is narrower in scope, but it provides detailed insights into energy consumption, emissions, and waste associated with specific production stages. Cradle-to-grave typically provides the most comprehensive conclusions but requires more complex data support and a higher investment of resources. Cradle-to-gate and gate-to-gate, on the other hand, are more simplified and are applicable to specific objectives but may miss some important life cycle impacts [56–58].

The system boundaries usually encompass feedstock production, processing, and conversion to biopower. Feedstock from dedicated crops could include land preparation, establishment, harvesting and restoration, transportation, and processing (e.g., chipping, pelletization, torrefaction, pyrolysis, and gasification). For agricultural and forestry residues, the LU and crop cultivation are normally neglected because they are considered by-products of crop harvesting [59]. The energy conversion includes various processes such as direct combustion, co-firing with fossil fuels (e.g., coal), combustion of biomass-derived fuels, and carbon capture and storage [60,61]. Equipment, construction, and demolition of power plants are typically excluded from the system boundaries, as their contributions are negligible compared to those of the fuel production or operation phase and can therefore be disregarded [55]. However, inclusion of these processes could provide a more holistic investigation of biopower generation with a more comprehensive inventory [62].

Most of the selected studies applied attributional rather than consequential LCA due to the complexity of the latter [63]. However, some important side effects or long-term environmental issues, such as LUC, should be appropriately considered in the LCA modelling to obtain a broader view of environmental implications [64]. We found that only three studies were conducted through consequential approaches. For instance, system expansion to include by-products, avoiding bioenergy feedstock as well as bio-electricity and bio-heat, preventing the input of grid-electricity [65], LUC for energy crop growing [66], and marginal technologies used for future technologies [67].

Functional Unit. Most of the studies (45/64) defined the FU as one unit of produced biopower, e.g., 1 kWh, MWh, MJ, or TJ electricity or heat. Considering the biomass supply chain, especially when cultivation is involved, one hectare per year is also used for comparison among biomass crops. One unit of weight of biomass is also used in some studies. A variety of other FUs were also observed, e.g., GHG emission in a power plant located area [68] and multifunctional output-related FUs [69]. When focusing on the power

systems, other FUs, such as the operations of the system, are also used [70]. Studies focused on the bio-electricity usage for vehicles also used the travel distance as the FU [71,72]. In addition, Tarighaleslami et al. used 1 kg of cheese as the function unit, as bio-electricity is considered to be the by-product from the dairy plant [73].

Multi-functionality. Functions other than electricity generation are barely discussed and normally beyond the scope of the studies. We found only one study used multifunctional units to enable the studied system with all product streams to be assessed, and therein, the functions of the investigated systems include equivalent number of logs and lumber to sales sites, electricity to the sawmill and community, and heat to the sawmill [69].

Impact categories. GWP is the most interesting environmental indicator for most LCAs (61/64). Eutrophication, acidification, and ozone depletion are also popular environmental indicators to be evaluated. The numbers for studies investigating these three impact categories are 34, 40, and 28, respectively. Especially for CHP technology LCAs, the numbers are 19, 20, and 13. In addition, Mohee et al. investigated the resource consumption in terms of energy for machinery, water, and transportation, chemical stressors in terms of inorganic fertilizers and biocides, as well as ecological health in terms of wastewater, ash, and emissions to air without specific categorization [74]. Weldu et al. focused their study on human health and ecotoxicity [75]. Zhu et al. specifically evaluated the direct and indirect water footprint [62].

Land use change. LUC is debatable for biopower and was excluded from most selected LCAs. Some claim that they did not include LUC because of the significant uncertainty with regard to the cultivation of different crops [71]. In the context of utilizing forestry or agricultural residues, the time frame in which the residues decay to CO2 and the conversion to energy occurs defines the period over which emissions take place [54]. Furthermore, some studies excluded LUC because they claimed that small-diameter wood residues come from existing forestry with no involvement of LUC [76]. In addition, Blengini et al. stated that they did not consider direct LUC because LU management for energy crop and agricultural purposes is similar; they also excluded indirect LUC since it was from other purposes to energy crop production [6].

However, LUC does cause changes in terms of release or storage of carbon due to the changes in soil organic contents, as well as involved processes such as transportation for biomass delivery [77]. There have been attempts to include LUC into the scope of LCA on biopower, for instance, emissions from different carbon stocks were modelled during the studied power plant lifetime, considering initial LUC [77]. Huang et al. investigated the effects of LUC caused by the removal of crop residues [78]. Menna et al. modelled the cultivation stage encompassing related agricultural processes [65]. Valeria et al. proposed a method that utilizes changes in soil organic carbon (SOC) storage as a proxy to quantify the impact of land use on soil quality [79].

3.3. Biofuels

Biofuels are fuel products derived from biomass materials using various technologies. To date, biofuels have been available in the market in various types, e.g., bio-oil, bio-ethanol, bio-diesel, bio-gas, bio-hydrogen, etc. The technologies for biofuel production have evolved from the first generation to the fourth generation, based on different feedstocks [80], namely, food crops, lignocellulosic biomass, algae, and genetically modified algae [81].

LCAs. We found 145 LCAs, among which 30 are about the first generation, 67 are about the second generation, 28 are about the third generation, and 20 are comparative studies. No study was found regarding fourth-generation biofuel, which is because of the technology's immaturity.

System boundaries. We observed that cradle-to-gate and cradle-to-grave system boundaries are the two most widely used approaches. The cradle-to-grave system boundary includes biomass cultivation, harvesting, transportation, pre-treatment, energy conversion, and end use. Cradle-to-gate system boundaries exclude the end use of the produced biofuels. Cradle-to-grave and cradle-to-gate are referred to as well-to-wheel [82] and well-to-tank [83,84] when vehicles are considered to be the end users of the produced biofuels.

Among 30 selected LCAs on the first-generation biofuels, 17 used cradle-to-grave and 11 used cradle-to-gate approaches, and 2 studies used the gate-to-gate approach [85,86]. For LCAs on second-generation biofuels, 26/67 used cradle-to-grave, 37/67 used cradle-to-gate system boundaries, and 4/67 used gate-to-gate approaches. Among 28 LCAs on the third-generation biofuels, 15 used cradle-to-grave, 10 used cradle-to-gate, and 3 used gate-to-gate system boundaries.

The attributional approach is used by most of the selected LCAs. However, when considering both the direct and indirect environmental impacts within a system, the consequential approach is more appropriate, e.g., when considering the indirect impacts of LUC [87–90].

Functional Unit. The majority of the selected LCAs (19/30 for first generation, 44/67 for second generation, 20/28 for third generation) define the FUs as one unit of produced biofuels. It is also reasonable to use one unit of agricultural land [88,89] or land for energy-crop cultivation [91,92] as the FU. This is specifically convenient for the comparison of different feedstock supply chains. For the third-generation biofuel, only three LCAs used one unit of area as the FU, with the studied algae biomass cultivated in open ponds or facilities [93–95]. Other FUs are also used when considering the usage of the produced biofuel, e.g., biofuel required for a vehicle to drive one unit of distance [96,97].

Multi-functionality. Biofuel production yields a variety of bio-products and by-products. For instance, the production of the Brassica carinata-based biodiesel also yields glycerine through transesterification, the oil extraction process yields cake meal, the straw is used to produce biochar, formic acid, and ethyl levulinate. For the second-generation biofuel, after fast pyrolysis, the separated oil phase section is processed through hydrotreating and yields diesel, gasoline, and jet fuel [98]. For the third-generation biofuel, in Roostaei et al., the products from microwave pyrolysis, hydrothermal liquefaction, and anaerobic digestion generate different combinations of bio-oil, bio-char, and bio-gas [99]. For feedstock LCAs, through a cradle-to-gate approach, the product is mainly biomass materials, and, thus, the by-products are less discussed.

Allocation is typically used to distribute the impacts when a studied biofuel system is involved with multi-functionalities, and it can be conducted with respect to mass, economic values, and environmental or impact significance. For example, Dornburg et al. investigated the sensitivities of three allocation scenarios, i.e., no allocation, allocation based on energy contents, and allocation based on economic values of products and by-products [100].

System expansion is another approach suggested by ISO [101] in which the system boundary includes external substituted product systems; for instance, the substitution of a driving operation by a conventional gasoline vehicle by a biofuel-based vehicle [102] or the substitution of grid electricity by electricity produced from palm oil residues [82], etc.

Impact categories. GWP (or climate change) is investigated by most of the LCAs. Consumption of fossil-fuel energy is another important environmental issue assessed in more than 50% of selected LCAs (19/30 for the first generation, 29/67 for the second generation, 17/28 for the third generation, and 10/20 for comparative studies). Various terms such as net energy ratio [95,103] and primary energy balance [104,105] are used. Fossil depletion is another commonly used term in LCAs applying software-built-in standard

LCA methods; for example, CML, IPCC, Ecoindicator, and Recipe in SimaPro [90,106] and Gabi [107].

Land-related impacts include direct LUC (e.g., with the unit of ha) and indirect consequential impacts due to LUC. LUC is of special interest for LCAs on biofuels, especially for studies on the first-generation biofuels, which involve the food versus fuel conflict. Studies also term LU as land requirements, land occupation, land demand, and land competition [82,84,96,100,106,108,109]. LUC is not often included in LCAs on the second- and third-generation biofuels since there is no food-versus-fuel conflict; it is considered in some studies, as non-food energy crops are also LU-intensive than traditional non-renewable fuels [91]. For instance, Nuss et al. and Aguirre-Villegas et al. considered LUC for the cultivation of wood biomass [103,110]. For the third-generation biofuel LCAs, the production of algae and micro-algae required LU was analyzed to show its benefits in this category in comparison with the first-generation biofuels [111–113].

Acidification and eutrophication are two important impact categories for biofuels. We found more than 50% of the selected LCAs included terrestrial acidification (84/145 in total, 21/30 for the first generation, 44/67 for the second generation, 12/28 for the third generation, and 7/20 for comparative studies) and aquatic eutrophication (83/145 in total, 20/30 for the first generation, 40/67 for the second generation, 15/28 for the third generation, and 8/20 for comparative studies). Although assessments of acidification and eutrophication yield more uncertainties, the impacts caused by harvesting, processing, fertilizer, pesticides, etc., are possibly in favour of fossil fuels when compared [92], thus it should not be excluded from the assessments.

4. Discussion

4.1. Synthesis

4.1.1. Temporal and Geographical Distribution of Reviewed Bioenergy LCAs

As shown in Figure 2, our statistical analysis illustrates that 15% of the studies were published prior to 2011, and 85% were published in and after 2011. It indicates the context of globally increasing interest in bioenergy technologies, especially those that can reduce greenhouse gas emissions. Our results show that more than 50% of the selected LCAs are based on Europe (119/233), followed by North America, 23% (53/233), and Asia, 18% (43/233). LCAs based on other geographical areas only account for 8% (18/233) of the total. This reflects the technological development status and the commercial scales of bio-technologies in the global energy market.

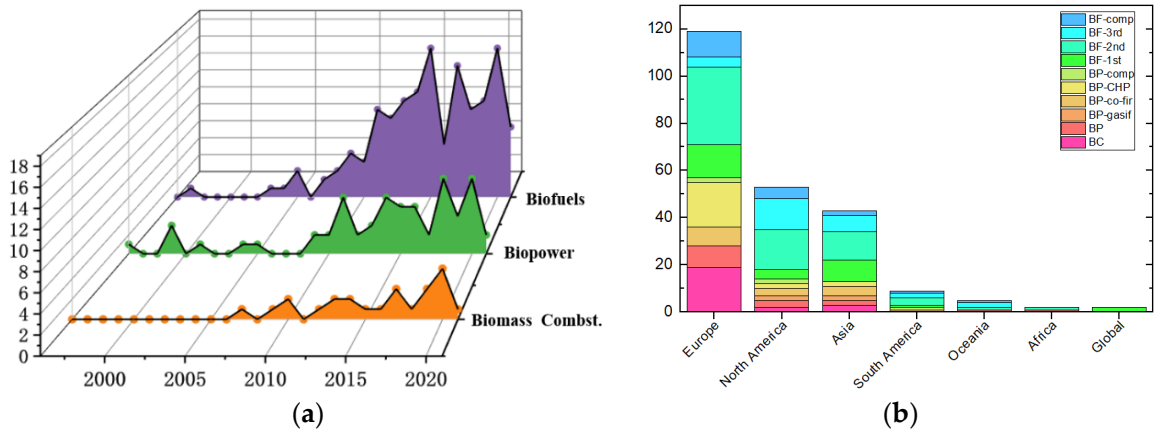


Figure 2. Temporal and geographical distribution of the reviewed bioenergy LCAs. (**a**) Annual publications of CLAs for biomass combustion, biopower, and biofuels; (**b**) geographical stacking

distributions of reviewed LCAs per bio-technology categories, i.e., biomass combustion, biopower (through biomass combustion, gasification, co-firing, as well as comparative studies), and biofuels (the first, second, and third generations, as well as comparative studies).

4.1.2. Scales of LCAs

We refer to Hellweg and Canals' LCA categorization and group our selected LCAs into small scale (i.e., product-, organizational-level), medium scale (i.e., local-, e.g., provincial-level), and large scale (i.e., country-, global-level). Our results show that small-, medium-, and large-scale LCAs fractionized 38%, 33%, 29% for biomass combustion, 54%, 20%, 27% for biopower, and 67%, 14%, 18% for biofuels, respectively. Small-scale LCAs normally focus on combustion appliances, power plants, and biofuel production systems. Medium- and large-scale LCAs provide assessments on broader spatial application of the studied biotechnologies in local, country, or global areas. We noticed that for the first- and second-generation biofuels, the medium- and large-scale LCAs accounted for 33% and 15%; however, only 11% for the third-generation biofuels. On the contrary, the small-scale LCAs accounted for 43%, 58%, and 86% for the three generations of biofuels, which reflects the maturity levels of these technologies.

4.1.3. Functional Units

The three most commonly used FUs are unit energy delivered, unit area of land, and unit weight of biomass. The application percentages of these three FUs in each technology are, 79% (energy), 21% (weight of biomass), and 8% (land) for biomass direct combustion; 70% (energy), 17% (weight of biomass), and 14% (land) for biopower; 67% (energy), 17% (land), and 8% (weight of biomass) for biofuels. Studies using other FUs on biomass direct combustion, biopower, and biofuels accounted for 1%, e.g., pellet boiler [31], 11%, e.g., unit drive distance of a vehicle [68], and 13%, e.g., unit drive distance of a vehicle [49,96,97,114,115].

4.1.4. System Boundaries

For biomass combustion, biopower, and biofuels, 57% of the LCAs adopted cradle-to-grave system boundaries, with the percentages of 92%, 66%, and 48% for the three categories, respectively. Cradle-to-gate system boundary applications accounted for 4%, 31%, and 48%. Biomass combustion systems include the cultivation through consumption in heat production facilities; hence, cradle-to-grave boundaries are appropriate to be applied. For biopower generation, the grave (end of life) phase usually refers to the biomass material's final conversion into biopower, in terms of electricity and heat, normally excluding the usage of biopower. For biofuels, the cradle-to-grave and cradle-to-gate boundaries are defined according to whether the usage of the produced fuels is consumed.

4.1.5. Impact Categories

Per our analysis, the most commonly investigated impact categories are energy (93%), GHG (61%), acidification (56%), and eutrophication (51%). LUC is included by only 9% of the LCAs, and impacts from indirect LUC are considered by only 4% of the total. By taking advantage of the LCA-software-integrated LCA method and database, more comprehensive impact category packages can be assessed. The most commonly used LCA software is SimaPro, with a 36% coverage of the selected studies, followed by Gabi, 12%. As shown in Figure 3, the LCIA results of the selected studies for biomass combustion, biopower, and biofuels are distributed with significant variations, in terms of GWP, AP, and EP, due to the complexity of the methodological choices. The broadest body of the "violins" is observed at or close to "zero", and for GWP, it normally refers to the carbon-neutrality of bioenergy technology. However, we should be aware that this does not mean there are no carbon

emissions during the life cycle; rather, it refers to the effect where an equal amount of CO_2 released by the bioenergy system is absorbed by the cultivated plant. Figure 3 summarizes the frequency of impact categories assessed in the reviewed LCAs.

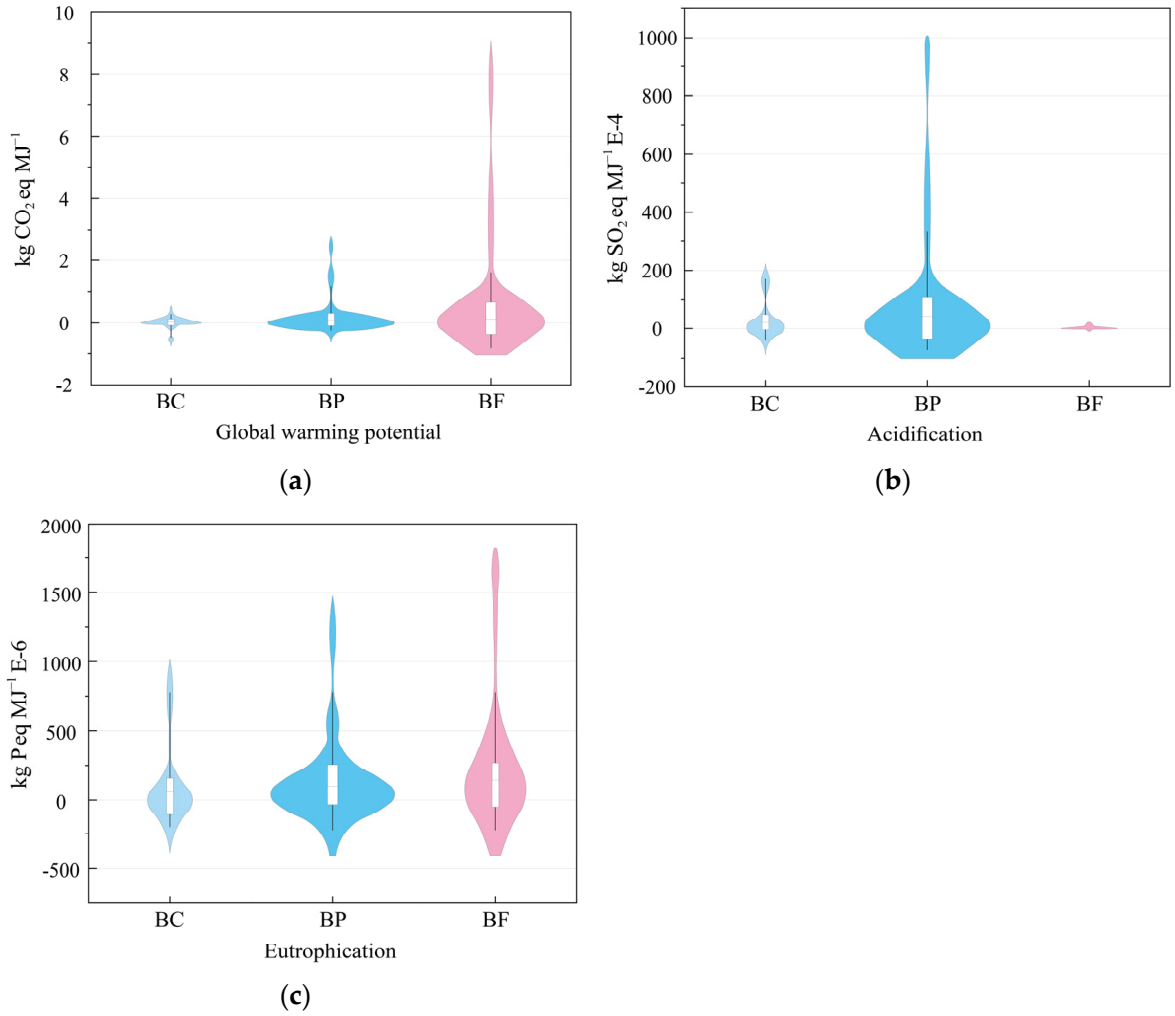


Figure 3. Environmental impacts in terms of (**a**) GWP, (**b**) AP, and (**c**) EP, per FU of biomass combustion, biopower, and biofuels. The width of the violin shape indicates the data distribution within this range.

4.2. Limitations and Difficulties of Current LCA Studies on Bioenergy Technologies

Our review focuses on the LCA studies regarding bioenergy technologies, and other aspects, such as economic and social indicators, are not discussed. We found some commonly existing limitations and difficulties that degrade the reliability of the LCAs and should be efficiently taken care of in future studies.

4.2.1. Absence of Site-Specific Data

Most of the published LCAs are contributed by Europe and North America. Moreover, the selected LCAs are performed at different spatial scales, which increases the complexity of the analyses, as the used data and assumptions may cause significant uncertainties due to the absence of site-specific data. It is important to recognize that many key issues used in LCAs are site-specific and of different levels of variation compared with commonly used environmental factors. For instance, carbon stock changes due to land use change and field emissions from cultivation [116], soil climate, temperature, and chemical and physical properties of the soil [112,115,117]. Only a few studies utilized site-specific data,

for instance, data in Northern Italy [34], Canadian emission factors [118], regional climate conditions [64], and site-specific field operational data for CHP systems [70]. For biofuels, four studies included site-specific data in their LCAs, i.e., climate conditions for crop cultivation [84], site-specific midpoint and endpoint characterization factors for four types of LUs [119], and site-specific wastewater treatment data for LCA on third-generation biofuels [111].

More than 50 percent of LCA studies are based in Europe (119/233), followed by North America (23 percent) and Asia (18 percent), with only eight percent of studies in other regions. This bias means that the results of most studies may not adequately reflect the reality in developing countries, where conditions for bioenergy production and use (e.g., infrastructure, regulations, type of biomass, etc.) differ significantly from those in developed countries. Developing countries may lack well-developed infrastructure, which can affect the efficiency of bioenergy production and environmental impacts. For example, biomass may be more difficult to collect and transport, leading to higher energy consumption and emissions [120]. Environmental regulations and policies vary considerably from country to country, which can affect bioenergy production methods and environmental management practices. The types of biomass commonly used in developing countries (e.g., agricultural waste) may be different from those in developed countries, and there are differences in their environmental impacts [121,122]. In order to improve the global applicability of the findings, future research should include more LCAs from developing countries and expand the geographical coverage. For LCAs from different regions, studies should analyze regional differences in depth, including differences in infrastructure, policy support, and biomass resources, to ensure that conclusions are comprehensive. Diversity of data sources should also be increased.

4.2.2. Consequential and System-Expansion Approaches

There are a wide variety of uncertainties when adopting a consequential LCA approach or system expansion, e.g., displaced electricity production increases the complexity of the studied systems [35,71,123]. Without a thorough investigation of the input uncertainties and their propagation mechanism, the reliability of the LCI and LCIA results is decreased. Only five studies performed either quantitative uncertainty or sensitivity analysis [66,84,104,124,125]. The lack of uncertainty and sensitivity analyses is a notable shortcoming in current LCA research on bioenergy technologies. Uncertainty mainly arises from data quality, model assumptions, and parameter selection. In LCA, input parameters usually have a certain degree of variability, which can lead to uncertainty in the output results. Uncertainty analysis assesses how uncertainty in the input data, assumptions, or parameters in a model affects the results of the study. Sensitivity analyses can help identify which input parameters have the greatest impact on the results. This helps the researcher to centralize the measurements, thus improving the reliability of the results. Without uncertainty and sensitivity analyses, the results of a study may be too sensitive to certain assumptions or data errors, thus reducing their reliability. The researcher may fail to identify potential sources of bias or error affecting the results, leading to incorrect decisions or conclusions [122,124,126].

4.2.3. Comparability Between LCAs Related to Functional Units

One of the difficulties caused by FUs is the different definition approaches, e.g., input biomass vs. output bioenergy. Furthermore, even with the same definition strategies, systems involved with different co-products are difficult to compare because of the variations due to different allocation procedures. Allocation procedures are dependent on the expertise of LCA practitioners and thus yield unavoidable subjectivity-caused uncertainties.

In addition, even for studies using the same FU with the same definition procedure, the comparison is also possibly difficult, e.g., a comparison between systems with different boundary conditions, e.g., cradle-to-grave vs. cradle-to-gate boundaries.

4.2.4. System Boundary Incomprehensiveness

For studies on biomass direct combustion and biopower generation, only 40% of the papers (46% for biomass combustion, 31% for biopower) included ash disposal within the system boundaries. Without considering ash disposal, the results may be biased, as the ash-disposal pathways are quite different; for instance, the ash could be spread on the land as fertilizer [35,40,42,45], transported for landfill [30], or transported to industrial end users [127]. The exclusion of ash handling from the system boundaries of biomass combustion and biopower studies is justified under certain conditions, such as negligible environmental impacts, focus on specific stages of the process, and reliable and applicable external data. The exclusion of the ash handling step may be acceptable if the ash handling method is uniform in the system under study and the environmental impact is negligible. Our focus was on a specific stage of biomass combustion (e.g., energy production), and the research question did not address the life cycle impacts of ash management; as such, the exclusion of ash handling may be justified. Exclusion may also be justified if reliable and site-specific data on ash handling are not available, and the use of default or generic data introduces significant uncertainties. The exclusion of ash disposal needs to be based on a combination of quantitative contribution analysis, data availability, and research objectives, supported by sensitivity analysis and transparent reporting [36,38]. For biofuels, a few studies considered the usage of biofuels by vehicles [49,96,97,114,115]; however, the vehicle life cycle is usually excluded from the system boundaries. Although it is arguable whether there is a necessity to include the vehicle life cycle, it should be considered if the structural specifications of the vehicles are different from conventional internal-combustion engine vehicles.

In addition, only a few studies included the life cycle of infrastructure within the system boundaries. It is arguable that the environmental impacts due to the equipment and facilities may be much less significant compared with the biomass life cycle; however, it may be not the case under some circumstances, for instance, within the context that the bioenergy technology are considered for large scale (e.g., national-scale) promotion, the environmental credits of the infrastructure should not be neglected.

4.2.5. Impact Categories Beyond GHG and Energy

Inclusion of as many impact categories into the environmental assessment increases the reliability of the LCA results. The environmental benefits of bioenergy are the most interesting impact categories for bioenergy technologies; however, they could also result in environmental burdens, such as acidification and eutrophication potentials, because of the release of SO_2 and nitrogen oxides. Furthermore, emissions due to direct and indirect LUC are often excluded because the uncertainties can cause significant variations in the results [66,71]. Among the selected studies, 44% excluded eutrophication, and 39% of the studies did not consider acidification. The environmental impacts of bioenergy technologies may vary according to geographical and climatic conditions, so biodiversity and water use are also important impact categories, but research on these needs to incorporate site-specific data and take into account regional differences. This component will be further explored in future studies. In addition, even with LCA software, the impact categories are often narrowed regarding the practitioners' interest and expertise, and thus, the objectivity and reliability of the results are degraded.

4.2.6. Absence of LCAs on the Prospective Biotechnologies

Our literature search finds no studies on fourth-generation biofuels, and this is likely because it is still in the research and development stage. However, future large-scale deployment of new-generation biofuels must be based on a full understanding of their life cycle environmental performance. Thus, comprehensive LCAs are encouraged, particularly focusing on fourth-generation biofuels.

4.2.7. Dependence of Life Cycle Assessment Software on Databases and Regional Changes

LCA software, such as SimaPro and GaBi, is an essential tool for performing LCAs. These platforms provide pre-built databases containing life cycle inventory (LCI) data for various materials, energy sources, and processes. Pre-built databases are often based on aggregated or averaged data, which may not accurately reflect site-specific conditions. For example, changes in soil carbon stocks due to land use change can vary significantly depending on local soil types, climate, and agricultural practices. Using generalized data from a database can lead to biased results, particularly when assessing technologies such as bioenergy with carbon capture and storage (BECCS) or biochar applications [112].

In addition, databases are often developed with a specific geographical focus. For example, the ecoinvent database, which is widely used in SimaPro, is mainly based on European data. When these databases are applied to other regions, such as Asia or Africa, the results may not take into account local variations in agricultural practices, energy mixes, or waste management systems. This is further illustrated by the Algal Biofuels life cycle assessment (ABLCA): productivity assumptions for open ponds in the SimaPro database (e.g., 20 $g/m^2/day$) were calibrated to the US climate. However, studies in the Nordic region report a significant reduction in algae growth efficiency due to the shorter growing season [94].

The reliability of LCA results depends on the quality and relevance of the data used. By addressing the limitations of LCA software and databases, and taking into account regional variations, future studies can provide more robust and actionable insights into the environmental performance of bioenergy technologies. This, in turn, will support more effective policy design and sustainable deployment of bioenergy.

4.3. Recommendations and Future Research

4.3.1. Adoption of Site-Specific Data

It is suggested to use site-specific data instead of the software's built-in database for the life-cycle inventory analysis whenever it is available. Otherwise, a careful and reasonable assumption must be made, and a well-estimated range of variations is suggested to be provided for the uncertainty analysis. When there is a lack of reliable field data, since, in many cases, they are difficult to acquire, certain estimations of these site-specific factors should be made. Further, site-specific aspects and (or) variations should be considered and used for justification of the data integrated within the software database prior to the conduction of the LCA case study, if the first-hand primary site-specific data are absent.

4.3.2. Functional Unit

The following stepwise process is for the definition of FU. As the main function of a generic bioenergy system is to deliver different types of energy to end users, it is reasonable to choose one unit of caloric value (instead of mass, otherwise heat value should be provided for conversion) of end products as FUs, especially when there are no co-products within the system. The calorific value as a fuel unit more directly reflects the amount of energy it provides and is easier to compare with other forms of energy (e.g., fossil fuels, other renewable energy sources, etc.).

However, if multiple by-products do exist in the system, an allocation methodology should be adopted to ensure that the allocation process is justified on the basis of a transparent, detailed, and clear explanation of the allocation logic. Common allocation criteria include those based on factors such as quality, economic value, or environmental significance, which should be determined by the objectives of the analysis and the characteristics of the system. For cases in which the end-use phase of the produced bioenergy is included within the system, FUs, such as unit distance of transportation, could be used for comparison with conventional fuelled vehicles. However, we suggest including both cradle-to-tank and cradle-to-grave into the analysis and interpretation, such that comparison could also be made with other systems, excluding final-use phases.

It is worth noting that different fuel units may lead to differences in the results of the analyses. Therefore, in order to improve the reliability of the analyses and to reduce the bias introduced by the choice of units, we recommend the use of multiple fuel units in the analyses. This multi-dimensional approach to the analysis helps to provide a more comprehensive understanding of the environmental performance of the system, reduces the limitations imposed by a single choice, and improves the insight and judgement of the environmental impacts of the system under study from a holistic perspective.

4.3.3. System Boundaries

The following system boundary definition strategies can be adopted in the LCA of bioenergy systems: For the direct combustion of the biomass for heat supply and biopower generation, a cradle-to-grave system boundary is recommended, including ash disposal. For biopower generation, cradle-to-gate is suggested, where the "gate" refers to the gate of the power plant, meaning where the produced electricity is ready to be transmitted to the grid or the produced thermal power is ready to be transported to the users. The cradle-to-gate system boundary is also suggested for biofuels, since the usage of biofuels is insignificantly different from conventional fossil fuels. The life cycle of infrastructure can be incorporated into the system boundary, especially when the studied system is in a large-scale promotion or pre-market scenario.

An example of an LCA study involving system expansion and a consequential approach is presented in Kauffman et al. [88]. Herein, the system expansion refers to the inclusion of impacts due to LUC, and the consequential approach refers to the consideration of substitution of fossil-based gasoline by the produced bio-gasoline. The well-to-tank life cycle system boundary includes (1) corn stover collection from the agricultural land, (2) feedstock transportation from the land to the biooil plant gate, (3) fast pyrolysis process in the biooil production facility, (4) the transportation of biooil from the production facility to the upgrading facility gate, (5) upgrading process of biooil for bio-gasoline production, (6) the transportation of produced bio-gasoline from the upgrading facility to the gas station, as well as (7) the collection and transportation of collected biochar as a by-product from the biooil production facility to the agricultural land where the corn stover is collected.

As shown in Figure 4, the GHG emissions contributed by these processes per hectare of land are, respectively, 0.12 tCO_2e/ha, 0.01 tCO_2e/ha, 0.10 tCO_2e/ha, 0.38 tCO_2e/ha, 0.42 tCO_2e/ha, 0.02 tCO_2e/ha, and 0.06 tCO_2e/ha [88]. The LUC related impacts in terms of the GHG emissions include the corn stover removal from the land accounting for 0.19 tCO_2e/ha; nutrient replacement for compensation of the removal of corn stover accounting for 0.12 tCO_2e/ha, as the removal of the corn stover will cause the nutrient loss of the land, thus, fertilizer with the same amount of nutrient is supposed to be used for balancing; the replacement of fertilizer by biochar accounting for -0.07 tCO_2e/ha, the carbon sequestration by biochar disposed back to the land accounting for -0.85 CO_2e/ha. Finally, the substitution of fossil-based gasoline by bio-gasoline accounts for -3.48 CO_2e/ha.

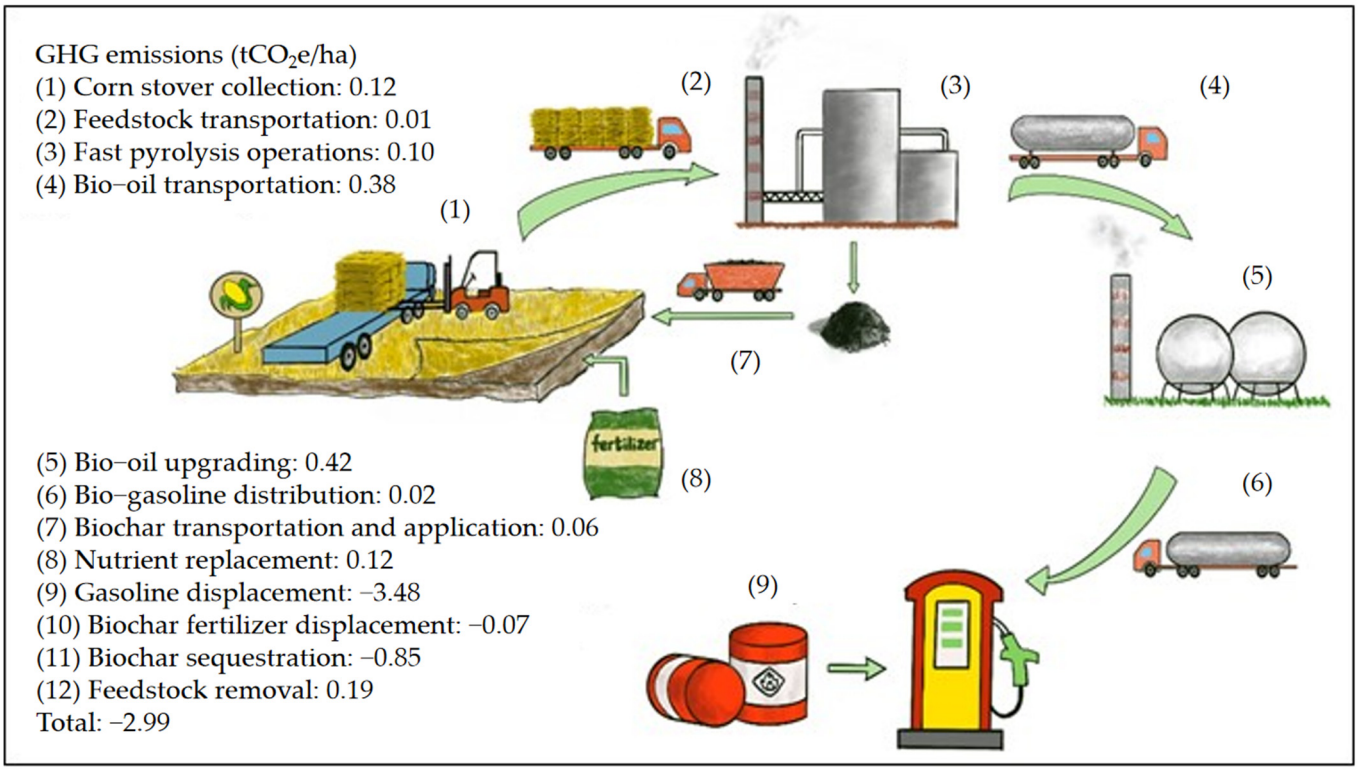


Figure 4. Fast pyrolysis pathway GHG emissions per hectare for bio-gasoline production from corn stover. The diagram is plotted based on the data gathered from Kauffman et al. [85]. The pyrolysis pathway is one of the scenarios within the cited paper and used for illustration of system boundary expansion and consequential LCA approach.

The total GHG per FU is summed up to be −2.99 CO_2e/ha [88]. It is important to recognize that the negative sign of the total GHG emissions per FU is the overall effect of the studied system. This effect considers both the emissions released from the life cycle processes and those avoided by the substituted processes. It has to be meaningful within a proper temporal scale; for example, the released CO_2 will act as a GHG, temporarily increasing carbon levels in the environment until it is sequestered again. This indicates that the so-called "carbon-neutrality" does not exactly mean climate neutral, and it has to do with the agricultural rotation time, and, thus, the temporal scale of the studied system has to be rationally defined [91].

4.3.4. Impact Categories

A full set of impact categories in addition to greenhouse gases and energy, such as eutrophication, acidification, loss of biodiversity, water depletion, and land use change, should be included in the life-cycle assessment of bioenergy systems [128]. Also, the LCA software is integrated with well-developed LCIA methods, taking advantage of their capability to perform analysis for the available impact-category packages, such that not only the environmental benefits but also the possible burdens of the bioenergy system could be assessed.

4.3.5. Uncertainty Analysis

In LCA studies, uncertainty arises mainly from data quality, model assumptions, and parameter selection. A comprehensive uncertainty analysis should be conducted when applying consequence and system extension methods. Sources of uncertainty, propagation pathways, and associated impacts on LCA outputs should be discussed to improve the reliability of results and the credibility of interpretations. Specifically, a variety of methods

can be used for the analysis. Monte Carlo simulation is a method for assessing the uncertainty of the results by randomly sampling the possible values of the input variables and simulating a large number of different scenarios. It can help the researcher to assess the distribution of the results under different assumptions and thus give more robust conclusions. Analysis of Variance (ANOVA) helps the researcher to assess the magnitude of the contribution of different factors to the results and reveals which factors have a significant impact on the variation in the results, thus providing more insight into the reliability of the results [66,122,124,126].

4.3.6. General Guidelines for Future Bioenergy LCA

Consider the following general guiding principles in future LCA of bioenergy systems (illustrated in Figure 5): (1) use cradle-to-grave system boundaries, (2) FU to be consistent, or otherwise convertible, (3) consider co-products and multifunctionalities, (4) take into account temporal and spatial scales, (5) use site-specific data, (6) quantification of input-data uncertainties, (7) use appropriate LCIA method, e.g., method with capability to evaluate as many impact categories, (8) include not only GHG and energy but comprehensive impact categories beyond, and (9) consider impact from direct and indirect LUC. Our recommended guideline is in line with the Glasgow Climate Pact, as we suggest the conducted LCAs to be readable and interesting to various stakeholders, including but not limited to policymakers, industrial audiences, research communities, as well as the general public, from different perspectives.

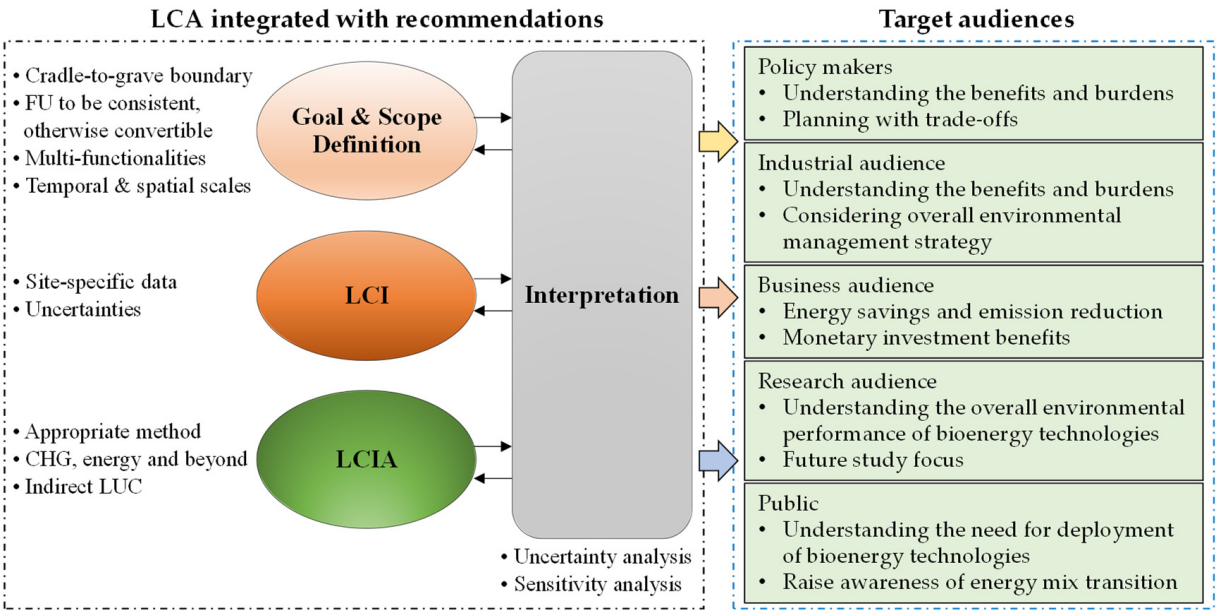


Figure 5. General guideline of LCA for bioenergy technology integrated with recommendations, which aims to serve as a reference to different groups of stakeholders with various interests in biotechnologies.

4.3.7. Fourth-Generation Biofuels

Fourth-generation biofuels represent an advanced stage in bioenergy technology, primarily characterized by the use of genetically modified algae and other microorganisms to increase the efficiency of biofuel production. These biofuels aim to overcome many of the limitations of previous generations, such as food-fuel competition and land use issues, through the use of non-food biomass and advanced genetic engineering techniques.

Although research on fourth-generation biofuels is limited due to its experimental nature, it can be inferred from the technologies involved that biofuel yields per unit area

may be higher for genetically modified (GM) algae than for conventional crops, reducing the land footprint required for biofuel production; the introduction of GMOs into natural environments may pose a risk to biodiversity; and fourth-generation biofuels are expected to have carbon-neutral or even carbon-negative emissions [129].

To advance the understanding and development of fourth-generation biofuels, future research should focus on and requires a comprehensive life-cycle assessment to evaluate the full range of environmental impacts of fourth-generation biofuels, including potential risks and benefits; research to improve genetic engineering techniques, optimize growth conditions and develop cost-effective production methods; and detailed studies of the environmental and health risks associated with GMOs used in biofuel production [130–132].

Fourth-generation biofuels hold great promise for sustainable energy production, but their environmental impact and technical feasibility require further investigation. As research progresses, addressing the challenges and understanding the full life cycle impacts will be critical to their successful integration into the global energy mix.

5. Conclusions

This work critically reviews LCAs on a broad portfolio of bioenergy technologies from a holistic point of view, regarding biomass combustion, biopower generation, and biofuels. By synthesizing some of the key findings of selected Lcas in bioenergy technologies, the current state of LCA practice is examined. Further, the selected studies are diagnosed in terms of the most important LCA aspects. A few limitations and difficulties are identified through an in-depth analysis of the selected LCAs, e.g., absence of site-specific data, uncertainties during consequential and system expansion application, incomparability due to inconsistency of FU definition, system boundary incomprehensiveness, and insufficient inclusion of impact categories beyond GHG and energy. These commonly existing shortcomings damage the reliability of the LCIA results and interpretation, thus degrading the practical usage values for decision-making, especially for the technologies on the experimental stage before large-scale deployment and promotion. The recommended generic guidelines aim to systematically reduce the ambiguity and inconsistency and provide an understanding of the comprehensive environmental performance of the studied bioenergy technologies. This enables decision-makers and stakeholders to utilize the results for policy design, considering a wider variety of benefits and burdens and finding out trade-offs within the context of global warming mitigation and overall environmental management.

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Conflicts of Interest: Author Yongsheng Li is employed by Shandong Tianrui Heavy Industry Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GHG	Greenhouse gas
LCA	Life cycle assessment
FU	Functional unit
LCI	Life cycle inventory
CLCA	Consequential LCA
LU	Land use
ES	Ecosystem services
CHP	Combined heat and power
GWP	Global warming potential
LUC	Land use change
CCS	Carbon capture and storage
CCU	Carbon capture and utilization

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