Benavides *et al.*
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Environmental analysis of biotechnologies for biofuels, bioplastics, and bioproducts: a greenhouse gas (GHG) emissions review

Pahola Thathiana Benavides[1*], Sweta Balchandani[1] and Ulises R. Gracida-Alvarez[1]

Abstract

Biotechnology and biomanufacturing development has the potential to strengthen the bioeconomy as new opportunities in many areas such as the energy, chemical, agriculture, pharmaceutical, and food industries can be unlocked. Biotechnology and biomanufacturing refer to the technologies that use microorganisms, molecular biology, metabolic engineering, and chemical processing to transform biobased resources (e.g., biomass) into new products. These microorganisms are genetically engineered in such a way that the production of new products happens more efficiently. Creating new products through biotechnology and biomanufacturing will promote shifting from a fossil-based economy to a bioeconomy. However, these new technologies will need to be evaluated from the accessibility, affordability, and sustainability point of view. In this paper, a review of recent studies evaluating the carbon footprint of biotechnologies to produce fuel, bioplastics, and bioproducts is presented. The assumptions, biogenic and coproduct credit subtraction, and co-product treatment methods in the life-cycle assessment (LCA) showed an important impact on the results of the different studies. Besides, integrated biorefineries presented an alternative to improve the environmental impact of bioproducts compared to single-product refineries.

Keywords Life-cycle assessment, Biofuels, Bioproducts, Biotechnological processes

Introduction

Biotechnology and biomanufacturing have been areas of increased attention in recent years. Through biotechnology, new chemicals and products can be created by using synthetic biology, metabolic engineering, and bio-based resources such as biomass [1]. Advancing biotechnology offers opportunities to revolutionize a vast portfolio of products from the energy, chemical, pharmaceutical, agricultural, and food sectors and help transform the current fossil-based economy into a bio-based economy (bioeconomy). Synthetic biology can direct a path to a sustainable manufacturing sector as many products, including fuels, plastics, and chemicals derived from petroleum and natural gas, can be produced with microorganisms with great potential for annual savings in global greenhouse gas (GHG) emissions [2]. Moreover, biotechnology has an attractive economic value with an estimated market size of US $1.37 trillion in 2022, with a potential to grow a at compound annual growth rate (CAGR) of 13.96% from 2023 to 2030 [3]. All these advantages have promoted different initiatives and policies, which have focused on establishing pathways to advance biotechnology and biomanufacturing [4–7]. The United States (US), for instance, had described the goals and plan to promote and invest in research and development (R&D) of biotechnology and biomanufacturing safely and responsibly. Some of the key points of

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*Correspondence:
Pahola Thathiana Benavides
pbenavides@anl.gov
[1] Energy Systems and Infrastructure Analysis Division, Systems Assessment Center, Argonne National Laboratory, 9700 S Cass Avenue, Lemont, IL 60439, USA

the US plan include coordinating the investment of R&D, adopting a biological data ecosystem and maintaining principles of security, privacy, and responsible conduct, improving, and expanding domestic production and market opportunities for bioenergy, and bioproducts and services, and boost sustainable biomass production [7]. Biofuels and bioproducts developed via biotechnologies will also help respond the increasing demand of fuels and products with innovative properties and unique characteristics, which it is also boosted by the decarbonization and net-zero goals all around the world to combat climate change, with countries like the US committing to decarbonize its economy by 2050 [8]. Electrification is one of the most relevant strategies for reducing GHG emissions in the net-zero emissions scenario by 2050 [9]; however, not all transportation sectors are suitable for electrification. For instance, electrification is infeasible for aviation fuels because the fuel energy density requirements are only obtainable through hydrocarbon fuels [10]. On the other hand, the industrial sector, including the chemical sector, is responsible for more than 30% of global CO_2 emissions. To achieve net zero by 2050 scenario, the emissions from the industrial sector have to decrease by more than 90% by 2050 [11]. Therefore, cost-competitive and environmentally sustainable aviation fuels (SAFs) and bioproducts will be essential to decreasing emissions in the aviation and chemical sectors, respectively, and be able to achieve government and industry goals to reach net-zero carbon and greenhouse gas (GHG) emissions [11, 12].

Biofuels and bioproducts have the potential to reduce greenhouse gas (GHG) emissions. However, policy decisions should be based on evidence that biofuels and bioproducts can produced in a sustainable manner. Social, economic, and environmental analyses will play an important role in evaluating the feasibility and sustainability of biotechnology and biomanufacturing. In fact, the definition of sustainable processes is based on the three pillars of sustainability (see Fig. 1) which include the minimization of environmental impact, economical viability, and social responsibility [13, 14].

In this paper, we focus the discussion on some of the environmental aspects of sustainability such as the evaluation of greenhouse gas (GHG) emissions of biofuels and bioproducts through life-cycle assessment (LCA). LCA takes a holistic approach to evaluate the environmental impacts of the supply chain of a product or technology and identify the key drivers that influence GHG emissions and other sustainability metrics. This comprehensive approach will include the product's life cycle from

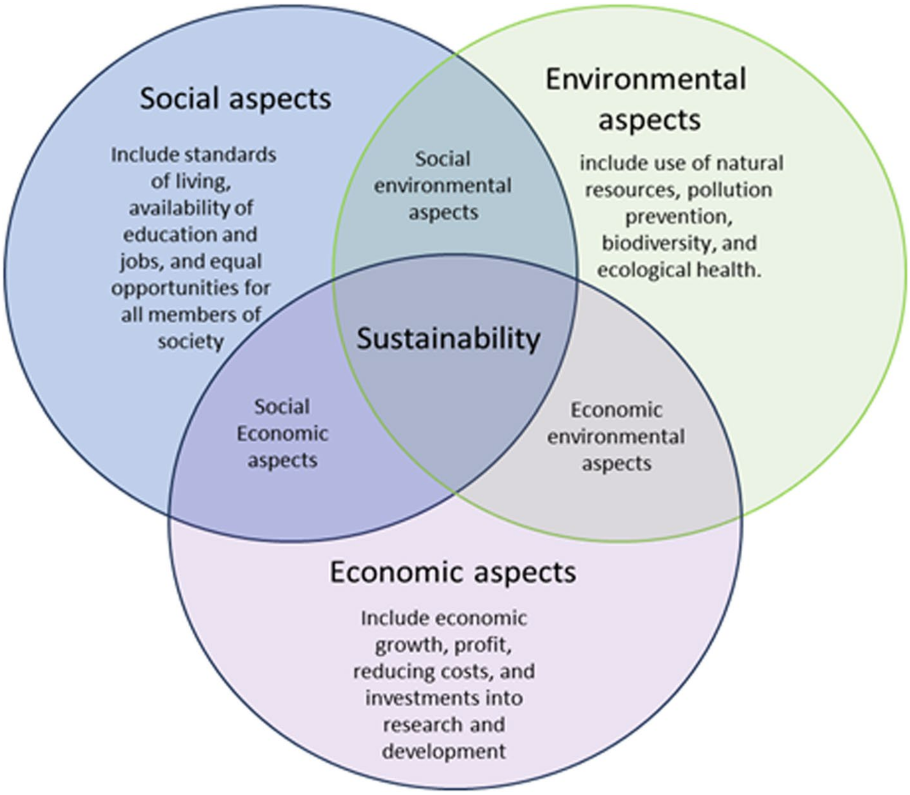

Fig. 1 Three pillars of sustainability were adapted from Olsson and Schipfer [11]

the raw material extraction and processing to manufacturing and its end of life. The results provided via LCA will not only help guide research direction but also pursue opportunities to mitigate the adverse environmental impacts, highlighting potential energy and environmental hotspots and benchmarking the technology developed here against their conventional counterparts.

This paper presents a review of LCA of biotechnologies, summarizes key aspects of LCA, and provides an updated overview of the GHG emissions of advanced fuels and bioproducts obtained through biotechnological processes. We conducted a literature review of the last 5 years of research on biotechnology pathways that focus on the production of biofuels and bioproducts and discussed the advantages and disadvantages of some of the technologies and feedstocks and some of the key aspects that drive the GHG emissions of the different technologies. This paper is organized in the following order. First, we discuss the technologies available to transform different biobased feedstocks into new fuels and products. We present the different steps involved in an LCA and summarize process modeling needs and available tools to determine environmental sustainability. Then, we summarized key LCA studies and discussed key assumptions such as allocation methodologies and co-product treatment methods. Finally, we discuss the conclusion.

Transforming biomass into fuels and products

Bioderived feedstocks can be utilized to build a sustainable bioeconomy; however, to meet the ambitions of decarbonization and net-zero goals, substantial quantities of these feedstocks will be required. The US has the potential to produce at least one billion dry tons of biomass resources on an annual basis without adversely affecting the environment [15]. This includes agricultural, forestry, waste, and algae feedstock that with special conversion technologies can be transformed into many fuels and products [15]. Three main conversion technologies can be used for this purpose: biochemical, thermochemical, and physiochemical conversion. Biochemical (e.g., enzymatic hydrolysis and fermentation) uses microorganisms to convert substrates (i.e., sugars) available in biomass into intermediate products, while thermochemical (e.g., pyrolysis, gasification, hydrothermal processing, combustion) usually involves high-energy consumption processes along with solvent or catalyst addition. Physiochemical conversion leverages mechanical and chemical transformation, for example, extraction (with esterification) where oilseeds are crushed to extract oil. The selection of the conversion technology depends on the type of feedstock quantity and characteristics as well as economic and environmental metrics, location, and project-specific factors [16]. However, in some instances, the combination of these conversion technologies has also been considered to achieve a specific fuel or product [17]. Because the focus of this paper is biotechnological production pathways for fuels and products, we focus the discussion on biochemical conversions. There are five major production steps required to produce fuels or products from biomass. The process steps are shown in Fig. 2. Starting with the feedstock production, this step includes the evaluation and input of the fertilizers, chemicals, and on-farm energy use. This stage also includes the assessment of the land use change (LUC) and land management change (LMC) depending on the feedstock used [18]. Feedstock logistics involves preprocessing which includes size reduction, grinding, and densification, while transportation, distribution, and handling include all steps involved in the movement of biomass from multiple locations to a centralized location (biomass depot) or

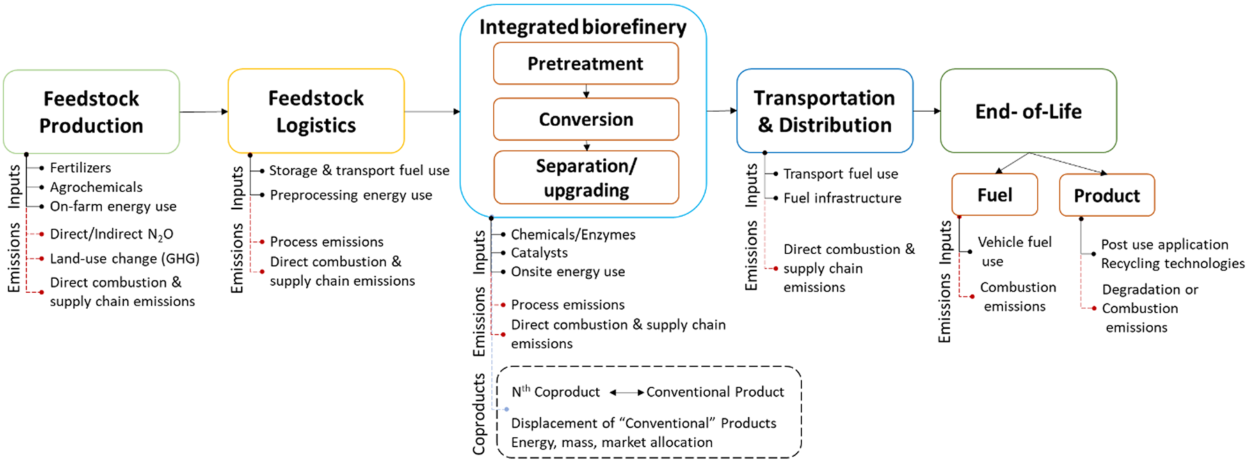

Fig. 2 Production steps to produce fuels or products from biomass

biorefinery process facility. Crops and lignocellulose are good sources of sugars to produce biofuels and bioproducts. For example, crops such as sugarcane and sugar beet contain sucrose and corn or cereals contain starch, which can be converted into glucose [19], while lignocellulosic biomass such as corn stover, miscanthus, and switchgrass contains pentose sugars, primarily xylose, and arabinose [20]. Extracting the sugars from these feedstocks requires chemical and physical procedures leading to the next steps, which happen in an integrated biorefinery. Integrated biorefinery is a concept attributed to the co-production of hydrocarbons with high-value products derived from biomass [21], in which the transformation of biomass happens in three parts: starting with pretreatment, conversion, and separation or upgrading to the final product. In the pretreatment, hexoses and pentoses are released from hemicellulose by physical or chemical or a combination of both processes and enzymatic treatments such as hydrolysis produce glucose from cellulose [19, 22]. Pretreatment is a vital stage for conditioning biomass for the enzyme hydrolysis step that yields the sugars, typically C5/C6. These processes are generally capital intensive and are estimated to represent about 18–20% of the total cost of a biorefinery [22]. The conversion includes fermentation, microbial, and enzymatic catalysts, while separation or downstream processes will depend on the nature of the products [14]. While fermentations have become a standard option for fossil-derived feedstock focusing on low-molecular-weight products that can be subsequently converted to platform chemicals or fuels, it faces some challenges which include having adequate mixing, oxygen input for aerobic conversions, process control, and increased yields. In microbial catalysts, the growth of cells happens first and then carries out the reaction to avoid lowering the yield because of diverting the product to the catalysts. In the enzyme process, the enzymes are isolated and immobilized on a solid support so they can be recycled [14]. Once the fuel or product is made, the following step is transportation and distribution through the different supply chains. The final step, the end of life, differs from fuel and product in that fuel is combusted during vehicle use while the bioproduct's end of life varies depending on the application.

Data and process modeling needs for sustainability evaluation through LCA

Process modeling is a fundamental part of the economic and environmental analysis of a production pathway. The integration of the different unit operations, the technology commercialization, and scale-up can be visualized through the process model, and with the combination of techno-economic analysis (TEA) and LCA, it becomes a comprehensive approach to help prioritize and guide research directions. The early incorporation of these integrated analyses in the design and development of a product (i.e., fuel or chemical) will help maximize process efficiency and minimize costs and environmental impact. According to Broeren et al. [23], early-stage assessment methods are essential to understand the potential environmental benefits and trade-offs of new bioproducts. In the initial part of product development, there is the freedom to design and adapt the production process to the needs of feedstock, synthetic routes, purification, downstream selection, and by-product treatment as data is limited. However, as R&D advance through the different stages, namely concept, process chemistry, process design, and piloting, more and higher-quality data become available for analysis, which limits the freedom and flexibility to modify the process. Therefore, to better guide R&D, early-stage environmental assessment methods should capture the most important benefits and drawbacks when there is still freedom to design and adapt the process [23].

Engineering, economic, and environmental challenges arise when modeling bioconversion processes, especially mixed, highly variable, and contaminated materials such as waste feedstocks. Scown et al. [24] reviewed the diversity of feedstocks and conversion technologies to biofuels and bioproducts and discussed process challenges, environmental benefits, and risks of feedstock utilization. Some of the criteria described for deciding the best use of feedstocks rely on the availability, moisture content, composition, and physical properties. For example, the success of using corn stover, one of the most popular crops produced in the US, and feedstock for deconstruction processes, depends on how to manage its composition variability when sourcing from different locations, harvesting timeframe, soil carbon losses, and pretreatment process [24].

To conduct LCA, there are four main steps [25, 26]. Defining the *goal and scope* to determine the objectives and how much of the life of the product the analysis will cover is the first step, followed by preparing the life-cycle inventory (LCI) to collect the material and energy inputs and outputs of the process. In the third step, the inventory serves as the impact assessment for evaluating the indicators and metrics of the impact categories, while the last step involves the interpretation of the results, critical review, and determination of sensitivities [27]. The LCI is usually informed by process modeling, computer-based tools, and experiments, and it represents a key part of the LCA. Material and energy balances of the different unit operations involved in the process, evaluation of the feedstock and product properties, co-products, or by-product fates are all part of the LCI collection. Data quality and availability can affect the reliability of the analysis and will enable rigorous comparisons. The system boundary is also an important part of LCA. It determines which steps or unit processes of the life cycle of the product should be included (e.g., feedstock production, reaction, separation or recovery, disposal) and the inputs and outputs. It also defines the temporal, spatial, level of detail, and data quality considered in LCA. The result will be highly dependent on the definition of the system boundary; therefore, it is an important aspect to look at when comparing analyses for the same products.

As mentioned before, biochemical conversion leverages the use of genetic, metabolic, and protein engineering methods as it is difficult to reach industrial-relevant titer, rates, and yields, also known as TRY metrics, with natural microorganisms [2, 28, 29]. The strains, proteins, and/or enzymes can be improved through these methods, benefiting fermentation processes, which are considered inefficient due to a large amount of subtracted reactant required for cell energy, cell growth, and other products. For instance, Ling et al. [30] engineered *Pseudomonas putida* KT2440 to transform glucose and xylose contained in lignocellulosic hydrolysates to produce muconic acid using a model-guided strategy to maximize the theoretical yield. The authors were able to express the D-xylose isomerase pathway by using adaptive laboratory evolution (ALE) and metabolic engineering in the strain, which enables efficient muconic acid production [30]. Coradetti et al. [20] studied the efficient conversion of pentose sugars (e.g., xylose and arabinose) by engineering transcriptional regulation of pentose metabolism in *Rhodosporidium toruloides*. The authors found that overexpression of transcription factors such as Pnt1 increased the specific growth rate approximately twofold earlier in cultures on xylose. The xylose growth dynamics were improved to a 120% increase in the overall rate of producing fatty alcohol in batch culture. The TRY metrics are also vital parameters that drive the fermentation processes. Improvement in the metrics will not only lead to increased production but also benefit the sustainability of the bioprocess. Klein and Benavides [31] use TEA and LCA tools to quantify the economic and environmental sustainability potential for eight bioproducts synthesized with hosts studied under the Department of Energy (DOE) Agile BioFoundry (ABF) consortium [32], which include the studies by Ling et al. [30] and Coradetti et al. [20]. In this work, the authors highlighted the effect of these TRY metrics on cost and GHG emissions of some biochemical pathways including biobased adipic acid with host pseudomonas putida, 1,3 butadiene with *Zymomonas mobilis*, 3-hydropropionic acid (3-HP) with host *Aspergillus pseudoterreus*, and 1,8 cineole with host *Rhodosporidium toruloides* [31]. Contour plots were developed for each of these bioproducts with the results of the TEA and LCA. These contour plots described the variation of the minimum selling price (MSP) and GHG emissions of each bioproduct as a function of productivity and yield in aerobic fermentations. It was found that in the case of adipic acid, the MSP was driven by productivity below 0.3 g/L.h and remained constant after productivities were higher than 0.3 to 0.5 g/L·h. Cost-effective MSPs of US $2.00/kg were achieved for bioadipic acid production only at a high yield and rate. For the GHG emissions, biobased adipic acid performed significantly better than its fossil counterpart since for any fermentation conditions, the GHG emissions varied between 1.1 and 3.6 $kgCO_2e/kg$ — lower than that of its fossil-based counterpart (9.4 $kgCO_2e/kg$) [33]. Productivity, however, did not influence the results as much as compared to its MSP. Bhagwat et al. [34] also discussed the improvement in MSP, global warming potential (GWP), and fossil energy consumption (FEC) with the advancement of these fermentation metrics for biobased acrylic acid produced via 3-HP intermediate from lignocellulose biomass. The authors indicated that at higher yields, more sugars were converted to 3-HP during co-fermentation, and fewer by-products (acetic acid and glycerol) were available for biogas production which significantly improved its environmental impact by lowering the GWP and FEC, while the MSP benefited greatly from incremental improvements to yield.

Co-product handling method and system-level vs process-level approach

For conducting the LCA of biofuels and bioproducts, various researchers [35–40] have suggested adopting mass-based, market-based, energy-based, or displacement methods. Usually, in any biorefinery, multiple products falling in the category of biofuels, bioproducts bio-based intermediates, and electricity are produced simultaneously to increase the profits through sales of products/energy while optimizing the utilization of the resources. This creates the necessity to determine which co-product handling method is the most suitable for the process under study. For instance, in a biorefinery producing bio-based value-added chemicals, a mass allocation method can be used to evaluate the LCA of the products. However, if the biorefinery also produces biofuels, then the market-based allocation would be an alternative [41]. Hence, it is important to ensure the correct selection of the co-product handling method based on the type of co-products generated within the biorefinery [41].

Further, a detailed life cycle impact study of the entire biorefinery can be obtained through both a system-level approach and a process-level approach. For the former, the material and energy consumption are equally distributed among all the processes across the refinery.

Contrarily, a process-level approach allows the researcher to evaluate the most material or energy intensiveness of any process. Usually, the separation process consumes more energy, whereas the impact due to utilization of materials is higher in the pretreatment or conversion process sections in a biorefinery. Cai et al. [21] used the system- and process-level approaches to assess the GHG emissions for renewable diesel blendstock derived from integrated biorefineries also producing adipic or succinic acid. Their estimated GHG emissions showed a wide variation due to the different approaches and allocation methods utilized.

Life-cycle assessment of biofuels and bioproducts from biotechnological pathways

Over the last few decades, the analysis of the supply chain of the feedstocks (or raw materials) required for producing bioproducts has increased substantially [42, 43]. This has yielded a chance to improve the economic and environmental sustainability of the proposed technologies at the laboratory or pilot scale itself before launching to the plant scale to meet the market demands. For this review, we analyzed the GHG emissions reported in 39 scientific publications, described for biofuels, bioplastics, and bioproducts and showed the data in Figs. 3 to 5. The selected studies only reported results per unit (i.e., kg, MJ, L) of the final product and included a broad range of feedstocks like food crops (i.e., corn, sugarcane, wheat), lignocellulosic materials (i.e., corn stover, rice husk, wood chips), and wastes (manure, wastewater, municipal solid waste [MSW], etc.). The upcoming sections describe the major findings for the different types of feedstocks and their bioproducts.

Biofuels

Food crops (e.g., corn, sugarcane, and wheat) have been widely used to produce bioethanol. The GHG emissions from food crop-based bioethanol range from 10 (corn) to 90 (switchgrass) g CO_2 e/MJ with lower average values identified in corn and sugarcane [44–46]. The greenhouse gases, regulated emissions, and energy use in technologies (GREET) model [33], which continuously updates the material and energy requirements associated with the production of biofuels, estimates the GHG emissions of sugarcane-based ethanol in 35 g CO_2 e/MJ. For corn-based ethanol, the GREET model calculates the GHG emissions within a range from 52 to 76 g CO_2 e/MJ, depending on the milling process (lower bound for dry milling and upper bound for wet milling). The integrated biorefinery from food crop resources might also explore the valorization of the waste produced within the same refinery. For instance, the GHG emissions of ethanol produced from corn can be reduced to 37 g CO_2 e/MJ if corn stover, a residue from corn harvesting, is also converted to ethanol in an integrated process. Integrated biorefineries can generate other co-products beyond biofuels as mentioned by Raut and Bhagat [47] who suggested efficient production of levulinic acid (LA) and hydroxymethyl furfural (HMF) from sugarcane biorefinery from molasses. Similarly, Longati et al. [38] carried out the comprehensive TEA and LCA of the production of microbial oil and biodiesel in an integrated biorefinery using sugarcane. The authors suggested that integrated biorefineries generate less GHG emissions.

Biofuel production from lignocellulosic materials has also been widely adopted as these feedstocks, which were previously considered agricultural residues, can be valorized through biotechnological processes [40, 49]. However, bioethanol from lignocellulosic materials shows a wider range of GHG emissions compared to that from food crops with values from − 97 to 155 g CO_2 e/MJ [37, 44, 45, 50–52]. The negative GHG emissions observed for corn stover corresponded to an integrated biorefinery combining ethanol production and anaerobic digestion of organic wastes. The biogas from anaerobic digestion was converted to different bioproducts (compressed natural gas, poly-3-hydroxybutyrate, and single-cell protein) for which credits were subtracted in the emissions of accounting for bioethanol [37]. As observed, integrative processes that incorporate different co-products can lead to reduced GHG emissions not only for food crops but also for lignocellulosic materials. Waste feedstocks have also been shown promising in producing bioethanol. The GHG emissions of bioethanol from cattle manure (71 g CO_2 e/MJ) and bread waste (47 g CO_2 e/MJ) are in the same range as those from rice straw, sweet potato, and wheat [44, 45]. Using MSW as a feedstock shows GHG emission for bioethanol ranging from − 1137 to 15 g CO_2 e/MJ [44, 53]. As observed in Fig. 3, bioethanol achieves considerably low GHG emissions when produced from MSW due to two major considerations in the analysis: (1) incorporating credits from removed non-biogenic components of MSW (plastics and metals) that generate an income by recycling/recovery processes and (2) credits from avoided MSW conventional treatment processes (landfill and incineration) [53].

Another important biofuel that can be obtained from lignocellulosic materials is hydrogen. With the exception of rice husk, the GHG emissions of biohydrogen are estimated between 13 and 47 g CO_2 e/MJ, with potato peels, sorghum stalk, and wheat straw showing similar values of GHG emissions (43–47 g CO_2 e/MJ) [35, 54] The higher emissions observed for rice husk compared to other lignocellulosic materials are associated with the use of fossil energy and combined heat and power (CHP) combustion emissions to provide the energy required for the

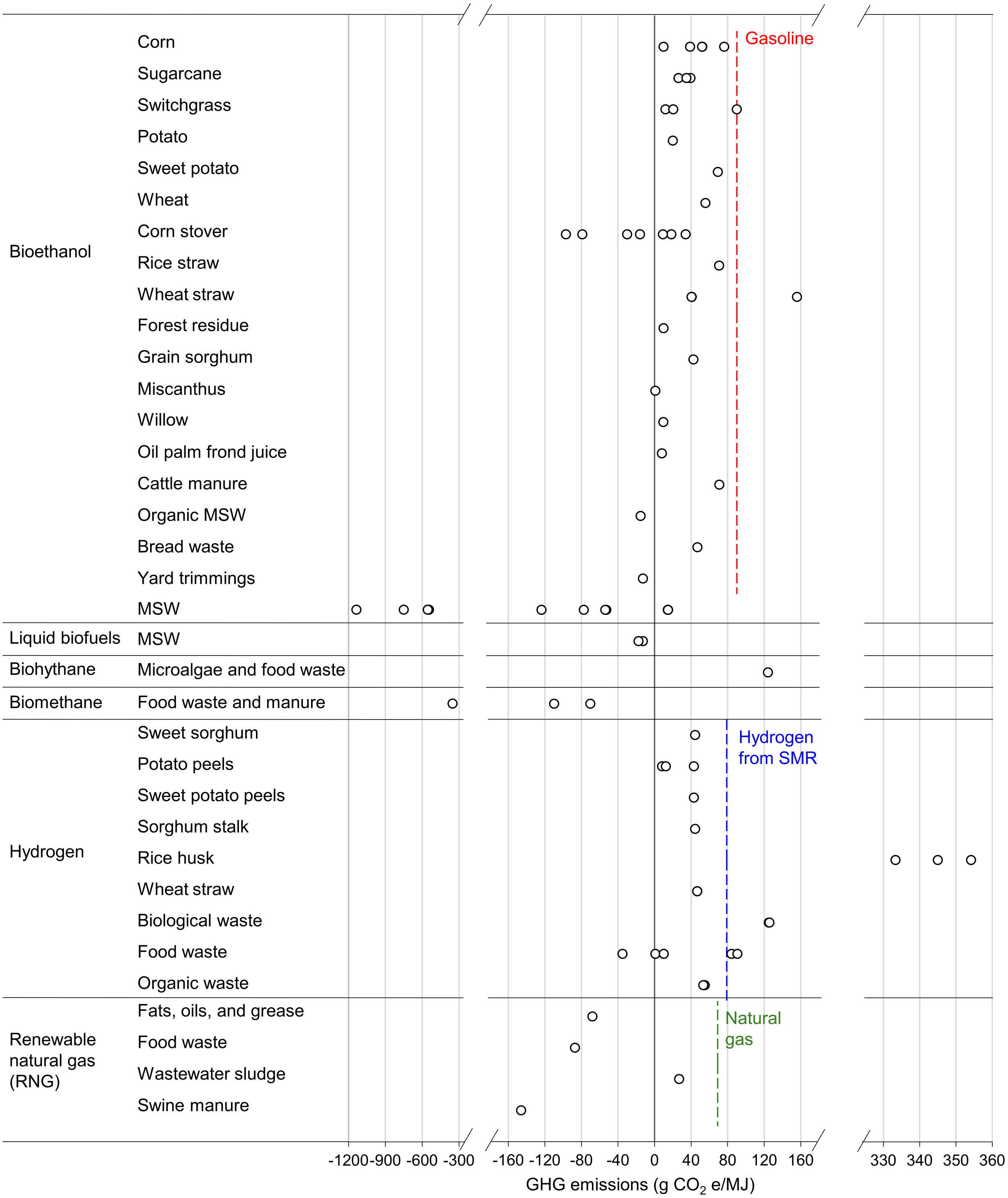

Fig. 3 GHG emissions of the production of biofuels from biotechnological processes. Detailed information on the data is available in Table S1 of the supplementary information (SI). GHG emissions of fossil-based gasoline, hydrogen from steam methane reforming (SMR), and fossil-based natural gas are estimated at 90, 79, and 69 g CO$_2$ e/MJ, respectively [33]. Note: Biohythane is known as a gaseous mixture comprised of hydrogen and methane [48]

dark fermentation process [55]. However, some studies consider using biomass as a source of CHP as a carbon–neutral energy generation strategy which consequently reduces the GHG emissions of the process [56]. The use of waste for biohydrogen production shows a wide range of GHG emissions (−35 to 126 g CO_2 e/MJ), due to the variability in the methods and processes utilized [36, 57–59]. For instance, the higher GHG emissions observed in biological and food waste are due to the absence of co-products [57, 59], while the negative GHG emissions were obtained for processes generating co-products for which credits were included in the emission accounting [58]. Organic waste is also used to produce other liquid biofuels (butanol and ethanol mix) as well as biohythane (a gaseous mixture comprised of hydrogen and methane) and biomethane. The reported GHG emissions are between −18 and −13 g CO_2 e/MJ for liquid biofuels, 124 g CO_2 e/MJ for biohythane, and between −352 to −70 g CO_2 e/MJ for biomethane [48, 60, 61]. The negative emissions of the production of liquid biofuels are due to subtracted credits from excess electricity generation and coproduced acetone and hydrogen [37], while those from biomethane are a result of subtracting emissions from avoiding conventional treatment of food waste in landfills or manure management [61]. Renewable natural gas (RNG), a biobased alternative to fossil-based natural gas, can be produced by waste feedstocks. Lee et al. [62] found that renewable natural gas produced from fats, food waste, and swine manure has negative GHG emissions ranging from −146 to −68 g CO_2 e/MJ, due to the subtraction of credits from avoided waste management. This study also evaluated wastewater sludge as a feedstock, which showed positive GHG emissions (37 g CO_2 e/MJ) because the credits from avoided waste management were lower compared to processing and combustion emissions.

The GHG emissions of biofuels produced through biotechnology showed lower values compared to those from fossil-based counterparts in most cases. For bioethanol, only one study using wheat straw showed higher emissions (156 g CO_2 e/MJ) than fossil-based gasoline (90 g CO_2 e/MJ) [33]. In the case of hydrogen, rice husk and biological food waste were the feedstocks showing higher emissions compared to hydrogen produced from steam methane reforming (79 g CO_2 e/MJ). For RNG, all the feedstocks evaluated presented lower GHG emissions than fossil natural gas (69 g CO_2 e/MJ). As previously discussed, the higher GHG emissions are due to several factors including energy-intensive processing and the futility of co-product credit subtraction. Recently, Bartling et al. [63] and Benavides et al. [64] reported the GHG emissions of several bio-derived blendstocks used in mixing-controlled compression ignition engines and advanced multimode engines, respectively. Their findings indicated that biotechnological conversion of feedstocks such as corn stover to produce bio-derived blendstocks like farnesene, alkoxyalkanoate ether-esters, mixtures of prenol and isoprenol, 2-butanol, n-propanol, isopropanol, and food waste, to generate isoalkanes from volatile fatty acids, achieves lower GHG emissions compared to those from fossil-based gasoline. The observed reduction of GHG emissions in these bio-derived blendstocks is lower than 60% compared to fossil-based gasoline. Similar percentage of reduction with respect to conventional counterparts was also observed in bioethanol produced from corn stover, forest residues, miscanthus, willow, oil palm frond juice, potato, poplar, and MSW and biomethane generated from AD of MSW. Hydrogen generated from sweet sorghum, potato and sweet potato peels, sorghum stalk, and wheat straw exhibits GHG emissions that are 40% lower than hydrogen produced from steam methane reforming (SMR).

Through this review, we identified that correlating the microbial species utilized for fermentation with the GHG emissions of bioethanol has not been widely evaluated or discussed. Microbial species can pose an important impact due to their influence on bioethanol and co-product yields [53]. Researchers have also aimed to compare the same biorefinery or product formation through different LCA approaches. Likely, Pereira et al. [65] presented a detailed LCA study of the ethanol production from sugarcane, corn, and wheat (first-generation feedstocks) through four LCA approaches, e.g., BioGrace (EU), GHGenius (Canada), and GREET (USA), and a research-oriented fourth, the Virtual Sugarcane Biorefinery (VSB). On the other hand, one of the impacts affecting the environmental performance of biofuels is the indirect land-use change (iLUC). This impact represents the GHG emissions associated with shifting the use of land from its previous purpose to cultivating crops for biofuel production. Although of considerable importance, some studies did not incorporate the impacts of iLUC as it was deemed out of the scope of the analysis. Consistency in the inclusion of this impact in the LCA of biofuels is also recommended.

Bioplastics

With respect to food crops used for bioplastics, corn is used to produce polyhydroxybutyrates (PHBs), polybutylene succinate (PBS), bio-polyethylene (BioPE), polylactic acid (PLA), and polymeric itaconic acid (PIA), while sugarcane is employed for PHBs processing. Between these two feedstocks, the highest GHG emissions were observed in the production of corn-based PHB (6.4 kg CO_2 e/kg), while the lowest were obtained in sugarcane-based PHB (−2.6 kg CO_2 e/kg) [66]. Sugarcane shows negative GHG emissions due to the subtraction of credits from co-product displacement (steam produced from bagasse) [67]. For corn-based PLA production, GHG emissions can increase due to biodegradation at landfills or composting facilities [68]. Lignocellulosic materials and organic products like glycerol, soybean oil, black syrup, corn stover, and sugar beet pulp present a wide variety of GHG emissions in the production of bioplastics, which ranged from − 2.4 to 5.9 kg CO_2 e/kg [68–73]. The lower and upper bound GHG emissions were observed in the production of PHB from soybean oil and PHA from cheese whey, respectively. It is noteworthy that in the PHB production from soybean oil, the authors subtracted the CO_2 uptake credit due to soybean growth [74]. The value of the CO_2 credit was higher than the total cradle-to-gate GHG emissions of the pathway leading to net-negative GHG emissions. Similarly to the analyses of biofuels, the variability of the GHG emissions strongly depends on the employed methods and assumptions. From the different waste feedstocks, the GHG emissions ranged from − 3.6 to 5.2 kg CO_2 e/kg [69, 71, 72, 75]. The net-positive GHG emissions found in the reviewed studies indicate that for bioplastics, the cradle-to-gate GHG emissions of the pathways were higher than the credits from avoided waste management and credits from CO_2 uptake from certain feedstocks. For the majority of the bioplastics (PLA, PHB, PBS, and Bio-PE), these high cradle-to-gate emissions were driven by the requirements of electricity and natural gas of the process [66, 68, 71, 75]. The net-negative GHG emissions are observed in PLA produced from wastewater sludge, food waste, and swine manure and considered credits from avoided waste management and CO_2 uptake in the plastic [75]. Similarly to biofuels, the production of bioplastics could benefit from integrated biorefineries to further reduce GHG emissions by the subtraction of co-product credits [21, 37].

The comparison of the GHG emissions of bioplastics with their fossil-based counterparts indicated that feedstocks like soybean oil, glycerol, black syrup, and corn stover generate bioplastics with lower GHG emissions compared to their fossil-based counterparts (polypropylene, high-density polyethylene, and polystyrene). Similarly, the production of PLA from waste feedstocks and the production of bio-polyethylene terephthalate (Bio-PET) from corn stover resulted in lower GHG emissions than fossil-based PET.

Bioproducts

A wide range of feedstocks has been investigated to produce bioproducts that replace existing fossil-based counterparts' markets [33, 39, 56, 72, 76–86]. The GHG emission result values vary significantly based on the chemical produced, type of allocation method, feedstock, and the process of transformation of feedstock to product. These are listed in Table S3 and shown in Fig. 5. The major aim is still being the reduction in overall GHG emissions along with the co-production of useful byproducts through different approaches [87].

Some chemicals that can be produced through biotechnology like ammonia, lactic acid, and succinic acid are of primary importance [88–90]. Ghavam et al. [77] presented the production of ammonia using organic waste with different scenarios of anaerobic digestion, fermentation, and CO_2 capture and sequestration. The authors suggested that a process combining anaerobic digestion, dark fermentation, and CO_2 captured, which is used for urea production, yields the lowest GHG emissions (0.091 kg CO_2 e/kg of ammonia) compared to the individual implementation of these technologies. Lactic acid, which is widely used in cosmetics, pharma, food, and polymer industries, has been studied by many researchers for biobased production using corn, corn stover, sugarcane, bread waste, and organic MSW. The GHG emissions ranged from − 0.6 to 18.1 kg CO_2e/kg of lactic acid depending on the initial feedstock, technology, and application of heat integration [78, 91]. The lowest GHG emissions from all the reviewed feedstocks are found for sugarcane feedstock with a value of − 0.6 kg CO_2e/kg of lactic acid [78]. The values of GHG emission for lactic acid production from bread waste indicate being an outlier from the rest of the crops since the latter contributes to the CO_2 uptake and therefore reduces the overall GHG emissions, whereas bread waste being a processed food waste does not provide the same attribute. Succinic acid is another widely used chemical that has been explored as an important co-product of biorefineries. GHG emissions from biobased succinic acid showed GHG emissions varying from − 0.01 to 7.5 kg CO_2e/kg of succinic acid. As observed, there is a wide variety of feedstocks that can be used (corn, corn dextrose, sorghum, giant reed, harding grass, corn stover, apple pomace, bread waste, mixed food waste, food waste, organic waste, and organic MSW). The lowest value is obtained when succinic acid is being produced using corn stover as a feedstock (− 0.01 kg CO_2e/kg) [78]. The major drivers for GHG emissions vary according to allocation methods, conversion technology, and feedstock usage. For instance, the prime contributors to the GHG emissions of succinic acid using bread waste are steam and heating oil, which contributed 45% and 50% of the total emissions, respectively [82]. This can be ascribed to the fact that bread waste is highly processed food, and its conversion to succinic acid is followed by many complex processing steps. On the other hand, if corn stover is used as a feedstock, the production of succinic acid can be done using simple fermentation of biosugars followed by separation and upgrading to the final product; in this case, the major hotspots are natural gas, chemicals, and electricity [33]. Balchandani et al. [56] discussed the production of gluconic acid and xylonic acid using corn stover, date palm clippings, and nonrecyclable paper using alkali pretreatment at similar processing conditions for all feedstocks. Nonrecyclable wastepaper was found to be most suitable in terms of economics and environmental impact among the three feedstocks studied. It was also found that the initial composition of the feedstock defines the overall conversion. For example, while nonrecyclable wastepaper had 51% cellulose and corn stover had 34% cellulose, the processing of nonrecyclable wastepaper provided more yield and hence less burden on the overall GHG emissions, which concludes the dependency of GHG emissions on the feedstock used along with its initial composition.

Production of nisin (a polycyclic antibacterial peptide) along with co-product lactic acid was also explored for GHG emissions estimation for three biobased feedstocks (corn stover, cheese whey, and sugar beet pulp) through mass and market allocation methods [80]. The authors suggested that using sugar beet pulp as a feedstock resulted in the lowest emissions (0.61–3.75 kg CO_2e-/kg of product) when compared to other feedstocks irrespective of allocation method. However, the values for GHG emissions using the market allocation method (nisin production) are too high since the burden (based on the allocation factors) is higher for the market when compared to the mass values. Further, another view concerning the type of feedstock used can be provided for instance, corn stover (used in many chemicals production in Fig. 5), which is usually the popular choice of researchers for conversion to biofuels, and bioproducts may hence not prove always to be more environmentally sustainable than other biowaste resources available. Also, like the production of lactic acid from bread, waste demonstrates higher GHG emissions; likewise, cheese whey (another processed food waste) shows similar behavior. The production of nisin from cheese whey also has the highest value for GHG emissions in comparison to all other chemicals under study (61.91 kg CO_2e/kg) [80]. In general, agricultural waste feedstocks tend to exhibit lower GHG emissions because of accounting for the biogenic carbon credits.

The process optimization and readiness level of any technology are also an important factor that affects the desired GHG emission reductions [92]. For instance, the GHG emissions of biobased isoprene exceed by more than a twofold margin compared to fossil-based isoprene [33]. The lower GHG emissions of fossil-based isoprene are attributed to the lower energy and material consumption due to single-stage reaction, while biobased isoprene requires three major reaction sections followed by separation, which potentially increases the material and energy demand. Similarly, the production of caproic acid involves multiple fermentation steps, and the process exhibits high GHG emissions of 14.90 kg CO_2 eq/kg.

Tools for evaluating LCAs

The data presented in Figs. 3, 4, and 5 majorly use tools such as GaBi, SimaPro, the GREET model, and OpenLCA for evaluating the LCA. These tools have their datasets, or importing data sets from other software is also possible. Some of the major datasets include the United States Life Cycle Inventory Database (USLCI) and ecoinvent. However, most of the studies developed the inventory data for their technologies by collecting data from plant/laboratory operations or developing process models through simulation. Environmental sustainability encompasses a range of different environmental impacts since different tools use diverse performance indicators for providing impact analysis, and sometimes, the same indicators might also have different units across different tools. This sometimes is the cause for discrepancies while comparing the impacts evaluated using distinct tools over the same technology. Further, comparing additional impacts, e.g., fossil energy and water consumption, could identify interesting trade-offs between the feedstocks and pathways that aid in future process design and decision-making [23]. The application of individual or combination of a tool for impact analysis sometimes reveals a huge difference in the overall results. Few other tools are also available for this type of environmental assessment such as GREENSCOPE developed by the US Environmental Protection Agency (EPA) for quantifying process sustainability through 139 performance indicators in material efficiency, energy, economics, and environment [93]. Similarly, the Materials Flow through Industry (MFI) tool developed by the National Renewable Energy Laboratory (NREL) is another interesting tool for sustainability assessment through the concept of supply chain and simulating different production scenarios over a range of available technologies [94]. The comprehensiveness of the datasets also varies significantly according to the development stage. Additionally, the application of normalization (compared to a reference value) and weighing of impact categories (more importance given to certain impact categories rather than others) may also affect the overall results pertaining to LCA [95].

GHG emissions — the most common performance indicator (or ($CO_2+CH_4+N_2O$ emissions)), are usually assessed by all the software's due to the industrial, political, and societal importance of the greenhouse gas emissions and their contribution to governmental policy decisions. The choice of tool for conducting LCA is dictated by all these factors along with the country's origin.

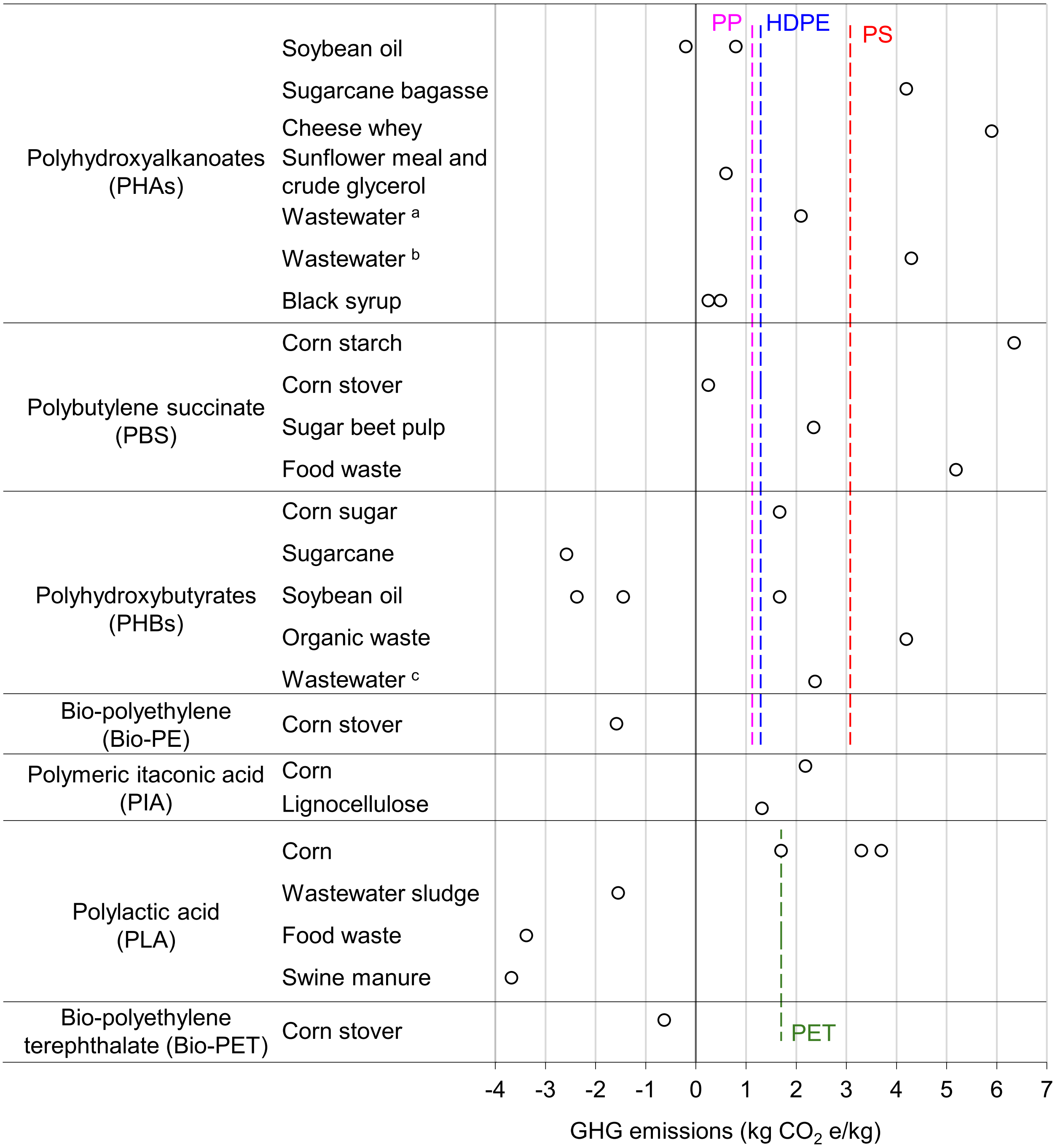

Fig. 4 GHG emissions of bioplastics from biotechnological processes. **a** Wastewater from paper mills. **b** Wastewater from the food industry. **c** Wastewater from the paper and the food industry. Detailed information on the data is available in Table S2 of the SI. GHG emissions of fossil-based polypropylene (PP), high-density polyethylene (HDPE), polystyrene (PS), and polyethylene terephthalate (PET) are estimated in 1.1, 1.3, 3.1, and 1.7 kg CO_2 e/kg, respectively [33]

For example, European countries usually prefer the database of ecoinvent along with the SimaPro software for calculation since the software is accepted widely by the European countries' governments [96]. On the other hand, GREET has significantly been adopted by the US government for making policy decisions [97].

Discussion

Figures 3, 4, and 5 indicate that even with the same type of feedstock and output product, the evaluated GHG emissions vary significantly depending on factors such as system boundary under study, method of evaluation (software and database used), type of co-products

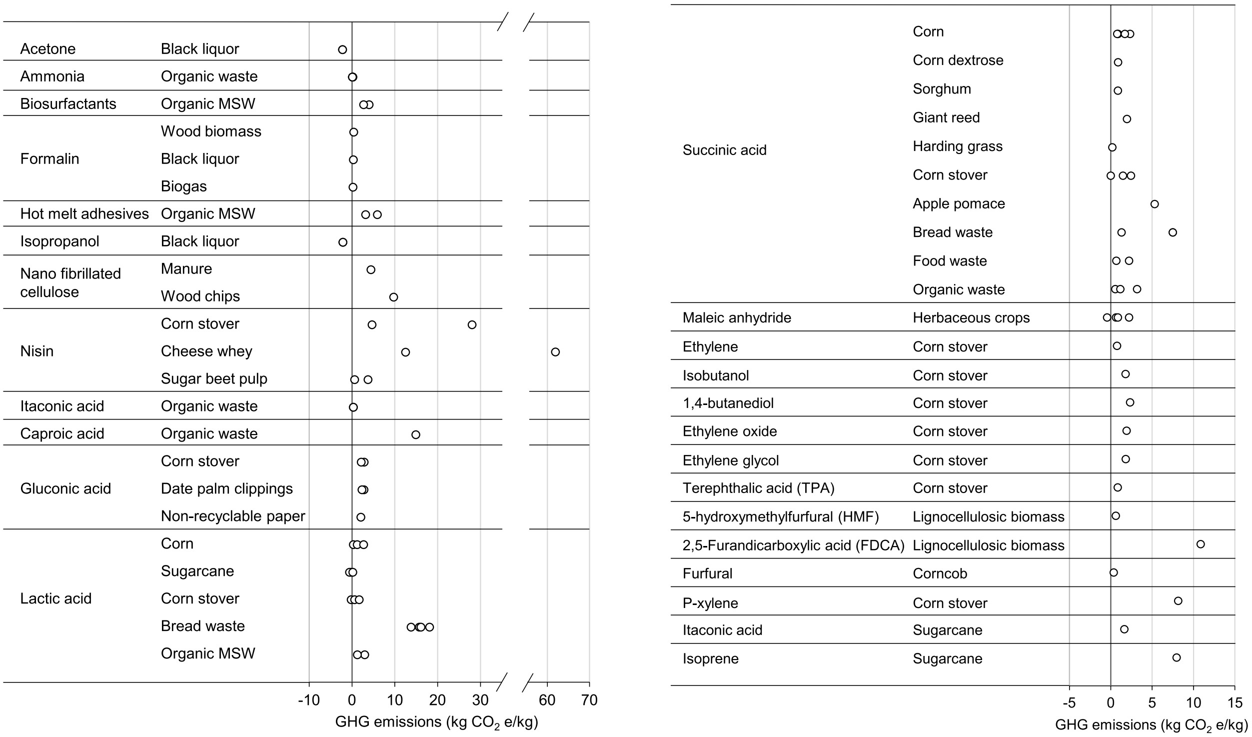

Fig. 5 GHG emissions of bioproducts from biotechnological processes. Detailed information on the data is available in Table S3 of the SI

produced, and respective co-product handling method, source for all input materials such as bio-based or fossil-based, type of electricity, inclusion of biogenic carbon credits, and avoided emissions. Therefore, for an accurate comparison of the different biotechnologies to produce biofuels and bioproducts using the same feedstock, it is extremely necessary to have a similar analysis methodologies comparison to reduce variability despite differences form tools utilization. There is a requirement for harmonization with assumptions made during LCA studies.

The results also indicate that every opportunity that is available to improve and optimize the process will translate into significant economic and environmental benefits, which can be achieved by process mass and heat integration. However, the process integration in turn also depends on the country of origin of the feedstock and its further processing along with the environmental, public health, and safety policies of the country. In this regard, the acquisition of accurate and case-specific LCI is another crucial category of work, which can be focused on by the researchers. In many cases, the LCI is obtained through process simulations and direct plant data, which could be proprietary and, therefore, not available in the open literature. Only a precise LCI is going to generate accurate results for life cycle impacts to make adequate decisions for the proposed technologies.

A good understanding of different areas of any biotechnology might also help in ultimately reducing GHG emissions. For instance, separation contributes almost 30–40% of the plant costs [98]. Hence, making an efficient change in process technology will result in economic and environmental benefits. Other aspects worth considering involve the definition and improvement of the type and quantity of the strain used in the biotechnological process, as these factors significantly impact the conversion yields [99]. Furthermore, strain performance can be improved through metabolic engineering techniques [100, 101]. Other important process parameters such as solid loading, temperature, pressure, and reaction conversion rate can also be evaluated and correlated with the GHG emissions of the process.

The reviewed studies highlight that to produce any biofuel or bioproduct, it is essential to have a steady supply chain of feedstocks and other chemicals along with advanced and safe processing technologies of feedstocks in a view to maximize the economic and sustainable aspects of the production [102, 103]. Therefore, the production and collection methodology of feedstock (agriculture waste, processed food waste, grain crops, etc.) also play a significant role in determining the total GHG emissions to produce bioproducts. For instance, the corn stover obtained after a single pass is expected to have a different contribution to GHG emissions compared to the two-pass obtained feedstock [104, 105]. Detailed studies in the same field for various feedstocks would be of great impact in the field of LCA. Other important aspects of the development of sustainable bioprocess include the identification of environmental, health, and safety issues, which are mostly driven by the separation processes [14].

Conclusions

Biotechnology plays a significant role in the current bio-based fuels and specialty chemicals market. In this paper, a survey of recent studies evaluating the LCA of biotechnologies to produce fuel, bioplastics, and bioproducts was conducted. The GHG emissions of the different products from biotechnologies are highly influenced by the assumptions utilized in the LCA, like the inclusion of the biogenic carbon credits or avoided emissions from waste emissions, and the generation of co-products in the biorefinery. Differences in these assumptions were a source of discrepancy among the reviewed studies which complicated the comparison of the data; therefore, harmonization of the assumptions within studies is strongly encouraged. The usage of different allocation and system expansion methods also led to a variation of the LCA results. Clarity in the methods should also be an important component of any LCA of bioproducts, for instance, details of the feedstock origin (e.g., sugar or glucose from corn), temporal and geographical representation, and assumptions (e.g., subtraction of credits from biogenic carbon uptake, avoided waste management, or displaced co-products) should be specified. Transparency and granularity while reporting inventory data will also help to understand variations of the results and identify key process stages for technology improvement. Further, consideration of integrated biorefinery can result in less overall GHG emissions compared to the production in single product biorefinery due to the emission burden allocation to the co-product and application to the mass and heat integration.

From the papers reviewed, there is considerable progress made around biofuels which achieve lower GHG emissions compared to fossil-based fuels. However, improvements in technology for bioplastics and chemicals could benefit from improvements in yields, energy-efficient separation technologies, heat integration, and process intensification. Every opportunity that is available to improve and optimize the process will translate into significant economic and environmental benefits. Process integration, synthetic biology, and genetic modification of microorganisms can induce substantial reductions in environmental impact. There is a huge emphasis on promoting circularity and decarbonization strategies by different stakeholders, which include the utilization of waste streams and reusable carbon streams such as nonrecyclable sections of MSW, sludges, and plastics to produce fuels and products. The distribution of feedstock, however, depends on the market potential of the final products, and the utilization of these waste streams for producing bioproducts encounters challenges such as efficient sortation in the case of MSW and toxic contaminants, which should be included in the evaluation of their sustainability. Finally, although this review focused on GHG emissions, environmental sustainability encompasses a range of different environmental impacts; therefore, focusing on a particular impact may obscure important trade-offs for other impacts and bias decisions.

Supplementary Information

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Supplementary Material 1.

Notes

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Authors' contributions

Sweta Balchandani: literature review, Investigation, Data curation, Writing-original draft, Writing-review and editing. Ulises R. Gracida Alvarez: literature review, Investigation, Data curation, Writing-original draft, Writing-review and editing, Visualization. Pahola Thathiana Benavides: Conceptualization, Methodology, Writing-original draft, writing review and editing, Supervision and project administration.

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Availability of data and materials

Data used to generate all the figures in the manuscript is provided within the supplementary information files.

Declarations

Competing interests

The authors declare no competing interests.

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