Volume 7
Number 17
7 September 2023
Pages 4021–4342

Sustainable Energy & Fuels

Interdisciplinary research for the development of sustainable energy technologies

rsc.li/sustainable-energy

ISSN 2398-4902

ROYAL SOCIETY OF CHEMISTRY

REVIEW ARTICLE
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Sustainable Energy & Fuels

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Cite this: *Sustainable Energy Fuels*, 2023, 7, 4031

Integrated techno-economic and environmental assessment of biorefineries: review and future research directions

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Biorefineries will be strategic players in achieving the circular economy and sustainability goals. This work presents a comprehensive review of the last decade of research on the Environmental and Techno-Economic Assessment (ETEA) of biorefineries. We compiled 102 articles applying an integrated ETEA approach to understand the technical, economic, and environmental implications of different biorefinery schemes. Bibliometric analysis has been first performed to map the keywords and locations of case studies and explore trends in biomass feedstock, conversion routes, and bio-based products. Then, computer-aided tools and state-of-the-art methodologies employed within the ETEA framework are reviewed. Finally, challenges and directions for research are discussed. The results show increasing interest in the topic, moving from the first to higher generations. Publications utilizing second-generation biomass dominate the research topic (65%), followed by the third, first, and fourth generations (16, 12, and 1%, respectively). An uneven distribution of publications was also observed, with the USA contributing the most (with one-third of studies), suggesting that governments are crucial driving forces of research. Biochemical routes such as fermentation and anaerobic digestion receive the most attention (together used in 59 out of the 102 articles), followed by thermochemical routes (*e.g.*, combustion, pyrolysis, and gasification used in 28% of the articles). Bioethanol is the main targeted product (in 29 articles), followed by biogas, biomethane, and biodiesel. Overall, the ETEA framework aids in designing and optimizing biorefineries to achieve sustainability goals. It helps evaluate the trade-offs between the economic viability and environmental sustainability of conventional and emerging biorefinery processes at different stages of deployment. This review contributes to the development of the ETEA framework, and it might be helpful to guide practitioners, decision-making, and future research on sustainable biorefineries.

Received 27th March 2023
Accepted 10th June 2023

DOI: 10.1039/d3se00405h

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1. Introduction

The world faces unprecedented challenges to reach sustainable development by balancing economic, societal, and environmental goals. Deep transformations are required across all economic and social sectors to progress toward the desired sustainable state. Future production and consumption patterns must build a solid economic framework within the planetary boundaries while ensuring social well-being.[1] Among the drivers for this change, innovative biorefineries and their bio-based products (or bioproducts) emerge as strategic players that may play a pivotal role by enabling the circular (bio) economy to help move closer to the Sustainable Development Goals (SDGs).[2,3] In a nutshell, a biorefinery is a facility that integrates processes converting biomass resources into renewable energy, fuels, and a plethora of platforms and specialty chemicals with widespread applications across sectors and industries. Notably, some bio-based products may replace fossil-based counterparts, thus reducing dependency on unsustainable foreign resources and avoiding environmental impacts associated with fossil resources. Hence, biorefining potentially provides synergies across several SDGs, for example, ensuring access to sustainable energy (SDG7), contributing to responsible production and consumption (SDG 12), or combatting climate change (SDG13), among others.[4,5] However, due to the inherent interactions between the SDGs, economic, social, and environmental trade-offs might also emerge related to using biomass resources, which can be often alleviated by using non-edible biomass resources. Nevertheless, challenges remain, and it is paramount to ensure that bio-based products contribute to a fully sustainable economy before taking actions to drive the widespread deployment of biorefineries.[4,6] As of today, beyond conventional biorefineries based on sugar,[7]

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energy crops[8] and lignocellulosic biomass, the large-scale deployment of biorefineries is still scarce, mainly because the bio-products delivered are not yet cost-competitive compared with conventional fossil-based alternatives despite potentially providing large environmental and social benefits. Other barriers include the complex nature of biomass feedstock, scarce availability of resources, productivity difficulties of conversion processes at the early stages of deployment, and lack of understanding and uncertainties regarding the environmental implications of their deployment at scale.[9] Hence, ensuring that advanced biorefining technologies simultaneously enable the three pillars of sustainability is fundamental to promoting their widespread deployment.

The maturity of the technologies and processes employed in biorefining varies greatly from low to high technology readiness levels (TRLs) – from new developments still as proofs-of-concept to commercial and operating scales (nine TRL levels). Regardless of the maturity level, an in-depth assessment and understanding of the technical, economic, and environmental implications are essential before starting the deployment of biorefineries on a large scale. Among the tools available to help in this task, Techno-Economic Assessment (TEA) is an efficient approach that evaluates the technical and cost performance of processes and systems and helps make informed decisions to improve performance.[10] Several studies have analysed biorefining systems' technical and economic aspects and biomass supply chains such as corn,[11] biowastes[12] and even algae biomass.[13] Different methods and tools are used to tackle the TEA studies depending on the level of details required, such as computer-aided scaling-up simulation exercises, and traditional economic indicators (*e.g.*, cash flow analysis, net present value, and payback period). Overall, the TEA results showed the importance of expanding to multi-product systems to improve economic viability and identified key uncertainties regarding market forces and fluctuating prices of raw materials.[9]

The TEA studies have a narrow focus, primarily analysing technical feasibility and economic performance. Although they examine the energy consumption, which can be used as a proxy for the environmental impacts when fossil resources are used,[14] this narrow TEA approach systematically neglects the environmental (and social) dimension, which risks inflecting undesired side effects.

To assess biorefineries from an environmental perspective, the Life Cycle Assessment (LCA) methodology is a broadly recognized support tool to assess and reduce environmental impacts considering the entire life cycle of any system.[15] LCA evaluates the life cycle environmental impacts associated with a product, process, or service based on a compiled inventory of relevant materials and energy inputs and outputs and interprets the results to support the decision-making process.[15] Previous LCA-based studies on biorefineries have shown that generally bio-based products improve the greenhouse gas (GHG) footprint compared with fossil-based counterparts. However, the improvement in the carbon footprint is often achieved at the expense of environmental trade-offs that cannot be overlooked, such as eutrophication and biodiversity issues, mainly associated with the cultivation of biomass.[5]

Although isolated TEA and LCA studies provide valuable information, embracing both techno-economic and environmental aspects is fundamental to ensure that sustainability is achieved. Hence, the integrated Environmental and Techno-Economic Assessment (ETEA)[16] approach emerged as a robust methodology to guide informed decisions and assist developers and policymakers in developing more environmentally sustainable technologies.[16] These ETEA studies serve as a supportive mechanism that evaluates the importance of using techno-economic and environmental evaluation as an essential decision tool in the business of biorefinery industries.[17–19]

Notwithstanding the previous literature reviews focusing either on TEA or LCA or combining both, a compilation of articles applying the integrated ETEA approach to assess biorefining systems regardless of the type of biomass and conversion technology is still lacking. Our review article fills this gap by going beyond previous studies since it provides a comprehensive review of previous studies published in the last decade applying the integrated ETEA approach. Given the capabilities of this integrated tool to guide the decisions on sustainable biorefineries, a review reflecting on the recent literature may be handy. Hence, this review article summarizes the main findings, provides recommendations, and identifies challenges associated with biorefineries' large-scale deployment.

The article is organized as follows. The concept of the biorefinery and the ETEA framework is further explained in the next section. Then, the methodology followed for the systematic bibliometric search strategy and the screening of articles is presented. The following section analyses the selected studies regarding the type of biomass, conversion technologies, economical or environmental research, economic and environmental indicators, and bio-based products delivered. Finally, recommendations, challenges, perspectives, and research gaps are presented, and the main conclusions are summarised.

2. Biorefinery concept and techno-economic environmental analysis

2.1. Biorefinery concept

The biorefining concept lies at the heart of sustainability and circular economy goals.[20] Biorefining involves creating a wide range of marketable bioproducts from different biomass feedstock materials involving numerous conversion technologies based on physical, chemical, biochemical, and thermochemical processes.[21] The core of the biorefining concept is the biorefinery plant. A biorefinery is an industrial facility where biomass pre-treatment and conversion into various bioproducts occur, which usually entails a very complex value chain involving activities across different locations and many actors, with often conflicting interests (Fig. 1).

First, biomass mobilization includes resource acquisition, transportation, and pre-treatment to the biorefinery plant. Several sequential processes (mechanical, chemical, thermochemical, and biochemical) are designed to obtain multiple products in the plant. Widening the product range (bioenergy,

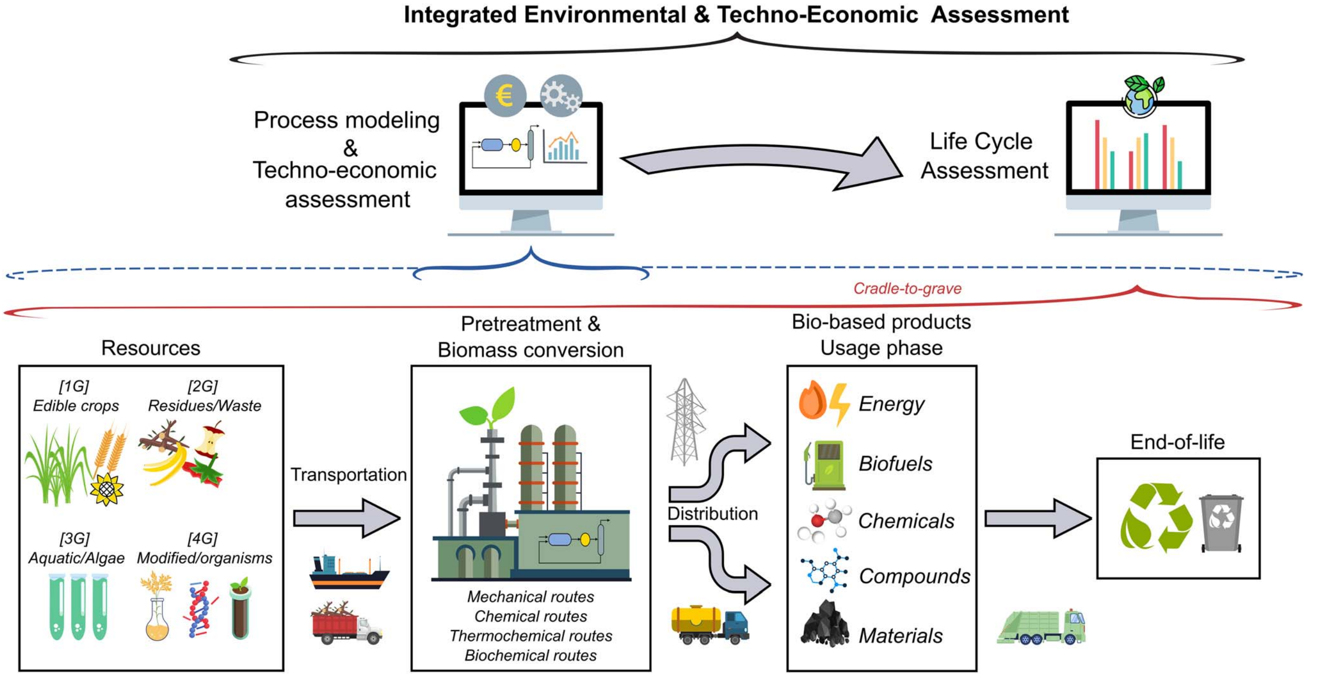

Fig. 1 Integrated environmental and techno-economic assessment as a methodology to evaluate the sustainability of the biorefinery value chains.

biochemicals, and biofuels) usually helps improve economic performance. For example, multi-product biorefineries can produce hydrogen[22] together with other biofuels[23,24] such as biomethane.[25] Recently, the so-called cascading biorefining schemes are gaining attention, aiming to reuse, recycle, and valorise biomass materials and biowastes generated along the value chains in sequencing processes, thus improving efficiency and recovering the most value from biomass.[26]

Biorefineries are often classified depending on the products obtained, the conversion routes, and the biomass input.[27] Considering the products, biorefineries can be classified into energy- and product-driven, the first producing fuels, heat, or power and the latter bioactive compounds, food, or other value-added chemicals as the main outputs. Regarding the valorisation pathways, there are four main conversion processes which are mechanical, chemical, thermochemical, and biochemical routes.[3] Before the biomass conversion itself, mechanical (or physical), chemical, biological, and combined pre-treatment processes are often required to deconstruct biomass, make the compounds readable for subsequent processes[28] and improve efficiency.[29] Concerning conversion, thermochemical routes rely on processes such as pyrolysis,[30] gasification,[31] hydrothermal carbonization,[32] and other thermal-based processes.[33] These routes convert biomass resources into energy or other valuable products by applying heat and chemical reactions. In contrast, biochemical routes use enzymes, bacteria, or other designed organisms to convert biomass to bio-based products. Biochemical processes include fermentation,[34] anaerobic digestion[35] or enzymatic conversion,[36] and combinations of routes. Chemical routes include transesterification and acid hydrolysis, which involve reacting agents such as alcohols or acids to obtain the desired product. Additionally, mechanical processes can lead to component separation, such as obtaining fractions with different chemical compositions.[37] Moreover, extraction methods can also be applied to recover extractable compounds of interest before further pre-treatment or conversion of the biomass to avoid their loss or degradation.[38]

Regarding raw biomass, biorefineries can be classified based on feedstock generation. First-generation (1G) biorefineries rely on dedicated feedstock cultivated on lands, such as edible crops or forest plantations. Although they are at TRL 9,[39] 1G biorefineries bring about issues related to food competition and insecurity with other crops, soil usage, and excessive water usage, hampering progress in some SDGs.[40] Hence, shifting from 1G biomass to higher generations is crucial. Second-generation (2G) biorefineries employ by-products and residues such as lignocellulosic biomass from forestry, agricultural activities, or municipal wastes. These 2G biorefineries are deemed more suitable alternatives as they help overcome previous issues reducing bio-waste generation but often suffer from competitiveness barriers.[41] Third-generation (3G) biorefineries rely on aquatic feedstock such as algae,[40] which are adequate for biodiesel due to their lipid content and may alleviate the land use issue when cultivated in close reactors.[42] However, drawbacks still exist related to risks for marine ecosystems, expensive cultivation and processing, and high-water demand and fertilizers.[40]

Finally, fourth-generation (4G) biorefineries employ genetically modified algae, cyanobacteria, and crops to increase productivity, improve environmental performance, and boost competitiveness.[43] Unfortunately, they also suffer from political and legal barriers, social acceptance issues, and uncertainties regarding their environmental impacts on ecosystems and human health.[41,42]

2.2. Integrated techno-economic and environmental assessment methodology

The industrial-scale development of biorefineries still faces major challenges and barriers, such as difficulties in mobilizing biomass resources, problems of economic viability, and uncertainties about their environmental implications. Regardless of the type of biomass, conversion processes, and bio-based products obtained, modern biorefineries should be environmentally sustainable, *i.e.*, contribute to economic growth and social and environmental goals.[26] Understanding the relationship and trade-offs between economic and environmental performance is essential for designing and scaling-up sustainable biorefinery value chains (Fig. 1). Hence, the integrated ETEA is a valuable framework as it combines technical, economic, and environmental indicators to shed light on the large-scale implications of biorefineries.

On the one hand, TEA is a widely used tool that allows for assessing systems' technical and economic feasibility before industrial-scale deployment. This is particularly relevant in biorefineries because the variability of the biomass resources and complexity of the value chains often deter economic viability. The TEA methodology consists of process modelling and development *via* process system engineering tools such as simulation and optimization methods.

The models representing the scale-up problem of the facilities are often built relying on first principles for every unit operation (thermodynamic data and energy and raw material balances), which can be gathered from experimental results or literature data. Besides spreadsheet software programs, computer-aided simulation tools such as Aspen Plus®, Aspen Hysys®, and SuperPro Designer® are broadly used to simulate the process operation inputs.[44] The simulations provide the mass and energy flows entering and leaving the system to estimate the capital and operational expenditures of the processes (CAPEX and OPEX) employed to compute the economic indicators (and environmental assessment).[45] Due to the unconventional nature of biomass resources and components, they are usually absent in the software simulation database. The National Renewable Energy Laboratory (NREL) database and Chemical Engineering Design book[46] report constitute a handy source[47] for data completeness and simulation guidance of bio-based processes. Economic indicators are financial metrics to evaluate the project's viability, such as the Net Present Value (NPV), payback period, or internal return rate. TEA has helped stakeholders understand technologies' long-term economic impacts at various commercialization levels.[48–50]

On the other hand, LCA is a standardized practical methodology[51] that studies biorefineries' environmental consequences from a life cycle view. In other words, LCA examines production systems' environmental impacts and burdens from the cradle to the grave (from biomass harvesting to industrial operations, usage stage, and end-of-life management such as waste disposal) or cradle-to-gate (from stock cultivation until the usage stage). LCA is typically used to examine how the whole value chains for manufacturing bioproducts and co-products would influence the environment. The goal of an LCA-based biorefinery study might be to compare the environmental effects of different process alternatives (technologies or designs) or to decide on the best uses of biomass feedstock.[52] The boundaries of the biorefining system depend on the LCA study, but cradle-to-gate is usually preferred over cradle-to-grave, starting from the biomass feedstock and raw material until the biorefinery plant gate.

Due to the multi-product nature of biorefinery systems, it is often difficult to avoid allocation issues and identify the functional unit on which the environmental impacts are calculated.[53] To carry out LCA studies, computer platforms such as SimaPro, GaBi, and Open LCA and databases such as Ecoinvent can help model the system, complete the inventory (life cycle inventory) and obtain the impact assessment results (life cycle impact assessment). The environmental performance is often assessed focused on climate change-related indicators (*e.g.*, global warming potential). However, it is essential to consider other impacts, such as eutrophication, land-use change, or biodiversity, to avoid shifting burden.[5] Integrating TEA and LCA in the ETEA framework contributes a powerful tool that can guide a wide range of stakeholders to make informed decision ensuring sustainability.[15] The following section explains the bibliometric analysis conducted in integrated ETEA studies of biorefineries, while the articles found are assessed in the subsequent sections.

3. Review methodology

This review aims to compile and assess the latest literature applying an ETEA to biorefineries. The methodology followed for the bibliometric compilation was a semi-systematic review based on three consecutive steps: bibliometric search, publications screening, and comprehensive analysis (Fig. 2).

The bibliometric search was conducted in the first search step using the following search engines and databases: Elsevier's, Scopus, Google Scholar, and Web of Science. We performed keyword searches considering a 10 year gap interval (2012–2022), including journal publications (articles and reviews but excluding books) applying TEA and/or LCA, either standalone or integrated. In total, 170 bibliographic records were found by using the following search string sequences of keywords: (techno-economic assessment AND life cycle assessment) OR (techno-economic AND life cycle analysis) OR (environmental impact AND environmental analysis) OR (economic AND environmental) AND (biorefinery) OR (biomass) OR (bioenergy) OR (biofuel) OR (anaerobic digestion) OR (biodiesel) OR (bioethanol) OR (ethanol) OR (microalgae) OR (optimization) OR (process simulation) OR (circular economy) OR (sustainability). This set of keywords represents our domain analysis; however, we might have failed to capture articles using infrequent keywords across the titles and abstracts.

In the second screening step, the curation step, the total articles found (170) were further filtered to select only those carrying out the integrated ETEA, resulting in 102 articles published from 2012 to 2022. The rejected articles included essentially studies applying either TEA or LCA in isolation. The 102 chosen articles were used to develop the results and

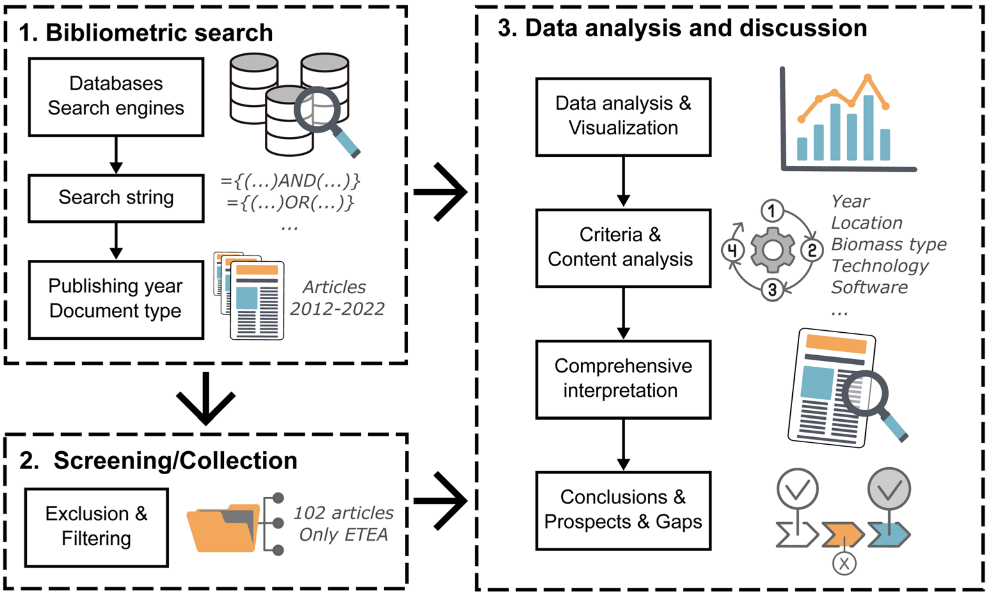

Fig. 2 Methodological framework followed in the literature review of integrated environmental and techno-economic assessment applied to biorefinery systems.

discussion sections to evaluate and provide the required research gaps to support the review topic.

Finally, in the third stage, the selected articles were first screened and examined based on the year of publication, location, type of biomass employed, conversion pathway, main products and methods, software, and assumptions used for the TEA and LCA assessments. Based on the findings, a comprehensive analysis is presented, providing conclusions and perspectives for future work and research gaps.

4. Results and discussion

4.1. Keyword analysis

Fig. 3 evaluates the relationship, co-occurrence, and evolution between the high-frequency keywords. All 102 articles and their keywords were considered, and a minimum of four co-occurrences was set as a limiting factor. Twenty-three high-frequency keywords were shown in total for the interval 2016–2022. The keywords with the highest co-occurrence were "life cycle assessment", "techno-economic assessment", and "biorefinery" (those with bigger nodes in Fig. 3). Notably, there is a strong connection between some keywords, for example, "life cycle assessment" and "techno-economic assessment", "biorefineries" and "biofuels. This highlights the importance of integrated ETEA approaches and tools to support informed decision-making to promote sustainable biorefineries.

Firstly, the purple-to-blue cluster (years 2016–2017) entails words such as "xylitol", "environmental impact", "greenhouse gas emissions", and "lignocellulosic biomass"—keywords concerning research on bioproducts' environmental impact and particularly climate-change-related impacts (greenhouse gas emissions).

Secondly, the blue-to-green cluster corresponds to the 2017–2019 gap. This cluster is related to the environmental and economic findings of biorefining, which is represented by keywords such as "biorefinery", "bioethanol", "life cycle assessment and "techno-economic assessment".

Finally, the green and green-to-yellow cluster (2019 onwards) contains keywords such as "sustainability", "circular economy", and "bioeconomy" (aligned to recent plans and goals) as well as "process simulation", and "optimization" related to tools. Moreover, "anaerobic digestion" also appears in this yellow cluster due to the growing interest in this conversion route. All these keywords demonstrate the increased attention in designing sustainable biorefineries and highlighting their role in meeting circular economy and sustainability goals.

4.2. Evolution of articles per type of biomass

Fig. 4 shows the evolution of the number of publications on ETEA applied to biorefineries by the type of biomass. Overall, over the last decade (2012–2022), almost two-thirds of the 102 published articles on the topic focused on 2G biomass (see the pie chart in Fig. 4), followed by 3G (16%) and 1G (12%). Moreover, 6% of the articles consider 1G and 2G biomass feedstock in the same biorefining process or for comparison purposes. Only one article considers 4G genetically modified algae feedstock.[54] The evolution of the number of publications shows increasing interest in applying ETEA approaches to biorefinery systems.[54–56]

Publications utilizing 2G biomass largely dominate the research topic. On average, we found seven articles in the first three years (2012–2014), while this figure increased to 49 articles (48% of the total) published in the last three years. In the 2012–2013 interval, only 2G biomass studies relied on agricultural feedstock derived from lignocellulosic biomass[55,56] and sewage sludge.[57] In 2014, 3G biorefineries emerged, showing increasing interest in algae-based biorefineries afterward. Comparative studies between 1G and 2G biomass also were conducted in 2014 and 2015, primarily between corn and another agricultural feedstock.[58,59]

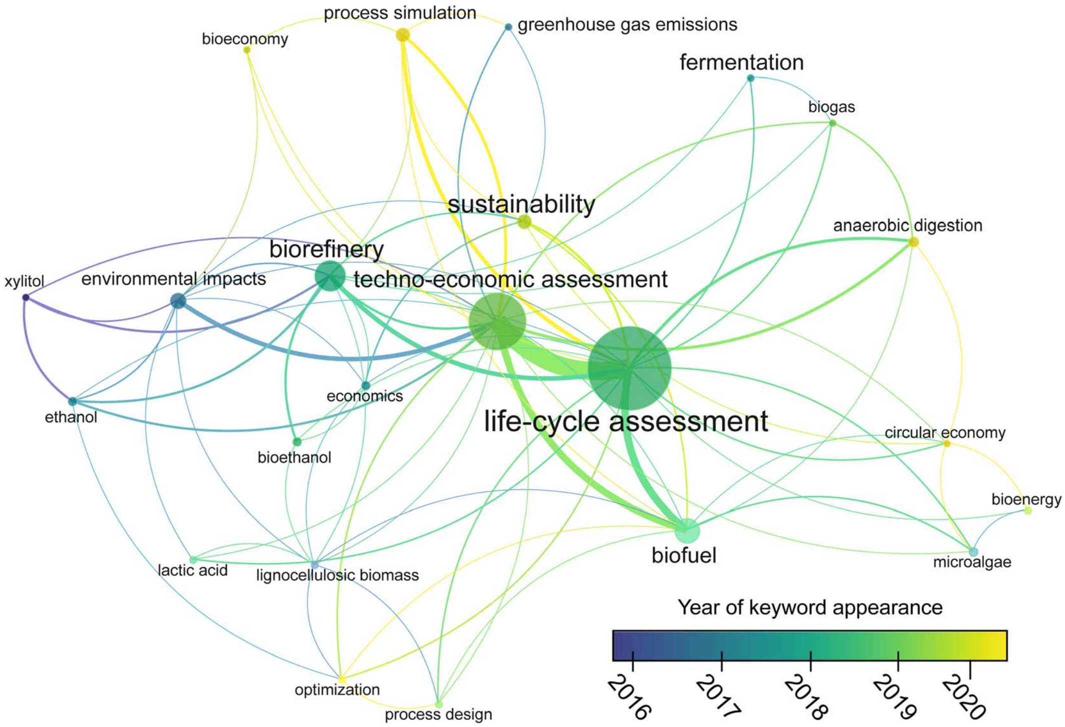

Fig. 3 Keyword mapping of the selected articles in the field of ETEA of biorefineries from 2012 to 2022. Each node corresponds to a keyword, and the links represent the co-occurrence of the keywords. The size of nodes is proportional to the number of appearances of the keyword. According to the scale, the node colour corresponds to the year of appearance (purple keywords appearing earlier and yellow latest). The figure was created using VOSviewer.[157]

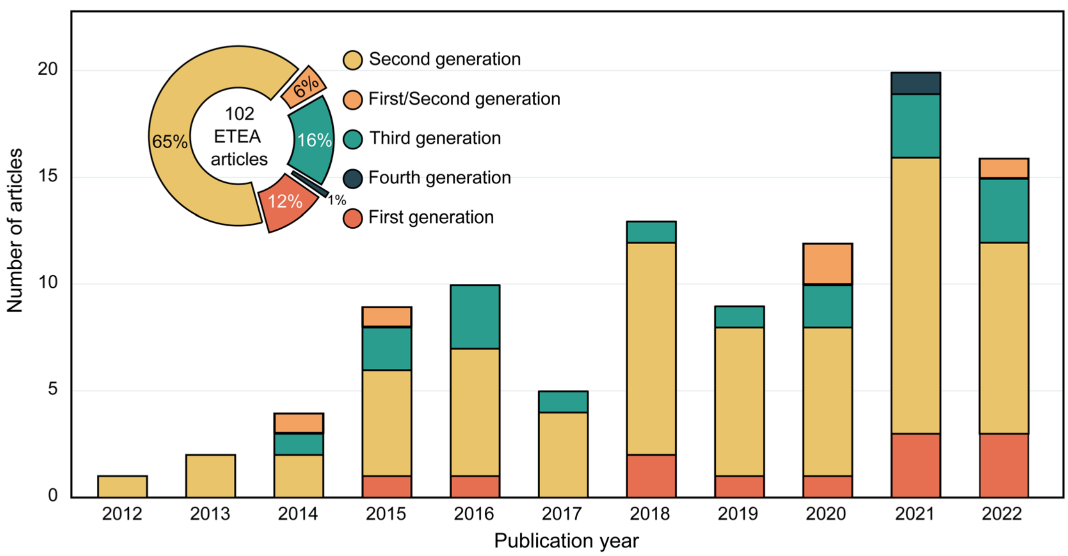

Fig. 4 Number of published articles that apply integrated environmental and techno-economic assessments to biorefinery schemes over time and per type of biomass feedstock.

These studies highlighted the need to shift 2G feedstock to reduce socioeconomic concerns and avoid direct competition with food crops and environmental impacts. Since 2018, 3G biorefinery studies have increased due to algae offering a diversity of valuable compounds and avoiding using additional land.[60]

4.3. Publications by the country of the case study

ETEA studies on biorefineries depend on resource availability, varying regionally and contextually with biomass resources. Fig. 5 shows the region of the technology implementation in the articles, which mainly depends on the availability of the

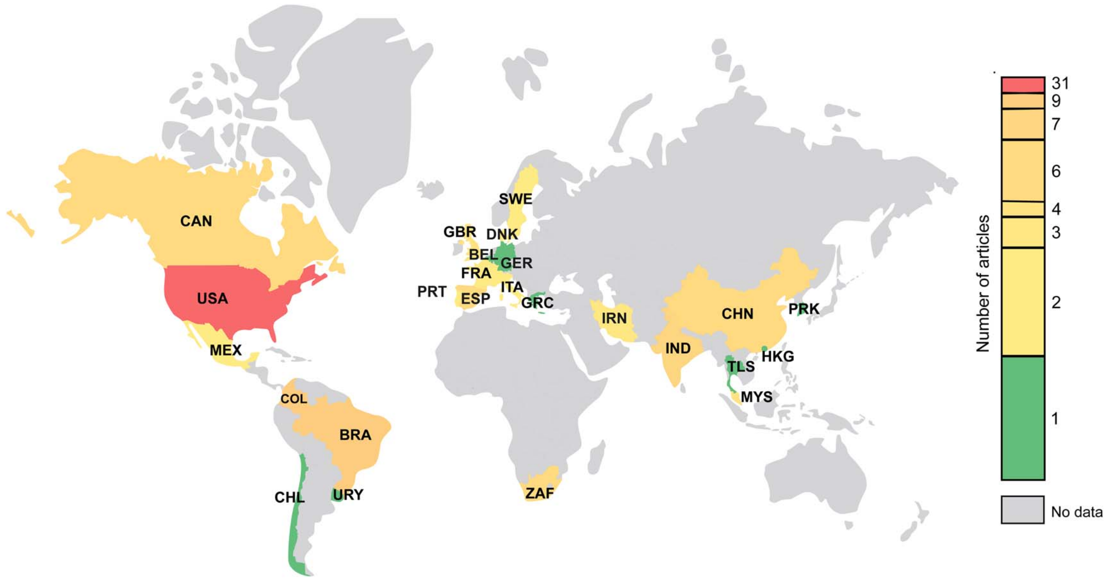

Fig. 5 Distribution of articles concerning the country of the biorefining case study. Countries with publications are labelled according to the ISO3 code abbreviation. The articles that used two locations for the case study were counted twice. The length of each colorbar segment is proportional to the number of countries with a particular number of publications.

biomass feedstock employed. Some projects had articles developed in two countries or used data from two countries to compare the findings (counted twice on the map in Fig. 5). One-third of the studies found are conducted in the United States of America (31 out of the 102 total), followed by Brazil/Colombia (9) and India (7). This might be because biorefining is actively promoted as a critical component of bioeconomic and sustainability strategies in those regions. For example, the United States of America[61] is the top producer of bioethanol (the most widely used biofuel for transportation), followed by Brazil,[62] but it mainly relies on energy crops such as corn and sugar cane, which threatens biodiversity and food security.

Seven research studies were reported in Canada (*e.g.*, ref. 63 and 64). The Canadian articles primarily used woody-based biorefineries motivated by abundant lignocellulosic biomass from forests and the associated industry.[65]

Six articles were also found in Spain, South Africa, and China. Only articles from South Africa were found in the African continent despite accounting for more than 15% of the total population, evidencing disparities in research output and opportunities within the continent and other countries. The South African research focused only on 2G biorefineries, mainly based on agricultural residues[66,67] and organic food waste.[68] South Africa has the largest sugar industry on the continent, and biofuel regulations and policies exist to mobilize domestic biomass endowments and promote economic growth and regional development.[69] This context has stimulated research on bioethanol production using sugarcane bagasse.[66,70] Moreover, South Africa faces problems with organic waste disposal due to the reduced capacity of municipal landfills, which also favoured studies focusing on other organic food waste.[71]

Latin America and the Caribbean are recognized for their vast natural resources, including land, water, and biodiversity, all of which have contributed to and benefited from the evolving bioeconomy.[72] Latin America has competitive advantages for implementing biorefineries based on energy crops, including available fertile land, a suitable climate, and low labour costs. Moreover, many Latin American countries have implemented regulatory frameworks and programs to promote biofuel production.[73] Notably, nine articles correspond to case studies in Colombia (second in the ranking after the USA). Similarly, as in Brazil,[74,75] most studies focused on bioethanol production from 1G crops such as sugarcane. However, Colombia has also investigated 2G biomass resources (*e.g.*, fruit wastes) to produce biofuels[76] and other biochemical products.[49,58,77] In other countries, such as Chile and Uruguay, the number of studies is quite limited because they are still in the early stages of biofuel development.[50,78]

For European countries, a great variety of integrated ETEA studies showed the shift from 1G articles to higher generations to implement modern and sustainable biorefineries. Spain,[79] Denmark,[80] and Portugal[81] show the highest number of publications in the EU (six, three, and two, respectively). Most articles rely on waste management processes such as anaerobic digestion to produce biogas or biomethane and other lignocellulosic feedstock materials.[82] Meanwhile some Spanish articles focus on 2G olive-based biomass to produce sugar value-added products.[83,84] Other Spanish articles rely on 3G microalgae for various bio-based products such as extracted oils and energy.[30]

Four articles were found in the United Kingdom, two entailing 2G biorefineries relying on sewage sludge and sugarcane bagasse[35,57] and two 3G biomass research.[89,90]

Seventeen articles were found in Asian countries, most related to 2G biorefineries. Several countries from Asia have embarked on this path of biorefinery development and growth. India had the highest number of research articles in Asia (seven), including those with comparison results with other countries such as China.[86,91] India relies heavily on imported oil, and the government actively promotes alternative bioenergy and research in the field.[26] Most Indian articles focused on bioethanol production from agro-residues and other wastes;[82] leaving aside dedicated crops due to competition with food resources and the need to sustain the rising population in the country.[85] Waste management by combustion is also a strategic topic of interest in India as it helps reduce waste collection and treatment costs, becoming an appealing business.[85] In China, six articles were found. China deals with critical challenges such as energy depletion and environmental deterioration because China is the world's largest energy consumer and relies heavily on coal, contributing to pollution and climate change.[86] To address these issues, policies and incentives have recently emerged to transition to cleaner energy resources and promote biorefineries and biofuel production.[87] Hence, the Chinese government is gradually phasing out financial subsidies to transition from 1G feedstock to advanced biofuels (2G and 3G biomass). This probably motivated all the articles found to rely on 2G biomass (agricultural residues and other wastes). The most commonly used technology is anaerobic digestion as a conversion process to investigate biogas production to satisfy the increased energy demand and reduce waste.[69] The remaining Asian articles are from Thailand,[32] Malaysia,[88] and Iran,[89] countries that currently promote the usage of edible vegetable oils (rapeseed and coconut, among others) in biodiesel plants to secure electricity in poor rural areas.

Notably, we found six articles that compare results from two countries. Two studies compared biorefineries' economic and environmental results in China and India.[82,90] Another study compares alternative lignocellulosic biofuels that can be blended with marine heavy fuel oils in Brazil and Sweden[91] and microalgae biofuel in the USA and Portugal.[92] Other studies refer to biorefineries in Belgium–India[16] and Portugal–Chile.[50]

Notwithstanding the dominance of North American studies, the number of articles based on Asian, Latin American, and European case studies increased strongly over time.

4.4. Biomass feedstock and conversion technologies

We next analyze the conversion technologies employed in the ETEA studies by the type of biomass generation (Fig. 6).

Considering the 102 articles compiled in the last decade, biochemical routes dominate over thermochemical routes (58% *vs.* 28% of the total, respectively). Moreover, many articles rely on a combination of both biochemical and thermal routes (14%).

Globally, the primary conversion technologies among all the routes were fermentation (29%) to obtain bioethanol and other value-added co-products and anaerobic digestion (12%) to obtain biogas later used for electrical or heating purposes,

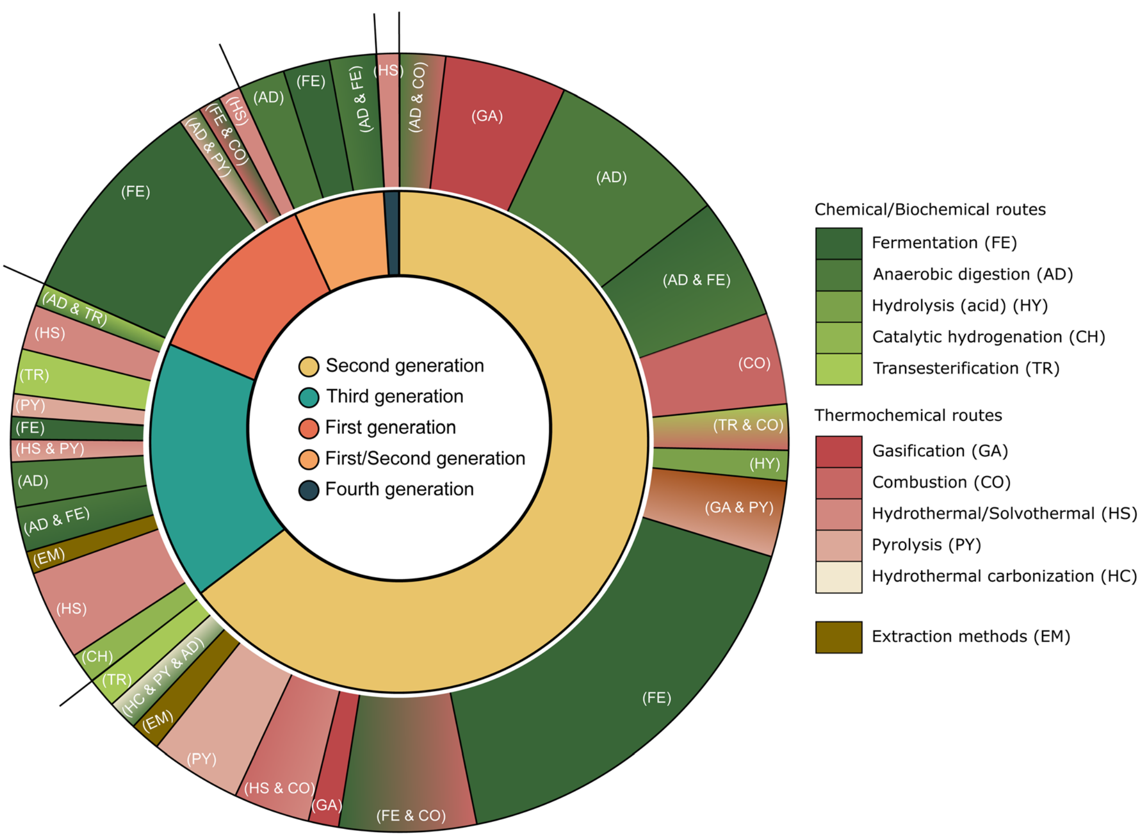

Fig. 6 Nested pie chart showing the biomass conversion routes of each biomass generation category. The inner ring corresponds to the biomass type, while the outer corresponds to the conversion routes. Chemical and biochemical are coloured with green colours while thermochemical routes with red. Portions coloured with a gradient correspond to studies combining conversion routes.

followed by pyrolysis and hydrothermal liquefaction (5% and 4%, respectively). Fermentation and anaerobic digestion were found in almost all biomass generations, while combustion and pyrolysis are more present with 2G and 3G biomass resources. The fermentation route is the dominant category in 1G and 2G biomass types (9% and 18%, respectively). Anaerobic digestion is also a focus of attention for 2G biomass (8%), together with the combination of fermentation and combustion (6%). For 3G biomass (algae), hydrothermal liquefaction emerged as the dominant route because it employs heated high-temperature water to treat the biomass, which is particularly promising for wet biomass such as algae.

Notably, some articles rely on integrating biochemical pathways or combining biochemical and thermochemical conversion technologies (14% of the total). For example, anaerobic digestion and fermentation can be integrated into a biorefinery to deliver bioenergy and biofuels derived from seaweed.[36,93] Another example is the integration of fermentation and combustion processes[94] into a biorefinery based on lignin or citrus wastes to deliver bioethanol and electricity.[95,96] Similarly, another article combines anaerobic digestion and combustion to produce biogas which is later burned to deliver bioenergy.[82] This abundance of articles combining various conversion routes to deliver multiple products supports the biorefinery concept as the cornerstone of the circular (bio) economy to maximize the value recovered from biomass and move to zero waste.

Solely one article employed 4G biomass based on a thermochemical process of hydrothermal liquefaction (HTL), converting dewatered microalgae into renewable liquid fuel (*i.e.*, bio-oil).[54] Since its primary reactant is water it is commonly used for conversion routes of 3G and 4G biomass due to its feedstock type (algae and water microorganisms).[97,98]

Biochemical conversion technologies use microorganisms and other organisms and enzymatic processes to transform biomass (*e.g.*, lignocellulosic and starchy) into biofuels and chemicals.[99] Fermentation processes[100] emerged as dominant because they are widely used commercially to produce bioethanol and other bioproducts from sucrose-rich crops like sugarcane and starch-rich crops like maize and wheat. Moreover, many articles employed anaerobic digestion based on agricultural residues or organic wastes (2G), such as sugarcane bagasse, which could be fed into a biodigester to produce biogas that could be upgraded to remove CO_2 to biomethane.[101]

Other chemical processes include acid hydrolysis, transesterification, hydrogenation, and other extraction methods. The most commonly used chemical process is transesterification, which reduces fatty acids from oils, fats, and grease biomass to alcohol and converts them into biodiesel.[102] Although transesterification can be applied to 2G[103] and 3G biomass,[33] microalgae (3G) are receiving increased attention due to their high content of free fatty acids, making them very appealing for biodiesel production.[63,98,104] Other chemical conversion routes of interest in the articles were catalytic reactions coupled with separation methods and hydrolysis/fractionation. The hydrolysis/fractionation procedure is a physicochemical treatment that allows fractionating biomass feedstock into cellulose, hemicellulose, and lignin, while the former two materials lead to sugars. These fractions can be later converted into chemicals, such as producing valuable organic compounds *via* catalytic conversion from cellulose.[105]

Regarding the thermochemical routes, direct combustion, gasification, and pyrolysis are the most widely used in the screened articles. These routes can be applied standalone, but often, they are combined with other conversion technologies (*e.g.*, fermentation and anaerobic digestion) to fully valorise the wastes generated in the downstream processes in a cascading approach. Combustion is the thermochemical reaction between biomass and oxygen in the presence of air to produce heat and electricity. In gasification, biomass is heated with a gasifier agent (such as oxygen) or in an oxygen-deficient environment (less than stoichiometric) to produce syngas, primarily composed of hydrogen and carbon monoxide.[106] Notably, only one article applied combustion or gasification to 3G biomass, most likely due to the high moisture content of algae implying low conversion efficiency. Pyrolysis is the thermal decomposition of biomass without oxygen into three products: bio-oil, pyrolytic gases, and biochar. These bioproducts from thermal routes can be directly used as combustion fuel to produce heat, electricity and bio-based products. Alternatively, they can be transformed into other valuable products,[107] providing a promising opportunity for sustainable chemical synthesis.[64,107,108] For example, biogas can be used as an intermediate to produce sustainable chemicals such as renewable methanol, liquid hydrocarbons or ammonia.

Besides these main thermochemical routes, other thermal processes employed in the articles are hydrothermal carbonization and hydrothermal processes. The hydrothermal carbonization process converts biomass into a carbon-rich and energy-dense solid (pellets), which can be used as fuel.[32] Only one comparative study applying ETEA assessed the best use of rice husk, comparing hydrothermal carbonization with pyrolysis and anaerobic digestion processes.

On the other hand, hydrothermal liquefaction is a thermochemical conversion that employs a high-temperature water reactant to produce liquid fuels (hydrocarbons) such as marine biofuel.[91] This route faces certain limitations, such as high energy demands, but ongoing research and development efforts will help to improve its energy efficiency and overall sustainability. Notably, hydrothermal reforming presents the advantage (over the other thermochemical routes) that the biomass feedstock does not have to be dried as it is processed with a high moisture content, thus reducing time and energy consumption at this early stage. Hence, although hydrothermal liquefaction is applied to all types of biomass generations (Fig. 4), many articles applied this technology for high-moisture 3G biomass, such as algae, for which this treatment is preferred over other thermal routes. For example, a hydrothermal liquefaction process could be used to convert fast-growing cultures or naturally occurring algal blooms into bio-oil and then further processed to transportation fuel.[109] Moreover, hydrothermal liquefaction is often combined with biochemical routes to pretreat biomass and make the compounds readable for the subsequent biological routes while increasing the system's performance.[110]

4.5. Bio-based products

Fig. 7 shows the targeted bio-based products across the articles reviewed, which are deeply linked to the conversion routes (Fig. 6). In total, 167 main products were extracted from the 102 articles reviewed, grouped into twelve product categories in Fig. 7. Note that some bio-based products might be end products, such as biofuels for transportation, while others, such as biogas, can be intermediate feedstock to also produce electricity or heat later. Remarkably, many of these bio-based products could replace fossil-based counterparts in providing the same service, thus reducing the dependence on fossil fuels. The top categories are other products, other biofuels, bioethanol, and biogas, followed by biomethane and biodiesel. The "Other products" category contains various biochemical products or commodity chemicals like furfural, levulinic acid, carboxylic acids, alcohols, and phenolics, which are considered promising valuable platform chemicals and renewable compounds derived from biomass resources.[45,88,111]

Phenolic compounds are particularly interesting as they are plant-based metabolites receiving great attention from several industries due to their bioactive properties. However, depending on the biomass precursor and the process conditions, the diversity of phenolics and their abundance considerably

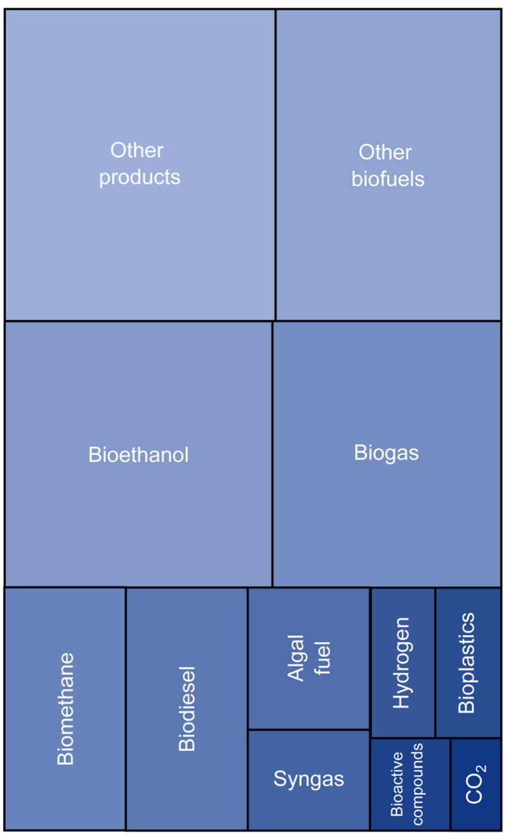

Fig. 7 Tree-map showing the main bio-based products targeted in the compiled scientific articles. Each bio-based product is represented by a rectangle sized proportionally to the times of the appearance of the product. Note that many articles deal with multi-product biorefineries delivering various bio-based products.

influence the outcome of the reaction and can also use the extraction method using low-severity conditions and before pretreatment.[112] The second category is "Other biofuels". This category includes biofuels for transportation other than bioethanol and biodiesel (the latter obtained *via* transesterification), for example, bio gasoline, renewable diesel (produced using hydrotreatment), isobutanol, kerosene, biocompressed natural gas, and other biomass-based marine and jet fuels. These biofuels are usually produced *via* biological or thermochemical reactions from 2G biomass[56] and 3G feedstock.[24] This great attention is motivated by current policies and carbon neutrality goals promoting next-generation fuels to decarbonize the transportation sector beyond the road (shipping and aviation).

Next, we found bioethanol, the main targeted product in many reviewed articles (29 articles), produced from fermentation routes. Bioethanol is a fuel produced worldwide from biomass feedstock, most commonly wheat,[25] sugar beet,[45] corn,[11] wood[113] and algae. Bioethanol is mainly used as fuel to power vehicles either purely or blended with conventional fossil gasoline. Other uses include producing heat and energy, nutrients, or as an intermediate feedstock in the chemical industry further transformed into other fine and specialty chemicals. Today, many countries have policy mandates to blend bioethanol with gasoline.

Current research is shifting towards the production of bioethanol from 1G to 2G lignocellulosic biomass, addressing the ethical concerns linked to the food *vs.* fuel debate. Producing bioethanol from lignocellulosic biomass requires a pretreatment step followed by enzymatic hydrolysis to separate the fermentable sugars from which bioethanol is biologically produced.[114]

Biogas is the second product attracting much attention (targeted product in 25 out of the 102 articles). After the war in Ukraine, biogas is being rediscovered as a strategic renewable product to reduce energy dependency on natural gas. Biogas is derived from the anaerobic decomposition of organic matter, mainly into methane, carbon dioxide, and nutrient-rich sludge, and involves a stepwise series of reactions mediated by anaerobic microorganisms.[115] The biomass feedstock could be any generation of biomass. Biogas is mainly produced from dedicated crops, agriculture or forestry residues (bagasse and crop peelings), and animal manure. Besides these 2G biomass materials, modern biorefineries have been increasing the usage of aquatic feedstock.[116,117] Biogas can be directly burned to produce electricity and heat. It can also be upgraded to biomethane (the main product is 12 articles, Fig. 7), which can be supplied to the natural gas network to cope with the unprecedented increase in natural gas prices. Furthermore, biogas is an environmentally friendly, cost-effective, and viable alternative that has proven sustainable in rural areas worldwide, notably in developing countries such as Thailand[32] or South Africa.[118]

Biodiesel—produced by transesterifying oils and fats from living organisms and oleaginous microorganisms—has also received considerable attention in the literature applying ETEA to biorefinery schemes (the main product in 12 out of the 102 articles). The primary use of biodiesel is for vehicle transportation blended with petroleum-based diesel.[55,114] The most widely used feedstock for biodiesel production is 1G feedstock (edible oil crops), but recent studies explored the use of waste cooking oils[100] and microalgae.

Finally, other targeted bio-based products are algal fuels (*e.g.*, biodiesel from algae), hydrogen, bioplastics, and captured carbon dioxide. These algae biofuels reduce the dependency on using food crops while producing environmentally and economically sustainable biofuels. This can be achieved by using flue gas in microalgae culture instead of pure CO_2 to improve their productivity.[97] Renewable hydrogen has gained significant interest in recent years as a sustainable energy carrier with multiple uses that can play a role in decarbonizing various industries and sectors. Most focus today is on electrolytic hydrogen, but hydrogen here is produced *via* thermochemical routes (*e.g.*, gasification) from 1G and 2G biomass feedstock.[119] Biological and thermochemical pathways can improve air quality and energy efficiency by producing hydrogen.[95,119]

Moreover, two articles applied integrated ETEA to produce bioplastics from 3G biorefineries.[33,120] Producing bioplastics is gaining tremendous attention because they can replace fossil-based plastics showing environmental and socioeconomic concerns. Packaging, textile, and biotechnological industries are among the bioplastic applications. Another important alternative is that bioplastics can be used as a feasible technique for treating municipal waste from landfills.[71]

4.6. Tools and methods for integrated ETEA of biorefineries

There is no standard approach and consensus on the tools to perform integrated ETEA in biorefineries.[122] Table 1 provides an overview of the methodologies, tools, assumptions, and indicators employed in the reviewed articles published in the last three years (48 articles from 2019–2022).

Regarding the scope of ETEA studies, most studies are cradle-to-gate (or well-to-tank with biofuels for transportation), *i.e.*, from the biomass cultivation and procurement to the point the bio-based products leave the biorefinery plant gates. This LCA approach provides a consistent baseline for comparison or replacement studies to compare the impacts of different products or production processes.[121] However, expanding the boundaries to cradle-to-grave or well-to-wheel (including the entire life cycle with the usage and disposal phases) provides a comprehensive picture of the impacts of bio-based products and the true implications for the Earth. For example, during the combustion of biofuels, biogenic CO_2 is released back into the atmosphere together with NO_x emissions, particulate matter, and volatile organic compounds, which predominantly occur during the biofuel combustion in the life cycle.[91] Omitting this usage phase of biofuel will underestimate the impacts on acidification, ozone depletion, and climate change, among others. Other partial scopes for the LCA studies are gate-to-cradle and gate-to-gate. The former starts from recycled materials at the end of the final phase.[112] The latter focused on the production process at the plant, from the entry of raw materials (gate) to the delivery of the finished products (gate).[122]

There are various software packages and databases available for conducting LCAs. These tools are handy in completing the data collection, building the LCA model, and expediting the analysis processes. SimaPro is the most popular software (employed in 21 of the 48 articles in Table 1), followed by Open LCA and GaBi (employed in 11 and three articles, respectively). Nevertheless, several articles performed the calculations manually and relied on literature data to complete the inventory. Ecoinvent is the most commonly used life cycle inventory database due to its completeness, accuracy, and consistency. ReCiPe, CML, and Cumulative Energy Demand (CED) are the most common methods concerning the life cycle environmental impact assessment methods. The ReCiPe method contains 18 midpoint categories, while CML contains characterization factors for twelve, and both include endpoint categories of damages to human health, ecosystems, and resources. CED is a suitable method to evaluate the overall energy consumption, which allows for assessing the shares of non-renewable and renewable sources of systems during the life cycle. Regarding the impact categories analyzed in the studies, climate change impacts assessing greenhouse gases is considered in all studies as it is perceived as the primary environmental concern today. Other environmental categories are acidification, eutrophication, ozone depletion, water use, and human toxicity, all environmental issues often associated with using biomass as a raw material.

To carry out the techno-economic assessment, process system engineering tools such as modelling and simulation are broadly used to model and optimize the design of the biorefinery processes. The process design is a crucial step that may be facilitated by software tools (simulation software) and includes selecting and configuring equipment and setting the operating conditions to ensure production goals. Aspen Plus is the most commonly employed process simulation software for modelling all unit operations in biorefineries (40% of studies employed Aspen). The simulation models evaluating the technical feasibility at scale are the basis for gathering all the inputs and outputs from the biorefinery systems that are subsequently employed to conduct economic and environmental assessments.[15] The Aspen Process Economic Analyzer (APEA) tool available in Aspen is widely used to estimate the capital and operating costs of the simulated process, providing a breakdown per unit operations and equipment. Many studies relied on literature data and manual calculations (almost 50% of the studies in Table 1). In particular, the database from the National Renewable Energy Laboratory (NREL)[8,38] appears valuable for research on sustainable biorefineries, as it provides information on biomass feedstock, conversion processes, and product yields and tools for simulation and economic and environmental analyses. Concerning the indicators to evaluate economic viability, Capital and Operating costs (CAPEX and OPEX), internal rate of return (IRR), net present value (NPV), discounted payback period (DPP) and return on investment (ROI) are the most commonly used parameters.

Several tools, methods, and indicators are available for conducting ETEA studies of biorefineries. The choice of the tool or method will ultimately depend on the goal and specific needs

Table 1 Tools, methods, and indicators for conducting an integrated environmental and techno-economic assessment of biorefineries

Feedstock/product	Scope	Process design and techno-economic assessment tools[a]	Economic indicators[b]	Life cycle assessment tools[a]	LCA indicators[c]	Reference
Organic waste and crops/biofuel and biogas	Cradle-to-grave	Manual/literature data	CAPEX and OPEX and a DCFR	Manual/literature data/LCI	GWP and FER	123
Lignocellulosic wastes (corn stover and wheat straw)/biochemical products	Cradle-to-gate	Aspen process economic analyzer	CAPEX and OPEX	SimaPro/Ecoinvent/ReCiPe	GWP, ODP, MEP, PMFP, TAP, WC, LOP and FFP	50
Sugarcane/bioethanol	Cradle-to-gate	SuperPro	CAPEX, OPEX, and O&M	Manual//Ecoinvent/CML	GWP, HTP, POCP, AD, AP, EP, ODP, FAETP, SAETP and TEPT	7
Algae/biofuel	Well-to-wheel	Manual/literature data from the NREL database	CAPEX and OPEX and a DCFR	Manual/literature data/LCI	GWP, POCP, PMFP, TAP, FEP, MEP and FD	124
Napier grass/electricity and heat	Cradle to grave	Manual/literature from the NREL database	CAPEX, OPEX, IRR and a DCFR	SimaPro/GREET/TRACI	GWP, TAP, HH CP, HH nCP, EP, ODP, and SP	8
Lignocellulosic agricultural wastes (corn stover, rye, and wheat)/biogas	Cradle-to-gate	Manual/literature from the NREL database	CAPEX and OPEX	SimaPro/NA/NA	GHG	125
Orange peels/biochemical products and steam	Cradle-to-gate	SuperPro	CAPEX and OPEX	CML/CML/CML	GWP, HTP, POCP, AP, EP, and FAETP	126
Agroforestry residues/marine biofuels	Cradle-to-grave	Manual/literature data from TRACI	CAPEX, OPEX and MFSP	CML/Ecoinvent/CML	GWP	91
Soybean/biochemical products	Cradle to gate	SuperPro	CAPEX, OPEX, TCI and MFSP	Gabi/Ecoinvent/Eco99	AP, GWP, ODP and HH	103
Lignocellulosic biomass feedstock/biochemical products	Cradle-to-gate	Aspen Plus	Exergoeconomic indicators	Manual/literature data/Eco99	Exergy-based indicators	89
Lignocellulosic wastes/bioethanol	Cradle-to-gate	Manual/literature data	CAPEX, OPEX, NPV and ROI	Open LCA/literature data/ReCiPe	GWP, PMFP, TAP, MEP, FAETP, TETP, FEP and FD	127
Sorghum/renewable diesel	Cradle-to-gate	Aspen Plus	CAPEX and OPEX	SimaPro/GREET/literature data	GHG	78
Sugarcane and lignocellulosic waste (bagasse and trash)/bioethanol	Cradle-to-gate	Virtual sugarcane biorefinery simulation	NPV, IRR and MSP	SimaPro/EMSO/CML	HTP by ingestion, HTP by exposure, ATP, TAP, GWP, ODP, SP, and AP	128
Farm wastes/biogas and bioplastics	Cradle-to-grave	SuperPro	CAPEX and OPEX	Open LCA/Ecoinvent/ReCiPe	GHG	112
Sugarcane bagasse/biochemical products	Cradle-to-gate	Aspen process economic analyzer	CAPEX, OPEX, NPV and DCFR	Open LCA/Ecoinvent/ReCiPe	GWP, FEP, PMFP and POCP	35
Algae/biofuel and bioplastics	Cradle-to-gate	Manual/literature data from CEPSI	NPV, DCFR, IRR and MFSP	Manual/literature data/Ecoinvent and GREET	GHG	33
Empty fruit bunch/biochemical products	Cradle-to-gate	Aspen process economic analyzer	CAPEX and OPEX	Manual/literature data/HIRA	GWP, FEDI and TDI	88
Algae/biofuel	Well-to-wheel	Manual/literature	DCFR, IRR and MSP	Open LCA/Ecoinvent & GREET/NREL	GWP	129
Waste oils/biofuels	Well-to-tank	Aspen Plus	DPP, NPV and IRR	Manual/literature data/Ecoinvent/Eco99	GHG	130
Olive pomace and grape marc/biochar and bio-oil	Gate-to-cradle	Aspen Plus	NPV, CAPEX/OPEX	SimaPro/Ecoinvent/ReCiPe	GWP, OD, TA, FE, ME, HT, POF, PMF, FD, HH, EQ and RA.	81
Duckweed/bioethanol	Cradle-to-gate	Manual/literature data from NREL	CAPEX, OPEX and DCFR	Open LCA/LCI/ReCiPe	GWP, EP FEP; WDP and HH	131

Table 1 (*Contd.*)

Feedstock/product	Scope	Process design and techno-economic assessment tools[a]	Economic indicators[b]	Life cycle assessment tools[a]	LCA indicators[c]	Reference
Corn/bioethanol	Cradle-to-gate	SuperPro	CAPEX, OPEX and DCFR	Open LCA/EcoInvent/ReCiPe	GWP, LOP, FRS, MEP/FEP, TAP and WDP	11
Sugar beet/biopolymers	Cradle-to-gate	Manual/literature data	DCF, MSP, DPP and OPC	GaBi/Agrifootprint/CML and ReCiPe	GWP, FETP, FEP, HTP, METP, MEP, ODP, PMFP, POFE, TAP, and TETP	45
Food waste/biochemical products	Gate-to-cradle	SuperPro	CAPEX and OPEX	SimaPro/EcoInvent/ReCiPe and CED	GWP also WDP, FRS, LU, HTPc, HTP, FETP, FEP, METP, MEP, TAP, PMFP, IRP and SODP	111
Wood/natural gas	Cradle-to-grave	Manual/literature data from CEPCI	CAPEX/OPEX costs, DCFR and MSP	SimaPro/literature data/TRACI	GWP	132
Algae/biodiesel	Cradle-to-gate	Manual/literature data	TCI, OPEX and MFSP	GaBi/Ecoinvent/ReCiPe	GWP, FE, HTC, IR, LU, ME, POFE, POFH and TA. FD, FC, FET HTNC and MET, OD, PMF, POFE TET, PED and CC	98
Lignocellulosic feedstock/biochemical products	Cradle-to-gate	BioSTEAM's database	CAPEX, OPEX, DCFR and MSP	Manual/literature data and BioSTEAM's	CC and FFD	133
Mango waste/biochemical products and bioethanol	Cradle-to-gate	Aspen Plus	NPV, IRR and MSP	SimaPro/EcoInvent/CML and Eco99	GWP, FRS and WDP	68
Corncob/bioethanol	Gate-to-gate	Aspen process economic analyzer	CAPEX and OPEX	SimaPro/NREL/CML	CC and FFD	121
Cyanobacteria/biofuels and biochemical products	Well-to-wheel	Manual/literature data	CAPEX, OPEX, DCFR and MFSP	OpenLCA/Ecoinvent/TRACI	GWP	54
Seaweeds/bioethanol and biogas	Cradle-to-grave	Aspen Plus and NREL	CAPEX, OPEX and TCI	SimaPro/CML/CML	ADP, FFDP, GWP, ODP, HTP, FETPl, METP, TETP, PMFP and AP	36
Sugarcane bagasse/biochemical products	Cradle-to-gate	Manual/literature data	CAPEX and OPEX	Open LCA/EcoInvent/IMPACT2002	GWP, ME, HTPc, HTP, RI, IR, ODP, FETP/METP, LOP, and AE	134
Lignocellulosic feedstock/bioethanol, hydrogen and biochemical products	Farm-to-gate	Aspen Plus	CAPEX, OPEX and MSP	SimaPro/Datasmart/CED	GWP	135
Lignocellulosic feedstock/biofuels and hydrogen	Cradle-to-gate	Aspen Plus	CAPEX, OPEX and NPV	Literature data/Ecoinvent/ReCiPe and CED	GWP, LOP	22
Wine pomace/biochemical products	Gate-to-gate	SuperPro	CAPEX and OPEX	Open LCA/literature data/Ecoinvent/ReCiPe	GWP, PMFP, HH, FRS, FEP, FETP, HTPc/HTP, IR, LU, WDP and TAP/TETP	136
Lignocellulosic feedstock/biochemical product	Cradle-to-gate	Aspen process economic analyzer	CAPEX, OPEX and MSP	SimaPro/Ecoinvent/ReCiPe	GWP and FD	105
Olive pruning/bioethanol and biochemical products	Cradle-to-gate	Aspen Plus	CAPEX, OPEX, NPV and MPP	SimaPro/Ecoinvent/ReCiPe	GWP, HTPc, FRS and WC	79
Guayule bagasse/biofuels	Cradle-to-grave	Aspen Plus	CAPEX, OPEX, MSP and DCFR	Open LCA/GREET/TRACI	AP, TETP, TAP, GWP, HTPc/HTP, ODP, AD	137
Citrus fruit peel/biodiesel	Well-to-wheel	Manual/literature data	CAPEX, OPEX, IRR, and NPV.	SimaPro/Ecoinvent/ReCiPe	GW, TAP, FPMF, and FRS	85
Lignocellulosic feedstock/bioethanol and biogas	Cradle-to-gate	Manual/literature data	CAPEX, OPEX, IRR, and NPV	SimaPro/Ecoinvent/ReCiPe	GWP, ODP, IRP, PMFP, HOFP, EOFP), TAP, FEP, MEP, TETP, FETP, METP, HTPc, HTPnc, LOP, SOP, FFP, and WC	138
Algae/biofuel and CO_2	Cradle-to-grave	Manual/literature data	CAPEX, OPEX and ROI	Open LCA/Ecoinvent/CED	GWP	139

Table 1 (*Contd.*)

Feedstock/product	Scope	Process design and techno-economic assessment tools[a]	Economic indicators[b]	Life cycle assessment tools[a]	LCA indicators[c]	Reference
Rice and wheat/biochemical products	Cradle-to-gate	Manual/literature data	CAPEX, OPEX and MSP	SimaPro/Ecoinvent/IPCC2021	GWP	140
Algae/biofuel and bioplastics	Cradle-to-gate	Manual/literature data	CAPEX, OPEX and MSP	Open LCA/GREET database	GHG	120
Sugar cane bagasse/bioethanol and biochemical products	Cradle-to-gate	Manual/literature data	CAPEX, OPEX and MSP	SimaPro/Ecoinvent/CML	GWP, ADP and ODP	141
Lignocellulosic feedstock/bioethanol and biochemical products	Cradle-to-gate	Manual/literature data	CAPEX, OPEX, IRR, TCI and MSP	Literature data/Ecoinvent/Eco99 and CED	GWP, ADP and ODP	142
Silver grass/bioplastics	Cradle-to-gate	Manual/literature data	CAPEX, OPEX costs, DCFR and NPV	SimaPro/NA/NA	GWP, PMFP and ODP	143
Sugarcane/biochemical products	Cradle-to-gate	Virtual sugarcane biorefinery simulation	CAPEX, OPEX, NPV and MSP	SimaPro/Ecoinvent/ReCiPe	GWP, ODP, HTPc, AP, FEP, LOP, and FRS	144
Farm waste/biogas, biofuel and biochemical products	Cradle-to-gate	Aspen process economic analyzer	CAPEX, OPEX, DCFR and MSP	SimaPro/USLCI/TRACI	GHG and GWP	145

[a] Techno-economic assessment tools: National Renewable Energy Laboratory (NREL); the greenhouse gases, regulated emissions, and energy use in technologies model (GREET); tool for reduction and assessment of chemicals and other environmental (TRACI), chemical engineering plant cost index (CEPCI), hazard identification and ranking assessment (HIRA), and U.S. Life Cycle Inventory Database (USLCI). [b] Economic indicators: capital expenditure (CAPEX); operational expenditure (OPEX); minimum selling product (MSP); minimum selling fuel price (MSFP); discounted cash flow of return (DCFR); internal rate of return (IRR); net present value (NPV); total capital investment (TCI); operating manufacturing costs (O&M); tool of reduction and assessment of chemicals (TRACI); return of investment (ROI); discounted payback period (DPP); optimum plant capacity (OPC); maximum purchasing price(MPP); minimum attractiveness rate (MAR). [c] Life cycle assessment indicators: GHG: greenhouse emissions, GWP: global warming potential, ODP: ozone depletion potential, AD: abiotic resource potential, AP: acidification potential, IRP: ionizing radiation potential, PMFP: particulate matter formation potential, HOFP: ozone formation potential for humans; EOFP: ozone formation potential for ecosystems; TAP: terrestrial acidification potential, FEP: freshwater eutrophication potential, MEP: marine eutrophication potential, TETP: terrestrial ecotoxicity potential, FETP: freshwater ecotoxicity potential, SAETP: seawater aquatic ecotoxicity potential, METP: marine ecotoxicity potential, HTTP: human toxicity potential; HTPc: human toxicity potential for cancer, HTPnc: human toxicity potential for non-cancer, LOP: land occupation potential, SOP: surplus ore potential, FFP: fossil fuel potential, WC: water consumption, CC: potential climate change, FER: fossil energy ratio, POCP: photochemical ozone creation potential, HH: damage to human health, EQ: damage to ecosystem, RA: damage to resource availability, FET: freshwater consumption, PED: primary energy demand, LU: land use, FRS: fossil resource scarcity, SODP: stratospheric ozone depletion, AE: aquatic eutrophication, RI: respiratory inorganics, HTP: human toxicity potential, ME: mineral extraction, HH CP: human health carcinogenic potential, HH nCP: human health non-carcinogenic potential, SP: smog formation potential, FEDI: fire explosion damage index, and TDI: toxicity damage index.

of the assessment, the stage of development, and the desired level of detail.

5. Strengths-weaknesses-opportunities-threats analysis and research directions

Based on the comprehensive review of the articles applying ETEA to biorefinery schemes, we next analyse the main strengths, weaknesses, opportunities, and threats (SWOT analysis). Table 2 summarizes the key findings from the SWOT analysis, which might be helpful for practitioners, decision-makers, and policymakers in designing and deploying sustainable biorefineries.

The integrated ETEA framework is a potent tool to ensure biorefineries' sustainability and guarantee that their deployment will contribute to the circular economy and sustainability goals. The ETEA allows for assessing and improving emerging technologies, providing insight into the technical feasibility, economic viability, and environmental implications of their potential deployment at scale. The integrated framework can be applied before and after the project completion, but it helps identify opportunities for improving both economic and environmental performance. The ETEA approach can be regarded as a systematic multi-decision approach as it integrates various economic and environmental indicators showing trade-offs.[146] It can be combined with multicriteria evaluation analysis (MCA) or multiobjective optimization (MOO) approaches that allow for making the best decisions for improved performance.[147]

Hence, the ETEA framework is handy for many practitioners, from scientists researching biorefining to technology developers, investors, and policymakers promoting the bioeconomy strategy.

Despite the strengths and valuable information, the ETEA approach also has weaknesses. For the TEA of biorefineries, process modeling and simulation tools are typically employed, from which data are gathered for the subsequent LCA study.

A large amount of data is required to conduct both the techno-economic and environmental assessments, which is often difficult to obtain. One problem the practitioner may face is the limited availability of reliable data due to the early stage of the technologies, which requires using proxy data. For the LCA data gaps, streamlined LCA methods and artificial intelligence techniques can generate proxy data for missing and unavailable information.[148,149] Hence, the assumptions made during the modeling phase and the practitioners' and local stakeholders' preferences will substantially affect all results. Nonetheless, researchers can show the study limitations that help improve ETEA in future investigations.

Additionally, the ETEA calculations are affected by several sources of uncertainty. Sensitivity analysis may help to identify the most critical parameters and how they affect the results. For example, cost parameters, raw materials, and utility prices are volatile and depend on market forces. The costs also vary greatly spatially, which is often not captured.

Table 2 Strengths–weaknesses–opportunities–threats (SWOT) analysis of the integrated environmental and techno-economic assessment (ETEA) framework applied to biorefineries

Strengths	Weakness
• Great potential ETEA applied to biorefineries to contribute to the circular economy and sustainability goals	• Complexity of the ETEA calculations
• ETEA allows for assessing emerging technologies	• Specialized practitioners
• ETEA provides insights into potential economic and environmental implications before deployment at scale	• Large uncertainties are involved both in costs and environmental impacts
• Systematic multicriteria decision tool	• Spatial variability of costs
• ETEA identifies opportunities for improving economic and environmental performance	• Lack of regionalized life cycle assessment environmental impacts
• Promote the usage and sustainability of bio-based products and market competitiveness	• Lack of absolute sustainability methods
	• Lack of social assessment guidelines and indicators
Threats	**Opportunities**
• Lack of standardization of the integrated ETEA approach	• Urgent need to reduce energy dependency
• Data limitations due to the novelty of technologies or specific to a particular region	• Valorisation and exploitation of biomass domestic endowments in a sustainable manner
• Lack of pilot studies	• Role of biorefineries coupled with carbon capture and storage to provide carbon dioxide removal and reach carbon neutrality
• Miscommunication of results to a broader public and policy	• Governments and policies support the deployment of biorefineries
• Life cycle assessment often focused on climate-change-related impacts	• ETEA helps avoid collateral environmental side effects
• Compatibility of input and output data for techno-economic analysis and life cycle assessment tools	• Increased market competitiveness
	• Growing concern about the need for bio-based products to meet sustainability goals
	• Increasing social awareness through communication with general society

Similarly, several uncertainties related to the impact pathway model and parameters affect the accuracy of the LCA data and results. There are still limitations in conducting LCA studies for specific regions due to the lack of local data. The environmental assessment usually omits spatial peculiarities of the case studies, such as the status quo of impact, environmental limitations (*e.g.*, ecological fragility to water consumption), variations in local regulations, differences in supply chain infrastructure, quantity depending on the season for some biomass, *etc.* Hence, the inventory and impact models should be regionalized, an ongoing problem receiving research attention today.

From the LCA methodological point of view, all the articles reviewed consider standard LCA approaches, which allow comparing different alternatives but fail to capture the sustainability level of the biorefining systems due to the absence of environmental thresholds. Life-cycle methods for Absolute Environmental Sustainability Assessment (AESA) have recently emerged to overcome this limitation. These AESA approaches enable comparing the impact of systems with the planet's carrying capacity (or a portion of the global threshold), thus providing insight into their environmental sustainability.[150,151]

Moreover, although the social pillar is fundamental for sustainability, there is a lack of ETEA studies applied to biorefining addressing social performance.[152] Incorporating social indicators *via* Social Life Cycle Assessment (S-LCA) will also create a framework accounting for social justice and measuring how technologies impact workers, local consumers, and societies as a whole.[153]

A threat is the lack of standardization of the integrated ETEA approach. Different methodologies, indicators, and assumptions can be used, which may lead to inconsistent results. This poses difficulties in comparing the results because the studies are often performed for different products and boundaries, making it challenging to choose the best alternatives. Consensus and harmonization need to be reached to avoid introducing biases into the results and decisions. This lack of standardization may also lead to difficulties effectively communicating the results and findings. The ETEA approach is inherently complex because it involves multiple data sources and entails a multicriteria analysis embedding economic and environmental indicators. Moreover, the interested audience is very diverse, from business investors to policymakers and governmental bodies, which requires using non-technical language and figures that are easy to understand by a broader audience beyond the scientific community.

A failed communication of environmental or economic results to the general public or policymakers will affect the decision-making process and, ultimately, the potential contribution of biorefineries to sustainable development. Additionally, by considering coordinated systems from the PSE tools (*i.e.*, the same process unit operations and energy and material balances), employing a comprehensive set of indicators to cover all stages of the product life cycle, and expressing TEA and LCA outcomes in comparable units it will provide a secure procedure.[15]

Regarding the opportunities, the geopolitical and energy crises may catalyse the deployment of both energy and product-driven biorefineries on an industrial scale to reduce dependency from abroad. Moreover, new commercialization mechanisms will emerge to scale up carbon dioxide removal technologies which are unavoidable to achieve net zero goals. This will open new opportunities and promote new business models coupling biorefineries with carbon capture and storage technologies, delivering marketable products and removing CO_2 from the atmosphere.[154,155] In the current context, the integrated ETEA framework is a strategic tool to ensure the sustainable valorisation of underutilized domestic biomass resources. ETEA help examine the feasibility and maturity of biorefining technologies shedding light on competition issues to exploit the resources available effectively. Conducting the ETEA studies of existing and novel biorefinery schemes will also help elucidate the economic viability and broad environmental implications beyond greenhouse emissions. The former is critical to identifying potential cost savings, market opportunities, new business models, and cascading multi-product approaches,[154,155] maximizing revenue towards zero wastes.[156] It may also help develop effective instruments and regulations promoting the commercialization of sustainable biorefineries.

On the other hand, understanding the broad environmental implications and hotspots when replacing fossil-based products and energy with bio-based ones is essential. Collateral damage might emerge as bio-based products help reduce climate change but often at the expense of creating new environmental problems such as eutrophication or biodiversity loss or shifting the burden to other echelons in the supply chain. Moreover, the ETEA results may be employed in optimization models to design and operate sustainable biorefining supply chains. Overall, the broad knowledge provided by ETEA studies is fundamental to guiding science-based decisions and policy-making and ultimately ensuring that biorefineries contribute to sustainability.[156]

6. Conclusions

This article comprehensively reviews the state of current research applying an integrated ETEA framework to biorefineries. Overall, our review compiled 102 articles published in the last decade and assessed them regarding the type of biomass feedstock, conversion technologies, targeted products, and tools and methods employed to perform the economic and environmental analysis. Most studies are case studies from countries with policies promoting bio-based products (one-third of the studies are conducted in the USA). This highlights the importance of developing adequate incentive structures, such as market-based or fiscal incentives, to drive research, innovation, and development. Overall lignocellulosic residues (2G biomass) received the most attention as biomass feedstock, with increasing interest in algae feedstock (3G). Regarding the conversion processes, the biochemical routes of fermentation and anaerobic digestion dominate the biorefinery pathways, followed by combustion, gasification, and pyrolysis. The targeted products are directly connected with the conversion routes, with bioethanol, biogas, biomethane, biodiesel, and hydrogen among the most studied due to their unique properties as a substitute for fossil-based fuels for shaping a sustainable economy. A broad spectrum of other co-products can be obtained in the cascading schemes. Hence, several studies highlight the importance of integrating processes to deliver multiple products (*i.e.*, multi-product biorefineries), which results in synergies and increase economic viability and resiliency, as ETEA shows. Concerning the tools and methods, from the TEA point of view, modelling and simulation tools are commonly used to integrate technical and economic data and assess the financial viability of biorefineries over their lifetime. Different software packages with advanced features and capabilities are also used for environmental assessment. Most studies focused on climate-change-related impacts and often neglected other environmental problems.

Despite the capabilities of the ETEA framework to make informed decisions that support the long-term success of sustainable biorefineries, challenges and unresolved issues remain. Our SWOT analysis identifies some of them (Section 5), for example, the large variability of methodologies making it challenging to compare results, the availability of accurate and comprehensive data, the complexity of calculations and results requiring specialized expertise to complete and interpret, the absence of absolute sustainability assessments, and, ultimately, the lack of standardization and normalization.

The integrated ETEA framework emerges as a powerful and effective tool to shed light on biorefinery systems' economic and environmental implications and identify opportunities for enhancing sustainability. The future of the ETEA framework is promising and dynamic and continues to evolve. Continued research and development efforts will improve its usefulness to drive the large-scale deployment of sustainable biorefineries.

Our review might be a valuable resource for researchers, practitioners, and policymakers as it synthesizes and integrates existing knowledge in ETEA as applied to biorefineries, providing an up-to-date understanding of the topic and offering recommendations for future research and innovation.

Author contributions

All authors conceived the research and designed the study. D. P-A and A. G-M performed the literature review, carried out the analyses, and created the illustrations. D. P-A and A. G-M wrote the paper. All authors contributed to interpreting the findings and revising the manuscript.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This publication was created as part of the grant TED2021-132614A-I00 funded by MCIN/AEI/10.13039/501100011023 by the European Union NextGenerationEU/PRTR. A. G-M thanks the Spanish Ministry of Science, Innovation, and Universities for the financial support through the "Beatriz Galindo" Program (BG20/00074). M. d. M. C. thanks the MCIN and the European Social Fund for the Ramón y Cajal grant (RYC2020-030546-I/AEI/10.13039/501100011033). Funding for open access charge: Universidad de Jaén.

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