



Life cycle sustainability assessment of bioderived advanced materials: A state-of-the-art Review

Rukayya Ibrahim Muazu^{a,*}, Polina Yaseneva^{b,*}, Nilay Shah^a, Maria-Magdalena Titirici^a

^a Department of Chemical Engineering, Imperial College London, South Kensington, London SW7 2AZ, UK

^b Department of Chemical Engineering and Biotechnology, University of Cambridge, UK

ARTICLE INFO

Keywords:

Advanced materials
Sustainability
Bioderived products
Life cycle assessment
Techno-economic
Social-LCA

ABSTRACT

Bioderived advanced materials possess unique functional properties together with a potential to improve environmental sustainability. This study conducts a critical review of literature on life cycle sustainability assessment (LCSA) of biobased higher-value products with emphasis on bioderived advanced materials including nanocelluloses (cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs)), and carbon materials (lignin carbon fibre (LCF) and hard carbons (HCs)). The environmental impact of CNCs production from Kraft and dissolving pulp via sulfuric acid hydrolysis is significantly influenced by the end-of-life (EoL) management of sulfuric acid either via recycling or neutralisation with sodium hydroxide. This highlights trade-offs and the need for more sustainable EoL options. Likewise, the production of CNFs using Kraft, dissolving and sulfite pulp via 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) oxidation followed by mechanical homogenisation or sonication indicates higher environmental impact compared with enzymatic hydrolysis. Sustainability of LCF is significantly influenced by the lignin recovery and fabrication technique, thus low-cost sustainable solvents and pathways for LCF production should be prioritised. Existing studies indicate the advantages of HCs production via hydrothermal carbonisation (HTC). However, the sustainability performance of HC is highly influenced by the carbon yield and electrochemical performance, therefore, a comprehensive optimisation of the operating variables is crucial for advancing the sustainability and development of bioderived HCs for energy applications. Significant methodological disparities were observed among the reviewed studies, leading to variations in assessment outcomes. Economic and environmental assessments are frequently presented as standalone results even for combined assessments, which further stresses the inherent heterogeneity across assessment tools.

1. Introduction

Substituting alternative materials for traditional ones across various applications represents a crucial measure in addressing the environmental challenges associated with the current conventional materials. This shift is also pivotal in achieving the net zero objectives, as the materials industry is energy intensive [1]. The emergence of advanced materials has facilitated remarkable technological progress across industries such as aerospace [2], construction [3], energy [4,5], and biomedical applications [6]. Advanced materials are designed or modified to possess specific properties that can outperform conventional materials in terms of strength, durability, electrical conductivity, thermal resistance, or optical and magnetic properties [e.g., [2,4]]. Consequently, the exploration of these materials with superior performance

and eco-friendliness has become a focal point for many researchers in the field of materials science and engineering [7]. In recent years, advanced materials belonging to the class of polymers, metals, ceramic, composites, and nanomaterials used in medical applications have developed considerably because of vast innovations in regenerative medicine and tissue engineering [8]. Biological and synthetic molecules such as polysaccharides, ceramic, polymer and metal based are being utilised for drug delivery, management of diseases, operative procedures, and post-operative applications (e.g., anti-adhesion barrier membranes) [9–12]. Achieving optimum functionality and biocompatibility with some of these materials such as metal-based (nanocrystalline metals) is a key challenge in the utilisation of advanced materials for biomedical applications. The construction and automobile and energy sectors have also witnessed significant progress in the use of new

* Corresponding authors.

E-mail addresses: r.ibrahim-muazu23@imperial.ac.uk (R.I. Muazu), py225@cam.ac.uk (P. Yaseneva), n.shah@imperial.ac.uk (N. Shah), m.titirici@imperial.ac.uk (M.-M. Titirici).

<https://doi.org/10.1016/j.jece.2024.114387>

functional materials including metal alloys, carbon materials, and nanocomposites. Nevertheless, despite the numerous functional advantages presented by new materials, some of these materials pose challenges and uncertainties in terms of resource extraction (e.g., critical resources), intensive embodied environmental burdens [13], and high processing cost. More recently, research focus has shifted towards novel bioderived advanced materials for various applications [7,14].

There has been a growing interest in the use of biomass for production of higher-value products such as advanced materials, biochemicals and bioplastics, as the bioeconomy concept offers opportunities to reduce greenhouse gas (GHG) emissions associated with the materials production. It adds to economic growth, sustainability of industries and reduces fossil fuel dependence [15,16]. Several organisations and governments have indicated commitment towards building a circular bioeconomy across various nations [16,17]. Currently, around 20,000 different types of bioderived products exist as identified by the USDA BioPreferred Program [18]. As at 2018, the global market size for the biobased sector (excluding fuel and feed) is valued at 3.43 trillion USD, which is projected to rise to 5.05 trillion USD by 2030, representing a 50 % increase [17]. According to the European Commission, biobased products and biofuels represent approximately €57 billion in annual revenue and involve 300,000 jobs [16].

Currently, the largest biomass-consuming sector is the biorefinery, with 803 operating biorefineries [19] and estimated feedstock consumption of 2.0 billion Mt in 2018 [20]. The biorefinery concept is an approach that mirrors the conventional petroleum refinery but instead of crude oil, it processes biomass to obtain a range of fuel and chemical commodities [21]. The utilisation of biomass hugely relies on its availability, suitability for specific applications and accessibility (optimal location of processing facilities). In this context, studies have proposed various design of sustainable supply chains to help address biomass feed supply issues [22,23] with lignocellulosic biomass considered as the most accessible bioresource for advanced materials.

The process of obtaining higher-value materials from lignocellulosic biomass starts with the identification and selection of suitable biomass material for the process and products to be developed. This is followed by the biomass pre-treatment stage to break down its complex structure via mechanical, chemical, or thermal methods to make the biomass more accessible for further processing [24]. The conversion routes to the various bioderived higher-value products vary with the intended application and type of biomass. For example, direct production of activated carbons from biomass would typically involve biomass preparation including sizing, pretreatment, thermal conversion (carbonisation), separation, and surface treatment depending on desired application [25,26]. While the production of biochemicals, and engineered materials such as nanocelluloses may start with biomass fractionation to break down lignocellulosic biomass into its main components (cellulose, hemicellulose, lignin, etc. using solvents in chemical treatments) [27]. In the case of biobased platform chemicals, several approaches exist. Acid hydrolysis, chemical synthesis and fermentation are commonly employed in the production of some of the most recently researched biochemicals including HMF, FDCA, succinic acid, levulinic acid, and adipic acid [28]. Electrochemical synthesis of some of these chemicals has also garnered research attention in recent years [29–32], more so, improved performance of the systems relating to process parameters, product yield, catalyst development and product purity is driving the development of various approaches to address the listed issues. Bioplastics or biobased polymers have received unprecedented global interest in the last decade, leading to several studies exploring different type of bioplastics to address the problems caused by fossil-based plastics. Common biobased polymers include polylactic acid (PLA), which may offer an alternative to polystyrene or expanded polystyrene; biobased polyethylene terephthalate (Bio-PET), which is a direct replacement for fossil-based PET; and biobased polybutylene succinate (Bio-PBS), which has similar properties to polypropylene [33, 34]. PET is one of the most used among these polymers, and it is derived

from ethylene glycol and terephthalic acid. The production of Bio-PET can proceed with the fermentation of sugarcane to produce ethylene glycol and the oxidation of p-xylene from lignocellulosic biomass, to produce terephthalic acid [34]. Production of biobased polymers is still a work in progress as several challenges are associated with the current techniques, feed sources, product performance and end of life management. For nanocelluloses such as cellulose nanocrystals (CNCs), cellulose from the fractionation step is hydrolysed usually with sulfuric acid (Fig. 1). Following the hydrolysis, CNCs are isolated through washing and filtering cycles [35,36]. Finally, the CNCs are characterised to determine its properties such as particle size, surface charge, and crystallinity. The production of hard carbons via HTC involves filtration of the product from hydrolysis, the product is then dried to remove moisture prior to heating in higher temperature furnace, surface treatment and/or modification is then carried out improve performance depending on the specific application (Fig. 1). Specific description of all the bio-advanced materials covered in this review including lignin-based carbon fibres, are provided in further sections.

The transition to bioderived advanced materials will deliver a range of benefits, however, it is associated with great uncertainty, more so, proposed pathways require rigorous assessment and continuous review to employ best options. To speed up the adoption of bioderived materials, it is necessary to show that these routes are both economically viable, environmentally beneficial, and socially sustainable. Policies and practices designed to prevent unacceptable environmental impacts should be based on comprehensive assessment that includes consideration of the economic and social concerns. Life cycle assessment (LCA) and techno-economic assessment (TEA) and social LCA (S-LCA) are standard methodologies that allow for the characterisation of environmental and economic and social aspects of technologies, respectively.

LCA is a globally recognised environmental impact assessment tool that examines the environmental impact of a product, process, or service over its entire life cycle, “from cradle to grave” [37,38]. It follows a standardised procedure set by ISO 14040–14044 [39], and systematically analyses a system to account for all the inputs and outputs within a defined system boundary.

TEA is focused on evaluation of the feasibility and economic viability of a process system. It uses information derived from mass and energy data for process development and technical optimisation [40,41]. It combines technical and economic data to evaluate the feasibility and profitability of the system. TEA is mostly applied at a stage where there is a commercial prospect for developing the technology at a pilot scale [40].

Social sustainability is about identifying and managing impacts, both positive and negative on different stakeholders. Social Life Cycle Assessment (S-LCA) is a methodology used to evaluate the social and socio-economic impacts of product or process system throughout its entire life cycle from cradle-to-grave (from extraction of raw material to the end-of-life e.g., disposal). It aims to improve the social performance of an organisation and ultimately the well-being of stakeholders [42]. Like the environmental LCA, social LCA follows a set of procedures as described by ISO 14044 [39,43], starting with goal and scope definition, inventory analysis, impact assessment, and interpretation. The framework for social LCA is based on a stakeholder approach where potential impacts on different stakeholder categories are considered. It extends the traditional LCA framework by considering social aspects like labour conditions, community well-being and human rights [42]. One of the complexities relating to S-LCA is data availability and system boundary definition, the use of generic data to conduct S-LCA has certain limitations [43]. Meanwhile it was argued that generic data has an advantage over using site specific data in relation to practicality [44], although many authors behind the S-LCA approaches claim that reasonable accuracy can only be achieved using site-specific data. Therefore, availability of data was recommended as basis for defining what to include in the LCA [43].

While the objective of sustainability assessment can be met by

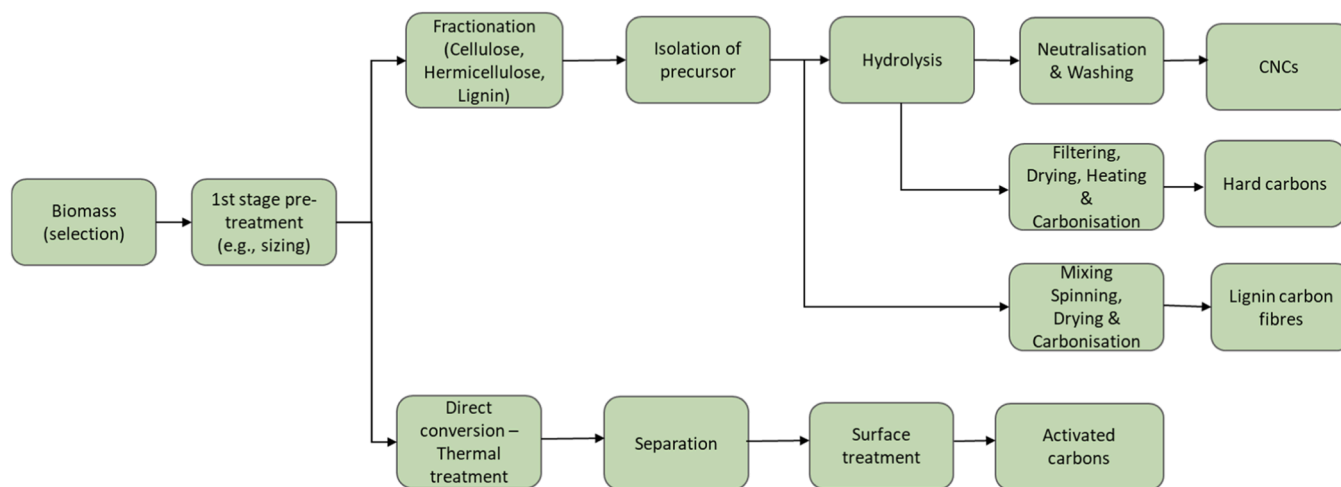


Fig. 1. A simplified flow for biomass conversion to advanced materials (example illustration).

adopting these three aspects, the concept of LCSA incorporates the Life cycle costing (LCC) [45]. A practical LCSA framework promoted by the Life Cycle Initiative is based on LCA, LCC, and S-LCA and addresses all three pillars of sustainability while building interconnectedness among these pillars [46]. LCSA also addresses sustainability issues from a holistic perspective, clarifying trade-offs between the three sustainability pillars, life cycle stages and impacts, products, and generations. Although both TEA and LCC are cost analysis tools used in modelling and calculating processes' economic impacts, the LCC follows standardised guidelines and have broader regulatory boundaries [47]. TEA and LCC may exhibit similarities in their choice of methods, indicators, and boundaries, influenced by the study's goal and scope. Considerable methodological flexibility in both methods makes it challenging to pinpoint specific differences. However, usually in TEA technological assessment is integrated with an investigation of economic feasibility from an investor's point of view. An high- in contrast typically aims to encompass the entire life cycle, emphasising a strong cost focus but not necessarily prioritising technical feasibility or revenue- and profit-related indicators that are crucial in business and investment decisions [48]. In the context of advanced materials from biomass, a preliminary search indicates that TEA has been more widely employed to assess economic impact while evaluating the technological performance of products.

Previous works have looked into existing sustainability assessments of some bioderived advanced materials [17,49,50], however, a holistic analysis that expands on the methodological aspects and dynamic landscape, and evaluates the potential for reducing environmental and cost impacts in the context of advanced materials is still required. Here, we critically review and analyse 71 studies related to sustainability assessment of higher-value bioderived products. The specific objectives of the review include the following;

- ✓ To establish an understanding of the current landscape in LCSA related to the production of biobased chemicals, bioplastics and bioderived advanced materials including CNCs, CNFs, LCF and HCs
- ✓ To provide quantitative comparative analysis of outcomes from existing assessments on LCSA of CNCs, CNFs, LCF and HCs
- ✓ To identify and highlight barriers for reduction of environmental, cost, and social implications of bioderived advanced materials and suggest possible directions for future research.

2. Review methodology

This section describes the approach employed in identifying and collecting existing studies for this review. A systematic review approach

was used [51], the objective of the review and time frame (i.e., articles on LCSA of bioderived advanced materials published from the year 2000–2023) served as the foundation for gathering relevant research studies. The timeframe was chosen considering the emerging nature of the subject reviewed – both development of life cycle methods [52] and research in the area of bioderived materials [53,54] have gained momentum in the last two decades. A literature search of previous studies on LCA, TEA and S-LCA was conducted in Scopus and Google scholar. The full names and the acronyms LCA, TEA and S-LCA (also SLCA, sLCA), were combined with key words to retrieve related studies on LCSA of bio-advanced materials. The initial search only focused on LCA and TEA, and a further search incorporated the social aspect. A set of search strings that combined two set of search key words (Fig. 2) and utilising the OR Boolean was used to run multiple searches at the same time. Keywords were interchanged for different search levels.

Screening of the search results was conducted first using title, abstract, and keywords. Articles not related to sustainability assessment (e.g., LCA, TEA or S-LCA) or biobased or bioinspired advanced materials (e.g., biorefinery co-products) were removed. The selected articles were further screened by full-text reading. Research articles adopting any of the sustainability assessment methodologies following standard guidelines (including review articles) were considered for detailed analysis (Fig. 2). Additional relevant articles from a separate review conducted by the authors were collected and merged with the screened articles for further analysis. Further screening of the collected articles was conducted to remove articles that are not focused on biobased nanomaterials, biochemicals and bioplastics. All articles collected were in English language.

3. Review of life cycle sustainability assessment of bioderived advanced materials

3.1. Bibliometric analysis

The VOSviewer software was used to perform a bibliometric network analysis of the collected studies by publication year, journal source, country, and keyword co-occurrence maps, and identify research areas receiving greater focus. A large number of the collected studies were in the past 2 years, United states of America (USA) and China had the most research activities followed by Canada, United Kingdom (UK) and India, while journals with the most published articles include Bioresource Technology, Carbohydrate Polymers, Journal of Cleaner Production and Green Chemistry (see Figure S 1 for illustration of the listed observations). Analysis on the keywords used across the collected publications is illustrated in Fig. 3. Each circle represents a keyword, while its size

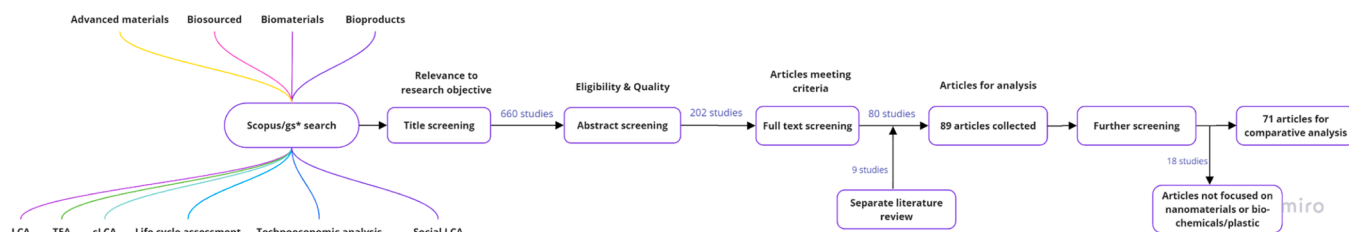


Fig. 2. Approach for selection of relevant studies (*gs = google scholar).

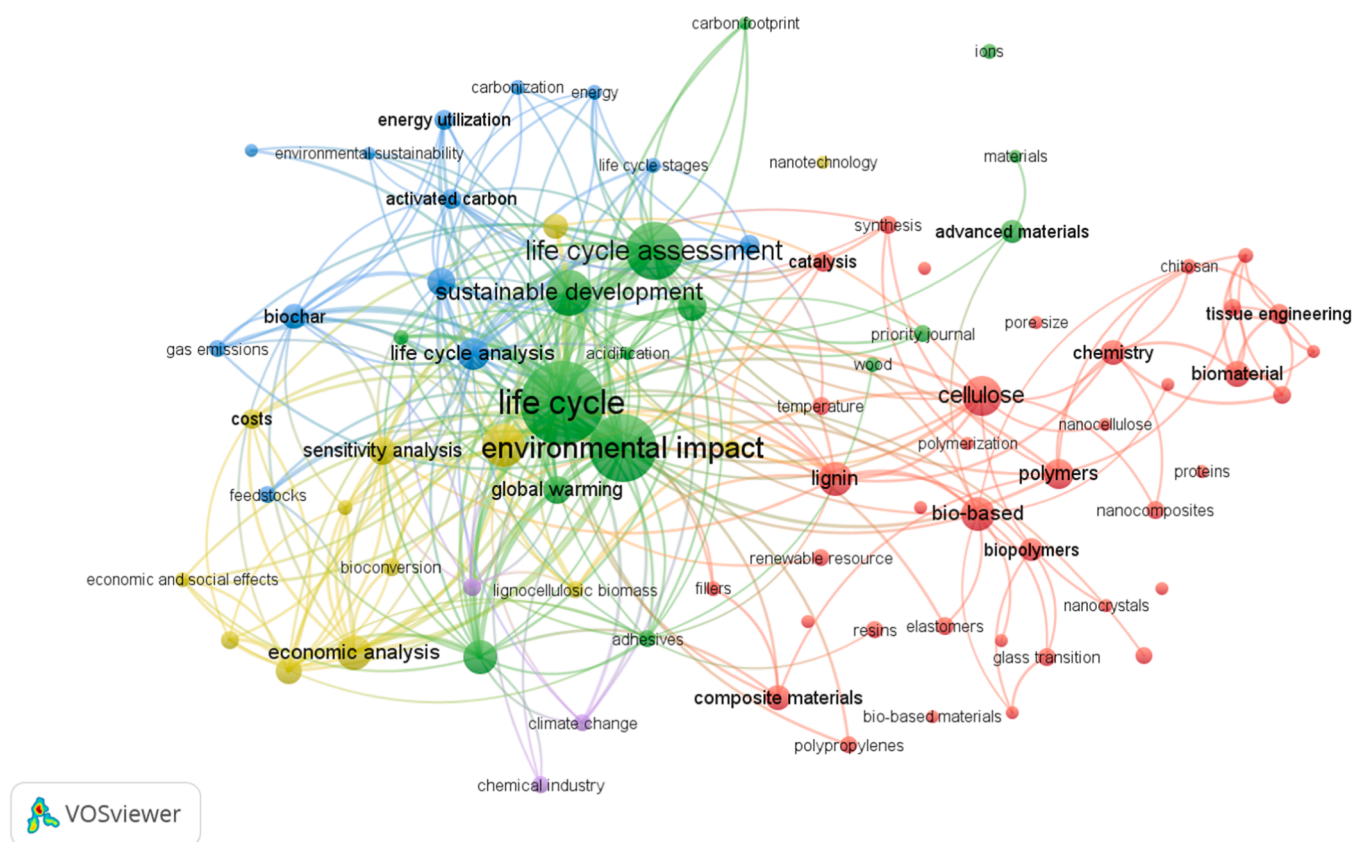


Fig. 3. keywords across collected studies related to LCSA of bio-advanced materials.

represents the number of times a pair of keywords co-occurred in the publications. From Fig. 3, research on the utilisation of lignocellulosic biomass precursors such as cellulose and lignin, the use of LCA and TEA, and to some extent S-LCA are receiving great research attention in this domain. More so, products of interest include biobased-chemicals, bioplastics, and nanomaterials. Hence, analysis in this study is focused on the listed biomass derived higher-value products.

3.2. Landscape of LCSA of biomass to higher-value products

Life cycle sustainability assessment framework entails sustainability assessment of products and services according to a triple bottom line model: environmental, economic, and social, by utilisation of LCA, TEA/LCC and s-LCA, respectively. LCSA framework adopts systems perspective and enables identification of potential conflicts or trade-offs between sustainability aspects. LCSA is based on three different methods which have different levels of maturity as well as different levels of data availability and its applications are only developing. Nevertheless, LCSA is globally accepted and the need of systematic application of LCSA for complex sustainability problems is constantly growing [45,55]. Today, environmental aspect of sustainability performance of biobased

chemicals and materials is by far the most studied one [19,56,57]. LCA is particularly well-suited for the evaluation of environmental impacts of various biobased product systems throughout entire lifecycles by utilisation of a set of quantitative metrics [58]. When economic aspect of production is considered, Life Cycle Costing (LCC) [59–61] or Techno-Economic Analysis (TEA) [48] could be employed alongside LCA to examine how process conditions and feedstock properties affect the feasibility and economic sustainability of technological solutions while concurrently assessing their environmental impacts. TEA and LCA are commonly applied simultaneously to assess biotechnological processes [62], though these are usually presented as standalone. While efforts are being made to combine TEA and LCA to enable systematic analysis of the different dimensions of sustainability [63,64] and/or to obtain single analysis indexes for products [41], there are significant hurdles with methods harmonisation and integration therefore, development of robust integrated methodology is still required [65]. LCC is better aligned with LCA as follows similar framework. Integration of LCA and LCC results has been demonstrated for chemicals production [61] and for biorefinery case study [66] through Multiple Criteria Decision Analysis (MCDA).

Due to the relative recency of social life cycle assessment method,

consideration of social and socioeconomic aspects alongside LCA for biobased bulk chemicals and materials is still rare, let alone integration of environmental and social assessments results.

The life cycle perspective spans from the extraction of resources, material production, manufacturing, logistics, use, maintenance, repairing, recovery of resources, and re-manufacturing, until the final disposal of waste [45]. A typical system boundary (cradle-to-grave) for the production of higher-value biobased products would include cultivation of the biomass feedstocks, post-cultivation processes, transportation, production (storage, pretreatment, material fabrication, assembly, storage), transportation, distribution, use, and End of life phase (Fig. 4). Adopting the complete cradle-to-grave or a more circular cradle-to-cradle, or truncated versions of the LCA system boundary depends on the assessor and it is often driven by the set questions, scope, and data availability.

This section provides a comprehensive review of the status and developments in sustainability assessment of higher-value products from biomass. A total of 71 studies evaluating the sustainability of various bioderived products including biochemicals, bioplastics, nanocelluloses and carbon materials were analysed. Table S 1 and Table S2 summarise the number of publications in each category of bioderived advanced products considered in this review. Among these products, biochemicals and bioplastics have been widely studied and their sustainability assessment and performance against their fossil counterparts have been reviewed in recent studies [17,28,33,34]. Hence, an overview of most recent developments is provided as it relates to these products, while a more detailed analysis on nanocelluloses and carbon materials is provided in further sections.

Fig. 5 shows the proportion of studies related to the various products evaluated in the reviewed studies, and the different sustainability assessment tools and system boundaries employed across these studies. Among the 71 studies, 27 studies conducted sustainability assessments related to various biochemicals, 12 studies were related to bioplastics/biopolymers, and 32 studies are related to nanocelluloses (CNCs, CNFs) and carbon materials (LCF, HC) (Fig. 5). Meanwhile, the system boundary adopted varies across the various studies with ~60 % employing a cradle-to-gate boundary which is common among LCA studies related to emerging technologies [28,40,67], 13 % and 1 % of the studies used the gate-to-gate and gate-to-grave assessment boundaries. Only 12 % of the studies used the full cradle-to-grave system boundary while the remaining did not specify system boundary used in the assessment. Most of these studies largely employed LCA in their analysis, about 38 studies conducted or included TEA in their analysis while only 6 studies focused on S-LCA (Fig. 5), this distribution correlates with the maturity of the assessment tool and data availability [45], but also highlights gaps in complete sustainability assessment among the

reviewed studies. Even so, the studies employing S-LCA focused on methodological development related assessment framework and indicators [68,69]. Other published works on social assessment of biobased products broadly discusses methodological approaches, such as identification of relevant indicators, stakeholders' categories, data collection methods and application of social impact assessments [68, 70–72].

3.2.1. Overview of LCSA of Biochemicals

Bioderived platform chemicals are considered key players in establishing a circular bioeconomy as they constitute the starting feedstocks for a diverse range of products used in various applications. Some of the biobased platform chemicals analysed in the reviewed studies include lactic acid, adipic acid, 2,5-furandicarboxylic acid (FDCA), 5-hydroxymethylfurfural (HMF), succinic acid, dimethyl ether (DME) [73–77] and other bulk chemicals assessed in previous review articles [19,78, 79]. Some of the studies assessing the impacts of biobased chemicals adopted the integrated biorefinery concept. A comprehensive review of biomass to bulk chemicals was conducted by Blanco-Cejas et al., [19] where they discussed methodological approaches in the context of emerging biochemical technologies as well as the complexities related to modelling of multifunctionality in LCA studies of biobased platform chemicals. The authors indicated the relevance of utilising a consequential approach in modelling several flows in the multi-systems, even so, such complex systems require careful consideration as it relates to the allocation process, a hybrid approach in some cases could be more useful. Ryan & Yaseneva [79] also provided an in-depth analysis related to pre-treatment technologies of woody biomass focusing on sugar production. The authors highlighted organsolv as the most environmentally friendly pre-treatment route but also discussed inconsistencies related to methodological approaches across the reviewed studies. More so, only a small fraction (~25 %) of the collected studies were harmonised to enable comparative analysis and usability of data and findings related to the environmental impacts. Most of the reviewed studies in this paper reported environmental impact related to global warming potential (GWP). Employing biobased routes to produce chemicals such as adipic acid could reduce greenhouse gas emission by up to 78 % compared with conventional adipic acid, meanwhile, environmental impacts of approximately 1.55 kgCO₂-eq, 9.16 kgCO₂-eq, and 2.72 kgCO₂-eq were associated with the production of 1 kg of caprolactone from corn stover [80], 1 g of FDCA from maize grain [81] and 1 kg of succinic acid from municipal organic biowaste [82] respectively. Schoppe et al., [83] reported the sensitivity of CO₂ impact to solvent (dichloromethane (DCM)) recyclability in the production of HMF, with 80 % reduction in CO₂ impact (kgCO₂-eq) when recycling of DCM was increased from 90 % and 98 %. An estimated GWP impact of

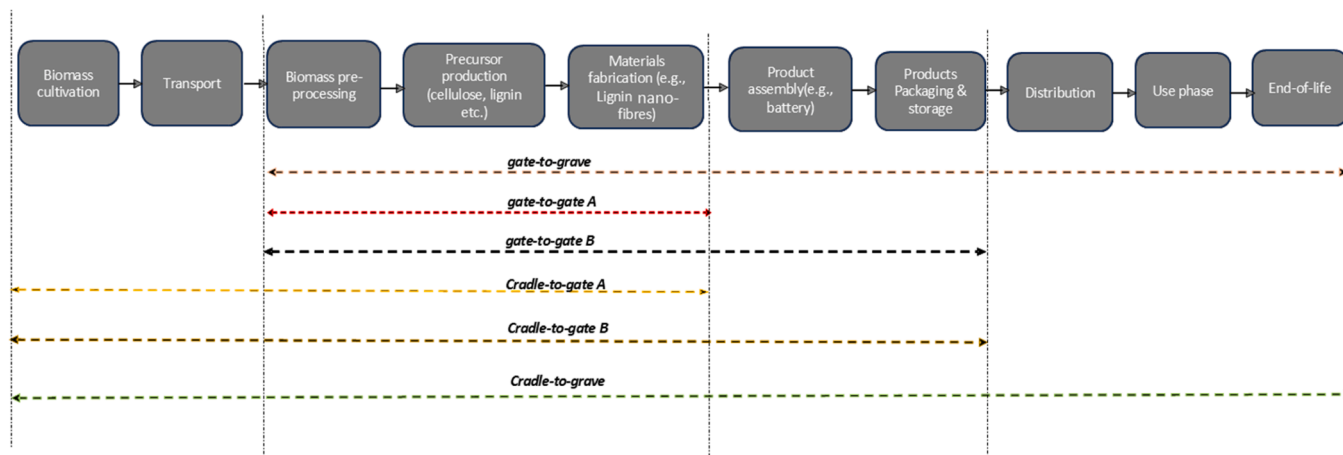


Fig. 4. life cycle stages of biomass to bioderived advanced materials (the case of LCF) showing various assessment boundaries.

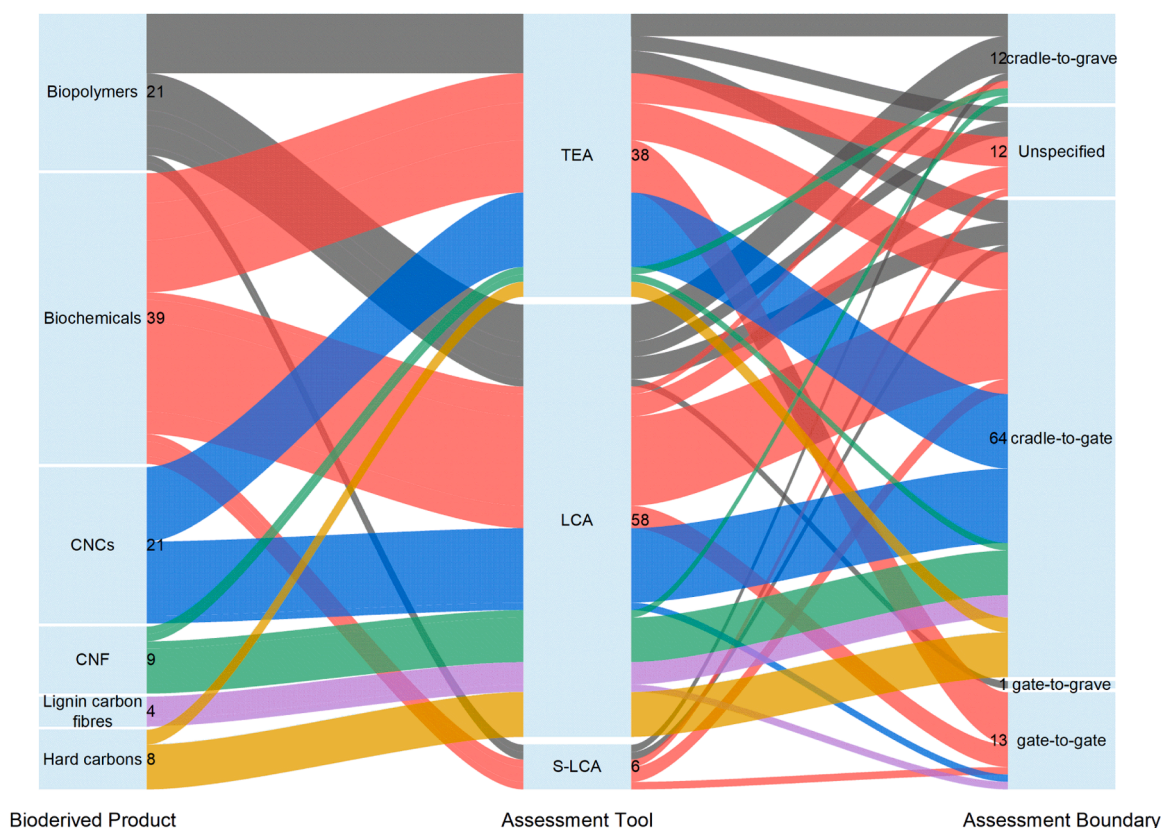


Fig. 5. Type of bioderived advanced products, assessment tools and boundaries reported in the reviewed studies.

levoglucosan production from sugarcane bagasse, range from 21 to 117 kgCO₂-eq per kg for different scenarios considered in a study by Zhang et al., [76]. While environmental impact reduction related to GWP (kgCO₂) could be achieved by adopting biobased chemicals, other impact categories are being overlooked particularly those related to toxicity and land use. Meanwhile, the economic performance may not fully align with the environmental benefits, which often raises the issues of trade-offs across these sustainability pillars.

For economic performance, the minimum selling price is the common economic indicator used among the reviewed studies. A baseline minimum product selling price (MPSP) of \$1.57 for 1 kg of lactic acid presents a market competitive product considering the market price of \$1.7/kg to \$2.1/kg for this commodity [84]. An estimated cost of producing dimethyl ether (DME) was \$11.9 for each GJLHV with recycling, while a lower cost of \$3.1 could be achieved with credit allocation for the CO₂ captured [85], emphasising the benefit of an integrated system. The product cost of biobased p-xylene and succinic acid were reported at \$3.9/kg [86] and \$1.6/kg [87] respectively. As for its environmental impact, HMF was the cost driver in the production of biobased p-xylene, estimated at \$1.22/kg based on \$0.34/kg of fructose. Therefore, a decrease in the price of fructose would lower the cost of HMF. Meanwhile, an MSP of \$1.5 was estimated for 1 kg of FDCA [88] and \$1.8 for 1 kg of caprolactone [80]. Biochemicals seem to attract high production costs compared to their fossil counterparts, which remains a challenge in the adoption of bio-sources for chemicals production. Additionally, the value of the product plays a crucial role in determining the overall efficiency of the product system. Consequently, the production of chemicals demonstrate greater potential for economic profitability when compared to fuels or less valuable by-products. Even so, it is worth noting that unlike the commodity chemicals, the higher-value chemicals are generally obtained in small quantities, so the high commercial value has to compensate the small scales of the projects.

In assessing the social and socio-economic impacts, 4 out of the 6

(Fig. 5; Table S 1) studies on S-LCA were related to biochemical production. These studies focused more on methodological developments while evaluating the biorefinery concept for production of various bio-products including biochemicals [71,89] and biofuels [90,91]. As described in section 1.3, social sustainability assessment requires more attention in promoting bioeconomy strategies, more so, it is particularly challenging in the application of S-LCA to emerging technologies mainly due to data limitations and uncertainty in relevant stakeholder and indicators. At the biorefinery process design stage, the stakeholders' knowledge and engagement in the system are very limited, and data is not available to assess social aspects. However, it is a top priority to ensure proper social conditions when the process is implemented [89]. Meanwhile, social performance of biorefineries was studied in other works where primary social data was available and a wider stakeholder perspective was investigated [89,92,93]. Rebolledo-Leiva et al.,[71] reviewed recent developments and gaps in assessing social elements from the life cycle perspective within the bioeconomy context. The review highlighted critical methodological issues including system boundaries and cut-off criteria, impact assessment methods, the selection of societal issues and stakeholders, and uncertainty. Unlike the environmental LCA, and TEA, where studies employed both tools in assessing the system sustainability profile, none of the 4 studies assessed the S-LCA in combination with either LCA or TEA.

3.2.2. Overview of LCSA of Bioplastics

Substituting fossil-based plastics with biobased ones presents potential for reduced energy cost, environmental and health related impacts of conventional fossil plastics. Key biopolymers analysed in the collected studies include polyhydroxyalkanoates (PHA), polylactic acid (PLA) and bioPET [94–97] and other bioplastics reviewed in previous studies [98–100]. In comparison with other products analysed in this study, a large part of the studies on bioplastics employed a cradle-to-grave system boundary, which may be attributed to the

significant attention on evaluating the sustainability of fossil-based plastics and alternatives in recent years, thus, emphasis has been on the end of life (EoL) management of plastics waste. Biopolymers including PLA, PHA, and polyhydroxybutyrate (PHB) were reported as having lower environmental impact and potentially lower cost implications compared with their fossil-based counterparts [97,101]. A study by Bassi et al., [94] showed that PHA from food waste and sewage sludge had four times lower environmental impact and eight times lower cost than fossil-based polyurethane and showed better performance than PHA from first-generation sugarcane and maize. Meanwhile, the use of depolymerised lignin as a replacement for polyol and phenol to produce polyurethane and phenolic resins attracted an MSP of \$1.4/kg of [95]. Biopolymers such as PHA attract high production cost due to high feedstock cost, small production scale, and uncertainty in the use of new technologies. The plastics pyramid and plastic spectrum have been used in previous studies [96] to rank various types of polymers according to their toxicity and preferability in terms of End of life (EoL) management, where biobased polymers appeared to be the least hazardous and most preferred in terms of EoL management [96]. Whilst it is generally believed that biopolymers such as PLA outperform fossil-based polymers in energy use and GWP, they perform worse in other impact categories such as eutrophication. While biopolymers are favoured due to their origin from renewable resources and their potential for biodegradability and composability, practical challenges arise from the demands of feed processing, cultivation, and uncertainties surrounding the end-of-life fate and pathways of biopolymers. In real-world scenarios, for biopolymers to excel in all aspects of sustainability compared to their fossil-based counterparts, certain studies have stressed the importance of optimising production parameters like chemicals (e.g., sodium hypochlorite during PHA extraction) and the utilisation of waste feed materials [101,102]. Advances in emerging biopolymer production technologies is imperative, even so, the sustainability evaluation of these new technologies may face obstacles due to limitations in available data, lack of maturity (scaling issues), limitations in consensus methodological choices, and among other factors.

3.2.3. Nanocelluloses

Nanocellulose is a promising candidate in replacing traditional fossil-based materials in many applications due to its exceptional functional and environmental properties (high mechanical strength, optical properties, reinforcing capabilities and tunability of properties, non-toxicity and biodegradability) [103,104]. The nanoscale form of cellulose is obtained through the breakdown of larger cellulose structures, which is achieved by disrupting the hydrogen bonding within and between the chains of cellulose molecules [105]. Nanocelluloses are characterised with unique properties such as high mechanical strength, biodegradability, and renewability. Three types of nanocelluloses exist including cellulose nanocrystals CNCs, CNFs and bacterial nanocellulose (BNC) [103,106]. CNCs are rod-like particles with diameters in the nanometre range and lengths of several hundred nanometres, while CNFs are long and thin nanofibers. Bacterial nanocellulose has the form of twisting ribbons with micrometre lengths with large surface area per unit. Due to advanced functionality, nanocellulose presents a wide range of potential applications in various areas including biodegradable films, composites, coatings, electronic devices, sensors, and drug delivery system [103, 106].

In this review 22 out of the 71 reviewed studies were focused on nanocelluloses and its derivatives. 19 of these studies addressed the environmental aspects of sustainability and 8 of the studies analysed economic indicators via TEA. The environmental impacts and price of nanocellulose production are primarily driven by the choice of initial feedstock and manufacturing process. The main production process for cellulose nanocrystals is sulfuric acid (SA) hydrolysis of Kraft pulp [107]. For Cellulose nanofibres (CNFs), production typically comprises several operations including mechanical disintegration process (high pressure homogenization, microfluidisation or micro-grinding) and

chemical pretreatment methods to facilitate mechanical disintegration [108].

3.2.3.1. Cellulose nanocrystals (CNCs). Table 1 presents literature analysis of environmental impacts and minimum selling price (MSP) for the CNCs produced from different feedstocks via acid hydrolysis method. Most of the studies used 1 kg CNC as a functional unit and employed cradle-to-gate system boundary. Kraft, dissolving pulps and cotton are processed directly into CNCs, while lignocellulosic feedstocks such as woody biomass, agricultural residues or sugarcane bagasse require additional pretreatment and bleaching steps.

Most of reviewed studies investigated production of CNCs from Kraft and dissolving pulp via sulfuric or citric acid hydrolysis [107–113]. Detailed analysis of environmental impacts of large-scale CNC production from Kraft pulp via sulfuric acid hydrolysis has demonstrated that major GWP contribution comes from management of sulfuric acid end of life either via recycling or neutralisation with sodium hydroxide. In countries with renewable energy mix the GWP impact value is ~ 12 kg CO₂eq/ kg CNC in scenario with sulfuric acid recycling and 15 kg CO₂eq/ kg CNC in scenario without acid recycling [109]. These GWP values corresponds well with similar study by Rajendran et al. [108] showing GWP of 11 for both scenarios with and without sulfuric acid recycling in the USA [112] LCA studies of sulfuric acid hydrolysis of dissolving pulp have demonstrated that GWP impact depends on the scale of CNC production process with impact values of 21 and 30 kg CO₂eq/ kg CNC for pilot scale process with [112] and without [113] sulfuric acid recycling respectively; and values of 7.5 and 12 kg CO₂eq/ kg CNC for large scale production with and without sulfuric acid recycling [107]. Acidification potential was the second most assessed impact category with only two studies looking at the range of different impacts [108,109]. The production of 1 kg of lignin derived CNCs (LCNCs) from thermomechanical pulp following acidic deep eutectic solvent pretreatment had an average GWP of 39 kgCO₂-eq and acidification potential of 0.17 kgSO₂-eq [114].

The reported MPSP of 1 kg CNCs produced from Kraft and dissolving pulp varied significantly between different studies. Thus Rajendran et al. reported MPSP value of ~ \$4.7 per kg CNC from Kraft pulp, while Rosales-Calderon et al., [110] and Lan et al., [107] obtained MPSP values of \$10 and \$4.4 per kg CNC from dissolving pulp, respectively. Substitution of sulfuric acid with citric acid for production of CNCs increased MPSP significantly to \$16.5 per kg CNC [111]. Two of reviewed studies investigated environmental impacts of CNC production from cotton. Zhang et al., [115] obtained GWP of 30–40 kgCO₂-eq/ kg CNC for production via SA hydrolysis with impact allocation to recovered sulfuric acid and glucose streams. While Ruiz-Caldas et al. [116] studied gate-to-gate process of CNC production from post-consumer textiles via citric acid hydrolysis and obtained GWP of 40 kgCO₂-eq/ kg citrated CNC.

Sugarcane bagasse is another commonly studied feedstock for CNC production via pretreatment/bleaching/SA hydrolysis process. Two reviewed directly comparable LCA studies on CNC production from sugarcane bagasse had a 10-fold difference in the evaluated GWP: Leao et al., [117] reported GWP of ~ 20 kgCO₂-eq/ kg CNC, while Katakojwala et al., [118] obtained ~200 kgCO₂-eq/ kg CNC. Bondancia et al., [35] reported GWP of 40 kgCO₂-eq/ kg CNC for production from sugarcane bagasse via enzymatic/organosolv pretreatment/bleaching/SA and citric acid hydrolysis. MPSP of CNC produced from sugarcane bagasse via sulfuric acid hydrolysis was reported by two studies as \$6.5/kg CNC [111,118].

3.2.3.2. Cellulose nanofibres (CNFs). Fig. 7 presents the environmental global warming potential impact (GWP) of CNFs production from 30 case studies among 8 reviewed articles. All the case studies have been normalised to a uniform functional unit of 1 kg CNF and a cradle-to-gate assessment boundary as shown in Fig. 6 (Table S2). Further 8 case

Table 1

Review of LCA and TEA assessments of CNC production from different feedstocks via acid hydrolysis All studies except ones marked * have the functional unit of 1 kg of CNC product and cradle-to-gate system boundary.

Feedstock	Process	Scale	LCA/TEA method	GWP, kg CO ₂ -eq per kg CNC		MSP CNC, \$/kg CNC		Reference
				with acid recycling	w/o acid recycling	with acid recycling	w/o acid recycling	
Bleached Kraft pulp (softwood)	Sulfuric acid (SA) hydrolysis	100 MT/day	TRACI/TEA	11.4	11.2	4.2–5.2	4.5–5.5	[119]
Bleached Kraft pulp (softwood)	SA hydrolysis	1 MT/day	EF/TEA	12.6	15.7	-	-	[120]
Bleached Kraft pulp (eucalyptus)	SA hydrolysis with acid recycling	125 MT/day	TEA	-	-	10.03	-	[121]
Bleached Kraft pulp (eucalyptus)	Citric acid (CA) hydrolysis with acid recycling	5 MT/day	TEA	-	-	16.5	-	[122]
Dissolving pulp	SA hydrolysis with acid recycling	100 kg/day	ReCiPe	21	-	-	-	[123]
Dissolving pulp	SA hydrolysis with acid neutralisation with NaOH	25 kg/day	TRACI	-	30	-	-	[124]
Dissolving pulp	SA hydrolysis different scenarios	50 MT/day	TRACI/TEA	7–8	12	4.6	4.3	[125]
Softwood	Thermomechanical treatment following by acidic treatment	Lab scale	TRACI	-	39	-	-	[126]
Woody & agricultural residues	SA hydrolysis	50 MT/day	TEA	-	-	5.1	7.2	[127]
Cotton	SA hydrolysis with acid and glucose recovery with co-products allocation	25 kg batch	Impact 2002+	30–40	-	-	-	[128]
Post consumer textile*	Citric acid (CA) treatment to obtain citrated CNC	Lab scale, gate-to-gate	EF	-	40	-	-	[116]
Sugarcane bagasse	Feedstock pretreatment, bleaching and SA hydrolysis (different parameters / scenarios investigation)	Upscaled from lab scale	CML	13.7–23.5	-	-	-	[129]
Sugarcane bagasse	Enzymatic hydrolysis/organosolv pretreatment / bleaching / SA-CA hydrolysis	72000 MT SB /a	CML	40	-	6.5–7.4 for SA CNC	9.9–11 for CA CNC	[130]
Sugarcane bagasse	Feedstock pretreatment / bleaching / SA hydrolysis within biorefinery scenario	4 MT/a	Impact 2002+	200–250	-	6.5	-	[131]

More environmental impacts category values can be found in [108]; * Gate-to-gate boundary

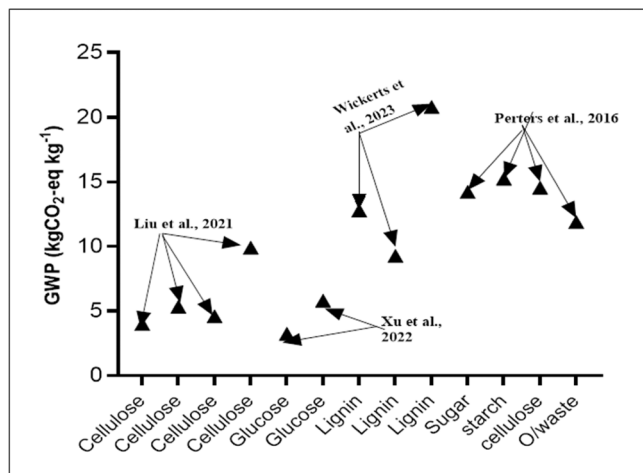


Fig. 7. Global warming potential impact (kgCO₂-eq) of Hard carbon production across the reviewed studies(O=organic).

studies from 2 articles related to nanolignin synthesis are also discussed in this section. Case studies on nanolignin are shown in Table S2. Most of the studies reported environmental impacts in terms of GWP while others reported a range of other environmental indicators [132,133] and only one study provided economic indication of CNF production [107].

The common feedstocks used for CNF production among the reviewed studies, include Kraft pulp, dissolving pulp, unbleached sulphate pulp and sulphite pulp [107,132,134,135]. Some of the studies used direct biomass or did not mention the specific precursor for all the case studies utilised [132,133]. In terms of pretreatment and fabrication approach, TEMPO oxidation followed by homogenisation is the most

widely utilised across the reviewed studies.

A GWP range from 190 kgCO₂-eq to 1160 kgCO₂-eq was associated with a lab scale production of nanocellulose via four different routes by a combination of chemical and mechanical approaches, including 1) TEMPO oxidation followed by sonication (TOSO) or homogenisation (TOHO) and 2) chloroacetic etherification followed by sonication (CESO) or homogenisation (CEHO) [134]. Of all the scenarios, TOHO had the least environmental implication as the TEMPO oxidation requires only ethanol while chloroacetic etherification requires isopropanol followed by ethanol, and unlike the homogenisation route, the sonication requires additional centrifuge step for purification which translates to increase energy usage. Turk et al., [133] reported similar range of values using unspecified precursor from wood source. Likewise, Piccinno et al., [136] reported a GWP values of 150 kgCO₂-eq from carrot food waste for a baseline scenario, and 140 kgCO₂-eq for another scenario with adapted Brazilian electricity mix. Meanwhile, GWP values in the range of 17.7 kgCO₂-eq to 88 kgCO₂-eq were obtained from cotton linters and recycled industrial waste sources (Table S2) via TOHO and enzymatic treatment followed by homogenisation (ENZHO) [132], in this case, lower GWP values were realised using the ENZHO method which may be attributed to less chemical use compared with TEMPO.

Apart from the biomass sources, pre-treatment approach and fabrication pathways significantly influence the environmental performance of CNFs. Moreso, the energy source plays a critical role in CNFs production as most of the case studies indicate high contribution of electricity use, thus, the environmental impact would strongly depend on the source of electricity. For example, a noticeable reduction in GWP was achieved from a baseline value of 7.56 kgCO₂-eq to −0.98 kgCO₂-eq by switching to renewable wind power from the country's energy mix, using dissolving pulp in both cases. However, this difference was not captured in the economic impacts with MSP values of \$2.87 and \$2.98 for the baseline and renewable wind energy scenarios respectively [107]. This highlights the imperative for developing integrated

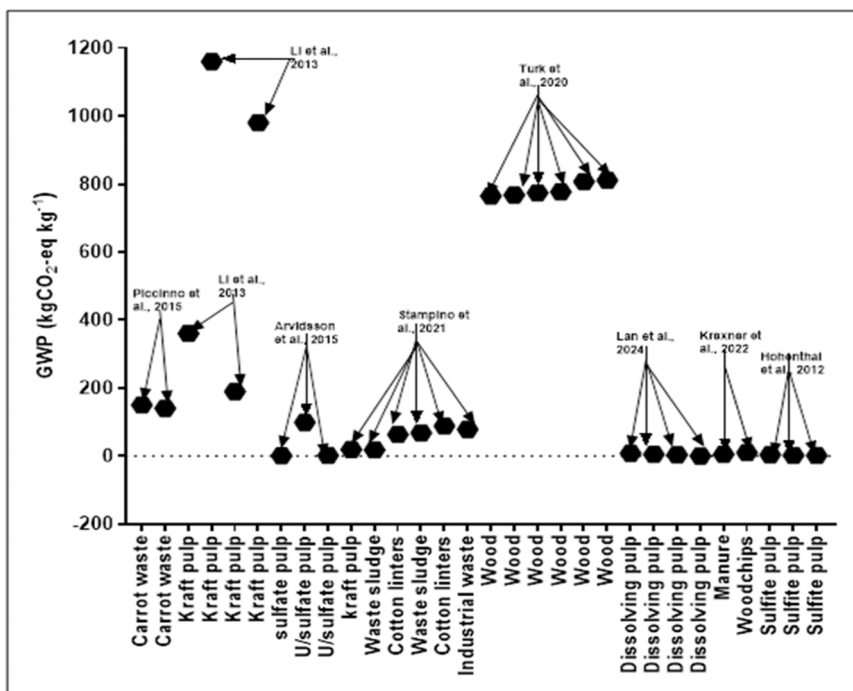


Fig. 6. Global warming potential impact(kgCO₂-eq) of CNFs across the reviewed studies (U=unbleached).

sustainability assessments approaches. Krexner et al., [137] also assessed the production of 1 kg nano fibrillated cellulose (NFC) from manure and wood chips with specific values of 4.41 kgCO₂-eq and 9.74 kgCO₂ respectively [137]. Production of NFC from manure had 45 % lower impact than that produced from woodchips across all environmental impact categories assessed in the study. At the cradle stage, the maize feed used in the woodchip scenario for biogas generation was considered to have a market value, unlike the manure scenario. Similar process components were used in the two scenarios, prioritising utilisation equality over allocation [39]. The pulp to NFC production stage had the largest impact contribution with electricity use contributing over 99 % to the NFC production stage. Meanwhile, Hohenthal et al., [138] obtained GWP values in the range of 0.75 kgCO₂-eq to 3.1 kgCO₂-eq for CNF production with sulphite pulp, using the enzymatic approach and TEMPO oxidation, this was captured in a review by Foroughi et al., [139]. In contrast with the other reviewed studies, the TEMPO route in the study by Hohenthal et al. [138] showed lower environmental impact compared to the Enzymatic route. While the reviewed studies are widely varied even for case studies from the same report, most of the studies reported lower environmental impact of the enzymatic pre-treatment route, and higher intensity of the chemical treatments.

Considering Nano lignin, Teh et al., [140] compared nanolignin production from Birch chips and oil palm Empty fruit bunch (EFB) via two synthesis pathways including treatment with alkali or organosolv followed by homogenisation and/or ultrasonication, respectively. In their study, the production of 1 kg nanolignin had a range of GWP impact from 76.2 kgCO₂-eq to 1052.13 kgCO₂-eq across eight scenarios. The two pathways associated with organosolv treatment for both biomass materials and synthesis routes, had the highest GWP impact. While homogenisation have higher GWP regardless of the biomass source, novel delignification method like organosolv is not necessarily a more ecologically benign alternative as compared to a conventional alkali pre-treatment process but dependent on the source of lignocellulosic biomass. Likewise, the environmental performance of lignin-nanoparticles from wheat straw showed relatively similar trend in a study by Koch et al., [141] with GWP range from 36.6 to 199 kgCO₂-eq per kg across various scenarios in a biorefinery setting. Out of all the

production stages/components, the burden of solvent (ethanol) and thermal energy use had the highest contributions to the GWP impact across all scenarios. Highlighting the need for more sustainable solvents and energy sources within the lignin value chain.

It is apparent that the selection of most appropriate pre-treatment combination, biomass type and energy source underpin the viability of CNFs production.

3.2.4. Carbon materials

Carbon materials such as carbon fibres and carbon nanostructures possess unique properties including high tensile strength, thermal and electric conductivity, stiffness, and chemical resistance which makes them also suitable for wide range of applications in aerospace construction, automotive and sport equipment, and energy devices, composites, and nanotechnology [142]. Bioderived carbon fibres can be produced by compounding and pelletisation of the organic precursors (e.g., lignin), followed by a series of heating and stretching processes to align the carbon atoms and improve the mechanical properties [143, 144]. Carbon nanostructures can be produced through various methods, including laser ablation, chemical vapor deposition (CVD), and hydrothermal carbonisation (e.g., hard carbons) [145].

Interest in biosourced nanocelluloses and carbon materials is mirrored by increasing concern and questions about their sustainability status. 8 of the 71 reviewed studies were related to carbon materials (lignin carbon fibres and hard carbons). All the 8 studies addressed the environmental aspect of sustainability with 3 of the studies incorporating the economic aspect via TEA.

3.2.4.1. Lignin carbon fibres (LCF). The results of 3 case studies related to lignin-based carbon fibres (LCF) is discussed in this section. Biobased LCF are commonly produced via the wet spinning, electro spinning and melt spinning technologies which supersedes the lignin recovery (lignin isolation) stage [142,146]. Industrial scale production of carbon fibre is currently via wet spinning while other technologies are still at laboratory scale.

LCF production from corn stover attracted a GWP of 19 kgCO₂-eq and 38 kgCO₂-eq using ethanol and acetic for isolation of the lignin precursor from corn stover respectively [146]. The two pathways were

associated with minimum selling price of \$12.02/kg and \$38/kg for ethanol and acetic acid pretreatment pathways, respectively. The type of solvent used indicates strong influence on the environmental and economic performance. While the energy requirement of acetic acid is higher due to higher boiling point (117.9°C) to evaporate the water from the solvent compared to ethanol (78.4°C), the cost of ethanol is almost 2x that of acetic acid. A prospective assessment of lignin-based carbon fibre attracted 1.50 kgCO₂-eq per kg of carbon fibre showing a potential 32 % reduction in climate impact compared to glass fibres [147]. Compared with other studies, the lower value 1.50 kgCO₂-eq per kg GWP impact obtained is attributed to several methodological choices and advanced technology for lignin recovery (lignoblast process), for example, the lignin precursor was considered a waste by-product of the pulp production and fossil energy was replaced with cleaner renewable sources in the Swedish region. Moreso, energy generated during pulping was used within the lignin-carbon fibre production system. A wide variation can be observed among the reviewed studies related to lignin carbon fibres, which shows that even within the same studies, factors such as the type of solvent employed and/or its utilisation approach, the type of biomass, energy sources, and LCA methodological choices can lead to variations in outcomes of assessments. This is common with LCA studies, and several efforts are being made to minimise the potential variations in LCA studies. Focus should be on developing low-cost sustainable solvents and fabrication approaches, likewise alternative energy sources for LCF production.

3.2.4.2. Hard carbons. Carbon materials with low dimensions, ordered nanostructures, and large surface areas with potential application as electrode materials, fuel, and catalysis, maybe produced via hydrothermal carbonisation (HTC) [148]. HTC utilises biomass or biomass-derived precursors such as glucose, xylose and starch in an aqueous-phase process to produce carbon materials [149]. The hydrothermal treatment is aimed at improving quality of the hard carbons compared with its conventional fossil counterparts. With renewed interest in the utilisation of carbon materials for advanced applications [148,150], sustainability assessments of hard carbons have also increased in the last decade [151–153]. However, a few studies related to environmental and/or economic performance of hard carbons exist. In this section, we reviewed and compared 6 studies and 16 case studies related sustainability of hard carbons production from biobased sources.

Fig 7 shows environmental impacts for the production of 1 kg hard carbons using various feed sources across the reviewed studies. Three data points that appeared as outliers including 1 case study by Trotta et al., [154] and 2 case studies reported by Moon et al., [155], are not shown in Fig. 7 but in Table S2. All the studies reported the environmental impact in terms of GWP (kgCO₂-eq) while only two out of the six studies assessed the economic impact. All the reported values were normalised to a uniform system boundary of cradle-to-gate and functional unit of 1 kg.

Liu et al., [156] employed the CML 2001 impact assessment method to compare four case scenarios of hard carbons from cellulose precursor via the HTC pretreated and direct pyrolysis routes. A range of GWP impact from 4.006 to 9.92 kgCO₂-eq was associated with the presented case scenarios. The HTC treatment stage and higher pyrolysis temperatures (1300°C) favour lower environmental impacts owing to higher electrochemical performance of the hard carbons. Using similar operational conditions and LCIA method (CML 2001), Xu et al [157] reported a GWP value of 3.25 kgCO₂-eq per kg of hard carbon obtained from glucose, further highlighting the influence of feed biomass on the assessment outcome. In comparison with the aforementioned studies, a higher GWP value of 246 kgCO₂-eq was reported for the production of hard carbons from glucose, this was associated with production cost of \$1.20 for the base case. Although hard carbons from glucose appeared to have higher electrochemical performance, the cost of glucose seem to be higher than that of cellulose. The cost of hard carbons from these two

precursors is dominated by the cost of electricity which constitute 60 % and 72 % of the total cost hard carbons from cellulose and glucose respectively. Meanwhile, using the ReCiPe method and a lignin based-precursor, Wickerts et al., [158] reported a range of GWP for three different energy sources using a mass-based allocation or main product bears all the burden (Fig. 7, Table S2). Using the same LCIA method, GWP values were obtained within the same range for other types of feedstock including sugar, starch, cellulose and organic waste as shown in Fig. 7[159]. For all the reviewed case studies, apart from the three outliers, GWP impact of hard carbons production from various bio-sources was in the range of 3–21 kgCO₂-eq per kg hard carbons. In a most recent study by Liu et al.[160], climate change impact values per kg of hard carbon were within the range reported in the reviewed study but could be as low as 0.4 kgCO₂-eq in a hypothetical future scenario. Although some of the reviewed studies reported a range of environmental impact categories including human toxicity potential, fossil depletion potential, eutrophication potential and water consumption [154,157,161], focus of analysis was mainly on GWP which also provides opportunity for comparison across all the studies. Existing studies have demonstrated the potential of HTC in production of hard carbons for anode materials in battery systems, however, combine optimisation of the carbon yield, electrochemical performance, feed biomass and choice of energy source would be essential for further sustainability assessment and development of the HTC technology.

4. Discussion

4.1. Methodological approaches in assessments of bioderived materials

Methodological challenges are common in sustainability assessments adopting the life cycle assessment approach. Previous LCA review studies have highlighted issues arising from differences in outcomes of various assessments [79,162–164]. This has resulted in a slow progress in terms of accessing useful and reliable information related to the sustainability of various technologies. Some of the recognised sources of methodological variability from life cycle perspective include reference functional unit, system boundary, management of multifunctional systems (allocation of burdens), type and quality of data, variability and uncertainty, carbon accounting, impact assessment methodologies and considerations (fate and cause-effect chain) within the specific assessment models. The methodological analysis is focused on the 32 studies related to nanocelluloses and carbon materials as this information is currently lacking in the literature [165] [154,159]. It is critical for developing relevant framework providing appropriate assessment guidelines and improved process design for commercialisation of these emerging technologies. Since the issue of functional unit, system boundary was resolved by normalisation of the outcomes of the reviewed studies, the following discussion spans over four main categories including scope and perspective, multifunctionality, data and uncertainty and impact assessment methods.

4.1.1. Scope and Perspective

Taking a closer look at the 32 studies related to bioderived advanced materials reviewed in this study. We note that, more than half of the studies used 1 kg of product as the reference functional unit (e.g., [35, 114,116,118,140,141]) and in reporting the assessment outcome which indicates some level of homogeneity in this regard. Moreover ~70 % of the 32 studies utilised the cradle-to-gate system boundary which is strongly attributed to the low TRL of these technologies and the absence of EoL data. The remaining studies adopted the gate-to-gate or cradle-to-grave system boundary (Section 3.2.3; Fig. 4). Adopting a uniform reference unit and scope across studies evaluating the potential of bioderived materials would facilitate progress in the utilisation of assessment outcomes for decision making and policy in this domain.

In terms of LCA perspective, Attributional (ALCA) and Consequential (CLCA) assessments respond to different questions. Attributional

approaches estimate the proportional share of global impacts attributable to the product being assessed and utilises average data within the specified system, while consequential study focuses on the changes implied by the use of analysed function [166], for example, the production of bioderived lignin-based carbon fibre (LCF) would entail a decrease in the demand of polyacrylonitrile (PAN)-based CFs, and thus it requires the use of marginal data [19]. While it is apparent that a large part of the reviewed studies employed an attributional perspective [114, 134], majority of the studies did not specify the assessment perspective. The common application of ALCA approach may be linked with its straightforwardness and access to average data for the system being assessed, whereas employing a consequential perspective requires data outside of the system which may be subject to large set of assumptions. Nevertheless, with the available data, practitioners are encouraged to prioritise CLCA as it is considered more accurate [166].

4.1.2. Multifunctionality

The case of multifunctionality arises when a unit process is yielding more than one functional flow including co-products, by-products, waste etc. simultaneously within the same time-frame. This means that the environmental burden should not only be assigned to the main product, but accordingly distributed among all relevant products. Approaches for handling multifunctionality can be broadly grouped into Allocation based on physical (e.g., mass, energy) or non-physical (e.g., economic) relationships and Avoidance of allocation through system boundary expansion, substitution or subdivision [37,39,167,168]. 14 out of the 32 studies indicated the use of allocation principles in their studies [35,108,112,116,118,133,136,137,146,147,169,170]. Meanwhile, only 10 of these studies clearly described the approach employed in managing the allocation within the assessments, and 4 of the 12 studies vaguely addressed the issue of allocation, while the remaining studies did not state any approach utilised in managing allocation issues (Fig. 8). These disparities further increase the complexity in transparent comparison and useful conclusions. Economic allocation was more utilised among the 14 studies while some of the studies used a combined allocation approach (economic and mass) to solve multifunctionality issues within the assessment [146,147,169]. While economic allocation is considered a fairer approach, it is often difficult with emerging technologies at laboratory scale mainly due to limitation in economic data for the various products. However, the use of mass allocation could sometimes lead to unfair attribution of burden, for example, Kulas et al., [146] encountered a large difference in attributing environmental burden to activated carbon using mass vs economic allocation for a multifunctional system producing carbon fibre, polyurethane, and activated carbon from waste lignin. For all the three products, the

relative mass of lignin derived AC was much greater than its value within the process. Similarly, in CNFs production, lignin as a co-product in the delignification stage constitute about 44 % mass of the output from that unit [133], attributing environmental burden to lignin would significantly influence the net impact of the final product CNF since 56 % of the specific burden associated with delignification will be attributed to holocellulose instead of 100 % when lignin is considered as waste material (often combusted for process energy).

4.1.3. Data and Uncertainty

While early assessments provide the greatest opportunity to influence design and ultimately environmental performance, it is the stage with the least available data, greatest uncertainty, and a paucity of analytical tools for addressing these challenges. Given the technological readiness level of the processes assessed in the reviewed studies, data availability, quality and reliability issues arise since the studies can be described as prospective in nature. This means that a large part of the data comes from the literature, laboratory experiments, numerous assumptions/projections and usage of multiple data sources[171], resulting in limitations of the outcome and increases variations among studies. The relative magnitudes of uncertainties associated with technology and market maturation and subsequent changes was illustrated by Bergerson et al.,[172], in which low TRL processes aiming for emerging markets were characterised with the largest uncertainties among the four different cases, meanwhile greater uncertainty lies in the technology related activities for the same technology aiming for mature markets [172]. The latter then competes with existing technology in terms of environmental performance, technical and economic viability and ideally social implications. In recent years, efforts have been made in proposing methods for conducting prospective assessments[171,172], the importance of understanding both the level of technology maturity and the level of the market to which the technology will be deployed are critical in defining factors of the emerging technology assessments. Uncertainty may arise from input data for the assessment (parameter uncertainty), as a result of normative choices (scenario uncertainty), and uncertainty associated with mathematical relationships (model uncertainty) [163,173]. Data limitations, variability and knowledge of the entire system considered most relevant in parameter uncertainty. In dealing with this, depending on the source, assigning a variability to the input, and then propagating it through all calculations to evaluate its effect on the outputs is a common approach. If the uncertainty comes from the stochastic nature of the system, a common approach is to assign a probabilistic distribution of the initial parameters. Sensitivity analysis can also be incorporated to test the influence of input parameters on the results. A recent study by Baaqel et al., [174] proposed a new method of

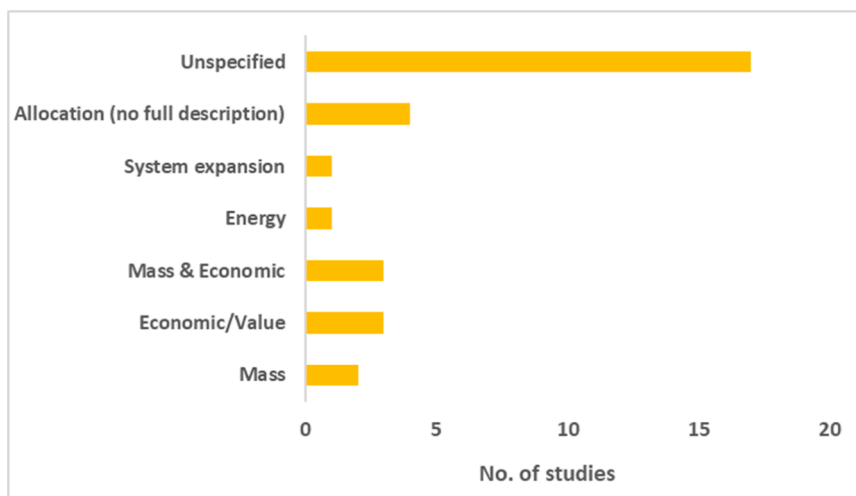


Fig. 8. The use of allocation principles among reviewed studies on nanocelluloses and carbon materials.

handling uncertainty in LCA in the context of emerging technologies, where authors suggested calculation of uncertainty in both foreground and background data by using a set of lumped background parameters linked to immediate upstream and downstream processes in a sensitivity analysis. Scenario uncertainty [114,134,170,175] and sensitivity analysis [35,137] was common among the works reviewed, this may be related to its usefulness for purposes beyond the study of uncertainty, for example, in the comparison of different operating configurations or the location of a production plant [19]. More so, it helps in predicting the range of possible outcomes which is welcome in the case of emerging technologies. Some of the studies assessed the parametric uncertainty [140,141] as data uncertainties are prevalent in the assessment of novel and emerging technologies. While assessing the sustainability of technology at industrial scales by extrapolating the laboratory data is characterised by high uncertainty, some of the studies [114,133,136] did not investigate the related uncertainties within such types of assessment, although Piccinno et al., [136] highlighted the absence of enough data for uncertainty due to single data source (laboratory experiments) and low number of experimental runs, and also argued that the absolute results would deviate more due to the scale of production chosen than to the uncertainty of the measurements. Hence, the study used scenario analysis to address variability related feed material handling. Even so, only the measurement of data quality and uncertainty can improve the robustness of the analysis. Despite the high uncertainty of laboratory data, implementing LCA studies in the early stages can assist in identifying hotspots which can facilitate future scale-up. However, laboratory scale assessment is often characterised with larger environmental impacts compared with similar technology at industrial scale [133,160]. Scale up of laboratory process where data is available while utilising appropriate techniques would facilitate more accurate estimation of the industrial LCA impacts. An integrative approach is one of the most promising ways to reduce the uncertainty and methodological issues associated with sustainability assessments related to new and emerging technologies. Coupling assessment studies with process design, for generating scenarios and the iterative optimisation of the new technological developments from an environmental perspective would partially address the mentioned issues [176–178].

4.1.4. Impact Assessment methodology

Life cycle sustainability assessment outcomes is hugely influenced by the assessment methods employed. Impact assessment methodologies constitute different scientific models that can be used to translate the life cycle inventory amounts into environmental impacts using characterisation factors. The impact assessment phase is associated with disparities across studies resulting from differences in the models, impact categories considered, and the indicators used in communicating the results. Several factors such as considerations used to model the cause-effect-chain, the substances consider in the pathway, and other modelling consideration differ across these assessment methodologies. For example, in the case of human toxicity, the CML2001 score is dominated by contribution from metals while the EDIP97 score is influenced by solvents and nitrogen oxides. Meanwhile, metals are also the main contributors for aquatic ecotoxicity in both methods but while it is vanadium for CML2001, it is strontium for EDIP97, resulting in considerable differences in the results even after normalisation [179]. Therefore, assessment methods should be chosen based on their relevance to the products or processes under consideration, even so, developments of guidelines for different product classification (e.g., PEF approach [180]) is strongly required to support uniformity among assessments. Studies analysing nanocelluloses and carbon materials employed a variety of methods, even within the same studies. The distribution of the methods employed in the reviewed studies is shown in Fig. 9. ReCiPe midpoint (H) [181] is the most utilised among the studies; it is considered a default assessment methodology that covers a broad range of impact categories relevant across many technologies. Very few studies reported the endpoint indicators (damage-oriented approaches) [136] which relate to issues of concern including Human health and natural resources. The utilisation level of CML [182], and TRACI [183] was similar across the studies, meanwhile, only two studies employed the Product environmental footprint (PEF) [180] method.

The global warming potential (GWP) which is the main indicator for climate change effects was the most reported category and available in almost all the impact assessments methods, implying greater divergencies in models used for its calculations. The method developed by The Intergovernmental Panel on Climate Change (IPCC) was largely employed among the studies, even studies combining economic and

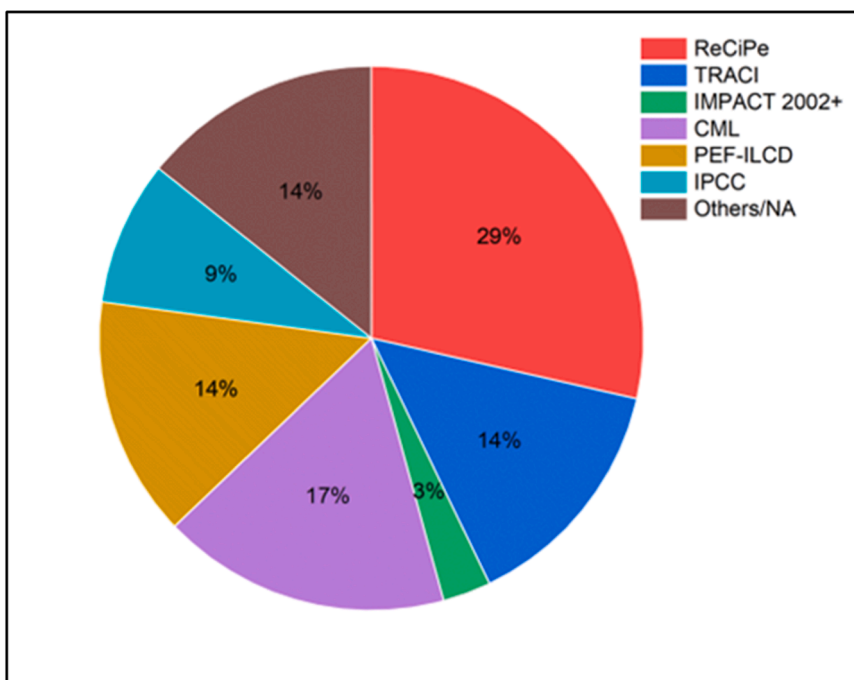


Fig. 9. Common LCIA methods used in sustainability assessments of Nanocelluloses and Carbon materials.

environmental performance mainly focus on GWP [140,146] and to some extent energy related indicators [35], while some of the studies presented a range of other impact categories [108,118]. Other studies combined various relevant methods according to the need of the assessment [112,133,134]. The assumptions necessary for the application of any methodology require an in-depth knowledge of both the protocol to be used and the process itself. Providing clear information related to the scenarios used for emissions flow should also be incorporated in assessments. It is important to develop a unified approach/-guidelines for impact assessment related to emerging biobased advanced materials, which should ideally embed considerations for the main product categories being investigated across research domains.

While it is difficult to draw realistic conclusions based on existing studies, some of the common methodological issues and system related issues across the studies of bioderived functional materials include i) resource use mainly acid utilisation and recovery approaches, ii) credit/burden allocation, carbon, iii) the effects of land use as an important resource indicator for bioderived products not fully captured, more so, biodiversity related issues, iv) limited process data, and lack of data related to toxicity of nanomaterials (knowledge on interaction of these materials with the environment is required), iv) clarity on projected performance in target markets for these materials.

4.2. Future perspective

Societies have increasingly focused on economic and climate change concerns, prioritising the reduction of energy-intensive processes, and the advancement of low-carbon materials has gained significant importance. Thus, research and development efforts are ongoing to explore the full potential of bioderived advanced materials such as nanocelluloses and carbon materials for high-value applications, and to scale up production for commercialisation. Sustainability assessment is the best and most promising way to measure the performance of new alternative materials against existing ones, at the same time, support the selection and process optimisation of most sustainable pathways. Addressing the three dimensions of sustainability considering all the three elements including social, economic and environmental concerns fully aligns with the ISO14040 standard, it requires building interconnectedness among these pillars and addressing trade-offs [45].

Due to the developing nature of LCSA and differences in maturity of sustainability assessment tools, research in the area of bioderived advanced materials is focused on development and improvement of assessment frameworks. Existing studies investigating the sustainability of these products indicate a significant gap in holistic assessments, lacking the elements of the three dimensions. The results of the individual assessments are presented separately without a broader discussion of inter-relationships between environmental, economic, and social aspects. None of the reviewed studies on nanocelluloses and carbon materials applied the three aspects of sustainability (3.2.3), more so, the low TRL of the assessed technologies presents limited data for complete assessments. In this case, a multilevel approach of assessment could be utilised where assessments are focused on different phases of the product development, while adopting an integrated approach to ensure appropriate components of the product system are incorporated and relevant indicators are used to inform decisions. Furthermore, application of tools such as the multicriteria decision analysis (MCDA) to complex sustainability problems to support integrated LCSA results interpretation and decision-making, has been broadly discussed in the scientific literature [184,185]. It is worth noting that no single tool is enough to cover all aspects of sustainability as the different tools constitute conflicting perspectives [186], highlighting the necessity for establishing a more uniform assessment approaches that would facilitate identification of most promising and sustainable pathways for commercialisation.

It is worth noting that the review methodology utilised in this paper maybe associated with some level of uncertainty due to the separate

search streams utilised, further the bibliometric analysis could also be improved by adopting advanced techniques to improve conciseness of the observation.

5. Conclusions

This study has presented developments and some of the bottlenecks in life cycle sustainability assessments of higher-value bioderived products with a focus on advanced materials including CNCs, CNFs, LCF and HCs, and suggestions to direct future research is highlighted. The production of CNCs from Kraft and dissolving pulp via sulfuric or citric acid hydrolysis is common among existing studies. For the sulfuric acid route, major GWP contribution comes from end-of-life management of sulfuric acid either via recycling or neutralisation with sodium hydroxide. Most of the studies related to CNFs, utilised Kraft, dissolving and sulfite pulp for production. While TEMPO oxidation followed by mechanical treatment (homogenisation or sonication) is the most widely used method for CNF production, enzymatic hydrolysis presents lower GWP (kgCO₂-eq) compared with the TEMPO route as a result of less chemical use. For LCF, the lignin recovery pathway and choice of solvent indicate strong influence on the environmental and economic impacts. Advance lignin recovery technologies such as the ligno-boost combined with low carbon renewable energy sources highlights potential savings on environmental impacts, however, development of low-cost sustainable solvents should be prioritised. Another potential hotspot within the LCF value chain is the fabrication technique which is dependent on the type of fibre and potential applications. Existing studies have demonstrated the potential of HTC in the production of HCs for anode materials in batteries, however, comprehensive optimisation of the carbon yield, electrochemical performance, feed biomass and choice of energy source is essential for further assessments and development of the HTC technology.

Compared with nanocelluloses and carbon materials, biochemicals and bioplastics have received wider coverage, even so, the existing information on their sustainability profile does not support robust decision as a result of wide variations in outcome of assessments.

A holistic approach in the assessment of bioderived advanced materials by addressing the three pillars of sustainability is currently scarce; the few studies that incorporated social aspects are focused on methodological development relating to S-LCA tool. A large part of the reviewed studies used the GWP indicator which shows potential reduction in environmental impact of these materials compared with their fossil counterparts. However, the issues of toxicity, land use and trade-offs are needing further attention. Biomass feed variability, availability and additional processing energy cost remains a challenge in sustainable production of bioderived advanced materials from biomass.

The adoption of a whole system approach to support science-based decisions in moving to green materials is imperative. Transition to green materials requires a robust multilevel assessment approach and continuous review of proposed options. Significant challenges observed with methods harmonisation and integration could be addressed through development of uniform integrated methodologies/guidelines for assessments.

CRedit authorship contribution statement

Nilay Shah: Writing – review & editing, Visualization, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Maria-Magdalena Titirici:** Writing – review & editing, Visualization, Validation, Resources, Investigation, Funding acquisition, Conceptualization. **Polina Yaseneva:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rukayya Ibrahim Muazu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known conflicts of interests related to this work. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Acknowledgement

The authors would like to acknowledge the financial support from the Engineering and Physical Sciences Research Council (EPSRC) UK, project grant: EP/W031019/1.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.jece.2024.114387](https://doi.org/10.1016/j.jece.2024.114387).

Data Availability

Data used in this study is provided in the supplementary section

References

- [1] L.M. Remy, "To reduce CO2 emissions, the materials industry needs to transition to a circular economy", Ellen MacArthur Foundation. Accessed: Jun. 09, 2023. [Online]. Available: <https://medium.com/circulatenews/to-reduce-co2-emissions-the-materials-industry-needs-to-transition-to-a-circular-economy-520d83620283#>.
- [2] E.V. Bhavya, S.S. Thakur, B. Choudhury, Advanced Materials for Aerospace Applications. in *Materials Horizons: From Nature to Nanomaterials*, Springer Nature, 2020, pp. 39–65, https://doi.org/10.1007/978-981-15-2267-3_3.
- [3] H. Affan, W. Arai, J. Arayro, Mechanical and thermal characterization of bio-sourced mortars made from agricultural and industrial by-products, *Case Stud. Constr. Mater.* vol. 18 (2023), <https://doi.org/10.1016/j.cscm.2023.e01939>.
- [4] C. Liu, F. Li, M. Lai-Peng, H.-M. Cheng, Advanced materials for energy storage, *Adv. Mater.* vol. 22 (8) (2010), <https://doi.org/10.1002/adma.200903328>.
- [5] C. Liu, F. Li, M. Lai-Peng, H.M. Cheng, Advanced Materials for Energy Storage, *Adv. Mater.* vol. 22 (8) (Feb. 2010) E28–E62, <https://doi.org/10.1002/ADMA.200903328>.
- [6] M. Pourmadadi, et al., Novel carboxymethyl cellulose based nanocomposite: A promising biomaterial for biomedical applications, *Process Biochem.* vol. 130 (2023) 211–226, <https://doi.org/10.1016/j.procbio.2023.03.033>.
- [7] R.F. Beims, et al., Functionalized wood as bio-based advanced materials: Properties, applications, and challenges, Elsevier Ltd, Apr. 01, 2022, <https://doi.org/10.1016/j.rser.2022.112074>.
- [8] M. Thakur, M. Chandel, A. Kumar, S. Kumari, P. Kumar, D. Pathania, The development of carbohydrate polymer- and protein-based biomaterials and their role in environmental health and hygiene: A review, Elsevier B.V., Jul. 01, 2023, <https://doi.org/10.1016/j.ijbiomac.2023.124875>.
- [9] M.S. Kang, E. Cho, H.E. Choi, C. Amri, J.-H. Lee, K.S. Kim, Molecularly imprinted polymers (MIPs): emerging biomaterials for cancer theragnostic applications, *Biomater. Res.* vol. 27 (1) (2023), <https://doi.org/10.1186/s40824-023-00388-5>.
- [10] R. Floriano, K. Edalati, K.D. Pereira, A.D. Luchessi, Titanium-protein nanocomposites as new biomaterials produced by high-pressure torsion, *Sci. Rep.* vol. 13 (1) (2023), <https://doi.org/10.1038/s41598-022-26716-8>.
- [11] B. Zhang, et al., Advancing collagen-based biomaterials for oral and craniofacial tissue regeneration, *Collagen Leather* vol. 5 (1) (2023), <https://doi.org/10.1186/s42825-023-00120-y>.
- [12] S. Akhlaghi, M. Ebrahimnia, D.S. Niaki, M. Solhi, S. Rabbani, A. Haeri, Recent advances in the preventative strategies for postoperative adhesions using biomaterial-based membranes and micro/nano-drug delivery systems, *J. Drug Deliv. Sci. Technol.* vol. 85 (2023), <https://doi.org/10.1016/j.jddst.2023.104539>.
- [13] D. Antypa, et al., Life cycle assessment of advanced building materials towards NZEBs. in *E3S Web of Conferences*, EDP Sciences, M, ay 2022, <https://doi.org/10.1051/e3sconf/202234904001>.
- [14] I.F. Myronyuk, V.I. Mandzyuk, V.M. Sachko, V.M. Gunko, Structural Features of Carbons Produced Using Glucose, Lactose, and Saccharose, *Nanoscale Res Lett.* vol. 11 (1) (Dec. 2016), <https://doi.org/10.1186/s11671-016-1723-z>.
- [15] FAO, Sustainable and circular bioeconomy in the climate agenda: Opportunities to transform agrifood systems, FAO, 2022, <https://doi.org/10.4060/cc2668en>.
- [16] EU - European Commission, Bio-based products - EU, Internal Market, Industry, Entrepreneurship and SMEs. Accessed: Jul. 26, 2023. [Online]. Available: https://single-market-economy.ec.europa.eu/sectors/biotechnology/bio-based-products_en#:~:text=Bio%2Dbased%20products%20are%20wholly,and%20paper%2C%20textiles%2C%20etc.
- [17] S.H. Mousavi-Avval, K. Sahoo, P. Nepal, T. Runge, R. Bergman, Environmental impacts and techno-economic assessments of biobased products: a review, Elsevier Ltd, Jul. 01, 2023, <https://doi.org/10.1016/j.rser.2023.113302>.
- [18] USDA - United States Department of Agriculture, BioPreferred ® Program, 2021. [Online]. Available: (www.biopreferred.gov/).
- [19] J. Blanco-Cejas, S. Martín, M. Linares, J. Iglesias, J. Moreno, Life cycle assessment applied to bio-based platform molecules: critical review of methodological practices, *J. Clean. Prod.* vol. 414 (Aug. 2023) 137513, <https://doi.org/10.1016/J.JCLEPRO.2023.137513>.
- [20] WBCSD World Business Council for Sustainable Development, Circular bioeconomy: The business opportunity contributing to a sustainable world, 2020.
- [21] J. Sadhukhan, K.S. Ng, E.M. Hernandez, Introduction. in *Biorefineries and Chemical Processes*, Wiley, 2014, pp. 1–41, <https://doi.org/10.1002/9781118698129.ch1>.
- [22] S. Seuring, M.M. Ller, From a literature review to a conceptual framework for sustainable supply chain management, *Clean. Prod.* (2008) 1699–1710, <https://doi.org/10.1016/j.jclepro.2008.04.020>.
- [23] S. Abdul, et al., A state-of-the-art review and meta-analysis on sustainable supply chain management: Future research directions, State—Art. Meta-Anal. Sustain. Supply chain Manag. Syst. Rev. Sustain. Supply chain Triple Bottom line, *Clean. Prod.* (2020) 123–357, <https://doi.org/10.1016/j.jclepro.2020.123357>.
- [24] J. Sadhukhan, K.S. Ng, E.M. Hernandez, Introduction, in *Biorefineries and Chemical Processes*, John Wiley & Sons, Ltd, 2014, pp. 1–41, <https://doi.org/10.1002/9781118698129.ch1>.
- [25] M. Amer and A. Elwardany, Biomass Carbonization, *Renewable Energy - Resources, Challenges and Applications*, 2020.
- [26] H.B. Goyal, D. Seal, and R.C. Saxena, Bio-fuels from thermochemical conversion of renewable resources: A review, Feb. 2008. doi: 10.1016/j.rser.2006.07.014.
- [27] M. Chen, et al., Design of a combined ionosolv-organosolv biomass fractionation process for biofuel production and high value-added lignin valorisation †, *Green. Chem.* vol. 22 (2020) <https://doi.org/10.1039/d0gc01143f>.
- [28] J. Blanco-Cejas, S. Martín, M. Linares, J. Iglesias, J. Moreno, M.T. Moreira, Life cycle assessment applied to bio-based platform molecules: Critical review of methodological practices, *J. Clean. Prod.* vol. 414 (2023) 137513, <https://doi.org/10.1016/j.jclepro.2023.137513>.
- [29] S. Gadkari, et al., RSC Advances Microbial electrosynthesis: is it sustainable for bioproduction of acetic acid ? †, *R. Soc. Chem. (RSC Adv.)* (2021) 9921–9932, <https://doi.org/10.1039/d1ra00920f>.
- [30] S.M. Venkata, et al., Biomass, Biofuel, Biochemicals: Microbial Electrochemical Technology, Elsevier B.V., 2019.
- [31] M. Sajid, X. Zhao, D. Liu, Production of 2,5-furandicarboxylic acid (FDCA) from 5-hydroxymethylfurfural (HMF): Recent progress focusing on the chemical-catalytic routes, *Green. Chem.* vol. 20 (24) (2018) 5427–5453, <https://doi.org/10.1039/c8gc02680g>.
- [32] M. Gausmann, C. Kocks, M. Doeker, A. Eggert, T. Maßmann, A. Jupke, Recovery of succinic acid by integrated multi-phase electrochemical pH-shift extraction and crystallization, *Sep Purif. Technol.* vol. 240 (Jun. 2020) 1164–1189, <https://doi.org/10.1016/j.seppur.2019.116489>.
- [33] I. Tsiropoulos, A.P.C. Faaij, L. Lundquist, U. Schenker, J.F. Briois, M.K. Patel, Life cycle impact assessment of bio-based plastics from sugarcane ethanol, *J. Clean. Prod.* vol. 90 (Mar. 2015) 114–127, <https://doi.org/10.1016/j.jclepro.2014.11.071>.
- [34] S. Walker, R. Rothman, Life cycle assessment of bio-based and fossil-based plastic: A review, *J. Clean. Prod.* vol. 261 (Jul. 2020) 121158, <https://doi.org/10.1016/j.jclepro.2020.121158>.
- [35] T.J. Bondancia, et al., Cellulose nanocrystals from sugar cane bagasse using organic and/or inorganic acids: techno-economic analysis and life cycle assessment, *ACS Sustain Chem. Eng.* vol. 10 (14) (Apr. 2022) 4660–4676, <https://doi.org/10.1021/acssuschemeng.2c00061>.
- [36] A. Liu et al., Cellulose nanocrystalline from biomass wastes: An overview of extraction, functionalization and applications in drug delivery, Jun. 30, 2023, Elsevier B.V. doi: 10.1016/j.ijbiomac.2023.124557.
- [37] European Union, International Reference Life Cycle Data System (ILCD) handbook: Framework and Requirements for Life Cycle Impact Assessment Models and Indicators. 2010. doi: 10.2788/38719.
- [38] G. Finnveden and A. Morberg, Finnveden and Moberg 2005 _ Environmental Impact Assessment _ Life Cycle Assessment, *Cleaner Prod.*, vol. 13, pp. 1165–1173, 2005.
- [39] ISO 14044:2006, 'ISO 14044:2006 Environmental management - Life Cycle Assessment, 2006.
- [40] I.G. Hakeem, et al., Techno-economic analysis of biochemical conversion of biomass to biofuels and platform chemicals, *Biofuels*, Bioprod. Bioref. vol. 17 (3) (May 2023) 718–750, <https://doi.org/10.1002/BBB.2463>.
- [41] Ö. Ögmundarson, S. Sukumara, M.J. Herrgård, P. Fantke, Combining environmental and economic perspective for bioprocess optimization, *Trend Biotech.* vol. 38 (2020) 1203–1214, <https://doi.org/10.1016/j.tibtech.2020.04.011>.
- [42] UNEP (United Nations Environment Programme), Guidelines for Social Life Cycle Assessment of Products and Organisations, 2020.
- [43] B. Weidema, ISO 14044 also applies to social LCA, Nov. 2005. doi: 10.1065/lca2005.11.002.
- [44] A. Jørgensen, A. Le Bocq, L. Nazarkina, and M. Hauschild, Methodologies for social life cycle assessment, Mar. 2008. doi: 10.1065/lca2007.11.367.
- [45] S. Valdivia, et al., Principles for the application of life cycle sustainability assessment, *Int J. Life Cycle Assess.* vol. 26 (9) (2021) 1900–1905, <https://doi.org/10.1007/s11367-021-01958-z>.

- [46] UNEP, Towards A Life Cycle Sustainability Assessment: Making informed choices on products, 2011.
- [47] Z. Barahmand, M.S. Eikeland, Techno-Economic and Life Cycle Cost Analysis through the Lens of Uncertainty: A Scoping Review, *MDPI* (Oct. 01, 2022), <https://doi.org/10.3390/su141912191>.
- [48] R. Mahmud, S.M. Moni, K. High, M. Carbajales-Dale, Integration of techno-economic analysis and life cycle assessment for sustainable process design – A review, *J. Clean. Prod.* vol. 317 (Oct. 2021) 128247, <https://doi.org/10.1016/j.jclepro.2021.128247>.
- [49] H. Liu, et al., Life cycle assessment of bio-based hard carbon for sodium-ion batteries across different production scales, *Chem. Eng. J.* vol. 495 (Sep. 2024), <https://doi.org/10.1016/j.cej.2024.153410>.
- [50] S. Kane, S.A. Miller, K.E. Kurtis, J.P. Youngblood, E.N. Landis, W.J. Weiss, Harmonized life-cycle inventories of nanocellulose and its application in composites, *Am. Chem. Soc.* (Dec. 05, 2023), <https://doi.org/10.1021/acs.est.3c04814>.
- [51] M.J. Page, et al., The PRISMA 2020 statement: An updated guideline for reporting systematic reviews, *BMJ Publishing Group*, Mar. 29, 2021, <https://doi.org/10.1136/bmj.n71>.
- [52] L. Pollok, S. Spierling, H.J. Endres, U. Grote, Social life cycle assessments: A review on past development, advances and methodological challenges, *MDPI* (Sep. 01, 2021), <https://doi.org/10.3390/su131810286>.
- [53] S.J. Eichhorn et al., Review: Current international research into cellulose nanofibers and nanocomposites, *Jan. 2010*. doi: 10.1007/s10853-009-3874-0.
- [54] A. Lourenço, J. Gominho, Lignin as feedstock for nanoparticles production, in *Lignin*, in: A. Sand, J. Tuteja (Eds.), Ch. 7, IntechOpen, Rijeka, 2023, <https://doi.org/10.5772/intechopen.109267>.
- [55] N. Leroy-Parmentier, S. Valdivia, P. Loubet, G. Sonnemann, Alignment of the life cycle initiatives “principles for the application of life cycle sustainability assessment” with the LCSA practice: a case study review, *Int. J. Life Cycle Assess.* 2023 28:6 vol. 28 (6) (May 2023) 704–740, <https://doi.org/10.1007/s11367-023-02162-0>.
- [56] N. Escobar, N. Laibach, Sustainability check for bio-based technologies: a review of process-based and life cycle approaches, *Renew. Sustain. Energy Rev.* vol. 135 (Jan. 2021) 1102–1113, <https://doi.org/10.1016/j.rser.2020.110213>.
- [57] L. Ladu, P.P. Morone, Holistic approach in the evaluation of the sustainability of bio-based products: An Integrated Assessment Tool, *Sustain. Prod. Consum.* vol. 28 (Oct. 2021) 911–924e6, <https://doi.org/10.1016/j.spc.2021.07.006>.
- [58] S. Nessi et al., Life Cycle Assessment (LCA) of alternative feedstocks for plastics production, *European Commission Joint Research Council (JRC)*, 2021, Accessed: Nov. 14, 2023. [Online]. Available: <https://doi.org/doi/10.2760/271095>.
- [59] P. Milani, D. França, A.G. Balleiro, R. Faez, Polymers and its applications in agriculture, *Pol. ímeros* vol. 27 (3) (2017) 256–266, <https://doi.org/10.1590/0104-1428.09316>.
- [60] J.H. Miah, S.C.L. Koh, D. Stone, A hybridised framework combining integrated methods for environmental Life Cycle Assessment and Life Cycle Costing, *J. Clean. Prod.* vol. 168 (2017) 846–866, <https://doi.org/10.1016/j.jclepro.2017.08.187>.
- [61] Q. Yu, H. Zhixian, Y. Zhiguo, Integrated assessment of environmental and economic performance of chemical products using analytic hierarchy process approach, *Chin. J. Chem. Eng.* vol. 15 (1) (Feb. 2007) 81–87, [https://doi.org/10.1016/S1004-9541\(07\)60037-8](https://doi.org/10.1016/S1004-9541(07)60037-8).
- [62] M. Fröhling and M. Hiete, Sustainability and Life Cycle Assessment in Industrial Biotechnology. 2020. [Online]. Available: <http://www.springer.com/series/10>.
- [63] S. Meramo, P. Fantke, S. Sukumara, Advances and opportunities in integrating economic and environmental performance of renewable products, *BioMed. Cent. Ltd* (Dec. 01, 2022), <https://doi.org/10.1186/s13068-022-02239-2>.
- [64] R. Mahmud, S.M. Moni, K. High, M. Carbajales-Dale, Integration of techno-economic analysis and life cycle assessment for sustainable process design – A review, Elsevier Ltd, Oct. 01, 2021, <https://doi.org/10.1016/j.jclepro.2021.128247>.
- [65] S. Meramo, P. Fantke, S. Sukumara, Advances and opportunities in integrating economic and environmental performance of renewable products, *Biotechnol. Biofuels Bioprod.* 2022 15:1 vol. 15 (1) (Dec. 2022) 1–18, <https://doi.org/10.1186/S13068-022-02239-2>.
- [66] M. Budzinski, M. Sisca, D. Thrän, Consequential LCA and LCC using linear programming: an illustrative example of biorefineries, *Int. J. Life Cycle Assess.* vol. 24 (12) (Dec. 2019) 2191–2205, <https://doi.org/10.1007/s11367-019-01650-6/TABLES/5>.
- [67] G. Thomassen, M. Van Dael, S. Van Passel, and F. You, How to assess the potential of emerging green technologies? Towards a prospective environmental and techno-economic assessment framework, 2019, *Royal Society of Chemistry*. doi: 10.1039/c9gc02223f.
- [68] A. Siebert, A. Bezama, S. Okeeffe, D. Thr, Social life cycle assessment indices and methodology to monitor the social implications of wood-based products, *Clean. Prod.* vol. 172 (2018) 4074–4084, <https://doi.org/10.1016/j.jclepro.2017.02.146>.
- [69] C. Reiting, M. Dumke, M. Barosevic, R. Hillerbrand, A conceptual framework for impact assessment within SLCA, *Int. J. Life Cycle Assess.* vol. 16 (4) (May 2011) 380–388, <https://doi.org/10.1007/s11367-011-0265-y>.
- [70] P.M. Falcone, E. Imbert, Social Life Cycle Approach as a Tool for Promoting the Market Uptake of Bio-Based Products from a Consumer Perspective, *Sustainability* vol. 10 (2018) 1031, <https://doi.org/10.3390/su10041031>.
- [71] R. Rebollo-Leiva, M.T. Moreira, S. González-García, Progress of social assessment in the framework of bioeconomy under a life cycle perspective, *Renew. Sustain. Energy Rev.* vol. 175 (Apr. 2023) 113162, <https://doi.org/10.1016/j.rser.2023.113162>.
- [72] I. D'Adamo, P.M. Falcone, E. Imbert, P. Morone, A Socio-economic Indicator for EoL Strategies for Bio-based Products, *Ecol. Econ.* vol. 178 (Dec. 2020) 106794, <https://doi.org/10.1016/j.ecolecon.2020.106794>.
- [73] M.G. Davidson, S. Elgie, S. Parsons, T.J. Young, Production of HMF, FDCA and their derived products: A review of life cycle assessment (LCA) and techno-economic analysis (TEA) studies, *Green. Chem.* vol. 23 (9) (May 2021) 3154–3171, <https://doi.org/10.1039/d1gc00721a>.
- [74] K. Dowaki, Y. Genchi, Life cycle inventory analysis on Bio-DME and/or Bio-MeOH products through BLUE tower process, *Int. J. Life Cycle Assess.* vol. 14 (7) (Nov. 2009) 611–620, <https://doi.org/10.1007/s11367-009-0092-6>.
- [75] P. Halder, K. Shah, Techno-economic analysis of ionic liquid pre-treatment integrated pyrolysis of biomass for co-production of furfural and levoglucosene, *Bioresour. Technol.* vol. 371 (Mar. 2023) 128597, <https://doi.org/10.1016/j.biortech.2023.128597>.
- [76] Y. Zhang, H. Yi Teah, F. Xu, T. Zhou, Z. Guo, L. Jiang, Selective saccharification of crude glycerol pretreated sugarcane bagasse via fast pyrolysis: Reaction kinetics and life cycle assessment, *Bioresour. Technol.* vol. 382 (Aug. 2023) 129166, <https://doi.org/10.1016/j.biortech.2023.129166>.
- [77] F.H. Isikgor, C.R. Becer, Lignocellulosic biomass: a sustainable platform for the production of bio-based chemicals and polymers, *Polym. Chem.* vol. 6 (25) (Jul. 2015) 4497–4559, <https://doi.org/10.1039/c5py00263j>.
- [78] I.G. Hakeem, et al., Techno-economic analysis of biochemical conversion of biomass to biofuels and platform chemicals, May 01, John Wiley and Sons Ltd, 2023, <https://doi.org/10.1002/bbb.2463>.
- [79] N. Ryan, P. Yaseneva, A critical review of life cycle assessment studies of woody biomass conversion to sugars, *Royal Society Publishing*, Sep. 20, 2021, <https://doi.org/10.1098/rsta.2020.0335>.
- [80] V. Thaore, D. Chadwick, N. Shah, Sustainable production of chemical intermediates for nylon manufacture: a techno-economic analysis for renewable production of caprolactone, *Chem. Eng. Res. Des.* vol. 135 (Jul. 2018) 140–152, <https://doi.org/10.1016/j.chemd.2018.05.026>.
- [81] C. Isola, et al., Life cycle assessment of photodegradable polymeric material derived from renewable bioresources, *J. Clean. Prod.* vol. 142 (2017) 2935–2944.
- [82] E. Stylianou, et al., Bioprocess development using organic biowaste and sustainability assessment of succinic acid production with engineered *Yarrowia lipolytica* strain, *Biochem. Eng. J.* vol. 174 (Oct. 2021) 1080–1099, <https://doi.org/10.1016/j.bej.2021.108099>.
- [83] H. Schöppe, P. Kleine-Möllhoff, R. Epple, Energy and material flows and carbon footprint assessment concerning the production of HMF and Furfural from a Cellulosic Biomass, *Processes* vol. 8 (1) (Jan. 2020) 119, <https://doi.org/10.3390/pr8010119>.
- [84] Y. Li, et al., Sustainable lactic acid production from lignocellulosic biomass, *ACS Sustain. Chem. Eng.* vol. 9 (3) (Jan. 2021) 1341–1351, <https://doi.org/10.1021/acscuschemeng.0c08055>.
- [85] L.R. Clausen, P. Elmgaard, N. Houbak, Technoeconomic analysis of a low CO2 emission dimethyl ether (DME) plant based on gasification of torrefied biomass, *Energy* vol. 35 (12) (2010) 4831–4842, <https://doi.org/10.1016/j.energy.2010.09.004>.
- [86] A. Shaji, Y. Shastri, V. Kumar, V.V. Ranade, N. Hindle, Economic and environmental assessment of succinic acid production from sugarcane bagasse, *ACS Sustain. Chem. Eng.* vol. 9 (38) (Sep. 2021) 12738–12746, <https://doi.org/10.1021/acscuschemeng.1c02483>.
- [87] Z. Lin, M. Ierapetritou, V. Nikolakis, Aromatics from lignocellulosic biomass: economic analysis of the production of p-Xylene from 5-hydroxymethylfurfural, *AIChE J.* vol. 59 (6) (Jun. 2013) 2079–2087, <https://doi.org/10.1002/aic.13969>.
- [88] H. Kim, J. Choi, J. Park, W. Won, Production of a sustainable and renewable biomass-derived monomer: conceptual process design and techno-economic analysis, *Green. Chem.* vol. 22 (20) (Oct. 2020) 7070–7079, <https://doi.org/10.1039/d0gc02258f>.
- [89] E. Cadena, F. Rocca, J.A. Gutierrez, A. Carvalho, Social life cycle assessment methodology for evaluating production process design: biorefinery case study, *Clean. Prod.* vol. 238 (2019) 117718, <https://doi.org/10.1016/j.jclepro.2019.117718>.
- [90] A. Souza, M.D.B. Watanabe, O. Cavalett, C.M.L. Ugaya, A. Bonomi, Social life cycle assessment of first and second-generation ethanol production technologies in Brazil, *Int. J. Life Cycle Assess.* vol. 23 (3) (Mar. 2018) 617–628, <https://doi.org/10.1007/s11367-016-1112-y>.
- [91] C. Valente, A. Brekke, I.S. Modahl, Testing environmental and social indicators for biorefineries: bioethanol and biochemical production, Springer Verlag, Mar. 01, 2018, <https://doi.org/10.1007/s11367-017-1331-x>.
- [92] D. Fürtner, L. Ranacher, E.A. Perdomo Echenique, P. Schwarzbauer, F. Hesser, Locating hotspots for the social life cycle assessment of bio-based products from short rotation coppice, *Bioenergy Res.* vol. 14 (2) (Jun. 2021) 510–533, <https://doi.org/10.1007/S12155-021-10261-9/TABLES/7>.
- [93] D. Costa, P. Quinteiro, V. Pereira, A.C. Dias, Social life cycle assessment based on input-output analysis of the Portuguese pulp and paper sector, *J. Clean. Prod.* vol. 330 (Jan. 2022) 129851, <https://doi.org/10.1016/J.JCLEPRO.2021.129851>.
- [94] S.A. Bassi, A. Boldrin, G. Frenna, T.F. Astrup, An environmental and economic assessment of bioplastic from urban biowaste, Ex. polyhydroxyalkanoate, *Bioresour. Technol.* vol. 327 (2021) 124813, <https://doi.org/10.1016/j.biortech.2021.124813>.
- [95] L. Dessbesell, Z. Yuan, S. Hamilton, M. Leitch, R. Pulkki, C.C. Xu, Bio-based polymers production in a kraft lignin biorefinery: techno-economic assessment,

- Biofuels, Bioprod. Bioref. vol. 12 (2) (Mar. 2018) 239–250, <https://doi.org/10.1002/bbb.1834>.
- [96] C.R. Álvarez-Chávez, S. Edwards, R. Moure-Eraso, K. Geiser, Sustainability of bio-based plastics: general comparative analysis and recommendations for improvement, *J. Clean. Prod.* vol. 23 (1) (Mar. 2012) 47–56, <https://doi.org/10.1016/j.jclepro.2011.10.003>.
- [97] R. Haylock, K.A. Rosentrater, Cradle-to-Grave Life Cycle Assessment and Techno-Economic Analysis of Polylactic Acid Composites with Traditional and Bio-Based Fillers, *J. Polym. Environ.* vol. 26 (4) (Apr. 2018) 1484–1503, <https://doi.org/10.1007/s10924-017-1041-2>.
- [98] Sebastian Spierling et al., Bio-based plastics - A review of environmental, social and economic impact assessments, *Cleaner Production*, 2018.
- [99] A. Lombardi, et al., Natural Active Ingredients for Poly (Lactic Acid)-Based Materials: State of the Art and Perspectives, MDPI, Oct. 01, 2022, <https://doi.org/10.3390/antiox11102074>.
- [100] S.S. Ali, et al., Bioplastic production in terms of life cycle assessment: A state-of-the-art review, *Environ. Sci. Ecotechnology* vol. 15 (Jul. 2023) 100254, <https://doi.org/10.1016/j.ese.2023.100254>.
- [101] M. Dieterle, J. Ginter, Life cycle (gap) analysis for advanced material recycling of PLA cups, in *Procedia CIRP*, Elsevier B.V., 2022, pp. 13–18, <https://doi.org/10.1016/j.procir.2022.02.003>.
- [102] E. Rueda, V. Senatore, T. Zarra, V. Naddeo, J. García, M. Garfi, Life cycle assessment and economic analysis of bioplastics production from cyanobacteria, *Sustain. Mater. Technol.* vol. 35 (Apr. 2023), <https://doi.org/10.1016/j.susmat.2023.e00579>.
- [103] K. Dhali, M. Ghasemlou, F. Daver, P. Cass, B. Adhikari, A review of nanocellulose as a new material towards environmental sustainability, *Sci. Total Environ.* vol. 775 (Jun. 2021) 145871, <https://doi.org/10.1016/j.scitotenv.2021.145871>.
- [104] J. Albarelli, A. Paidosh, D.T. Santos, F. Maréchal, M.A.A. Meireles, Environmental, energetic and economic evaluation of implementing a supercritical fluid-based Nanocellulose production process in a sugarcane biorefinery, *Chem. Eng. Trans.* vol. 47 (Mar. 2016) 49–54, <https://doi.org/10.3303/CET1647009>.
- [105] T.V. Patil, D.K. Patel, S.D. Dutta, K. Ganguly, T.S. Santra, K.T. Lim, Nanocellulose, a versatile platform: From the delivery of active molecules to tissue engineering applications, *Bioact. Mater.* vol. 9 (Mar. 2022) 566–589, <https://doi.org/10.1016/j.bioactmat.2021.07.006>.
- [106] P. Phanthong, P. Reubroycharoen, X. Hao, G. Xu, A. Abudula, G. Guan, Nanocellulose: Extraction and application, *Carbon Resour. Convers.* vol. 1 (2018) 32–43, <https://doi.org/10.1016/j.crccon.2018.05.004>.
- [107] K. Lan, et al., A modeling framework to identify environmentally greener and lower-cost pathways of nanomaterials, *Green. Chem.* vol. 26 (6) (Feb. 2024) 3466–3478, <https://doi.org/10.1039/D3GC04036D>.
- [108] N. Rajendran, T. Runge, R.D. Bergman, P. Nepal, C. Houtman, Techno-economic analysis and life cycle assessment of cellulose nanocrystals production from wood pulp, *Bioresour. Technol.* vol. 377 (2023) 960–9524, <https://doi.org/10.1016/j.biortech.2023.128955>.
- [109] Z. Hao, W.Y. Hamad, P. Yaseneva, Understanding the environmental impacts of large-scale cellulose nanocrystals production: Case studies in regions dependent on renewable and fossil fuel energy sources, *Chem. Eng. J.* vol. 478 (Dec. 2023) 147160, <https://doi.org/10.1016/j.cej.2023.147160>.
- [110] O. Rosales-Calderon, B. Pereira, V. Arantes, Economic assessment of the conversion of bleached eucalyptus Kraft pulp into cellulose nanocrystals in a stand-alone facility via acid and enzymatic hydrolysis, *Biofuels, Bioprod. Bioref.* vol. 15 (6) (Nov. 2021) 1775–1788, <https://doi.org/10.1002/bbb.2277>.
- [111] T.J. Bondancia, et al., Production of Nanocellulose Using Citric Acid in a Biorefinery Concept: Effect of the Hydrolysis Reaction Time and Techno-Economic Analysis, *Ind. Eng. Chem. Res.* vol. 59 (25) (Jun. 2020) 11505–11516, https://doi.org/10.1021/ACS.IECR.0C01359/SUPPL_FILE/IEO0C1359_SI_002.XLSX.
- [112] L. Tan et al., Combining ex-ante LCA and EHS screening to assist green design: A case study of cellulose nanocrystal foam, 2018, doi: 10.1016/j.jclepro.2017.12.243.
- [113] H. Gu, R. Reiner, R. Bergman, and A. Rudie, LCA study for pilot scale production of Cellulose Nano Crystals (CNC) from wood pulp', 2015.
- [114] S. Zargar, J. Jiang, F. Jiang, Q. Tu, Isolation of lignin-containing cellulose nanocrystals: life-cycle environmental impacts and opportunities for improvement, *Biofuels, Bioprod. Bioref.* vol. 16 (1) (Jan. 2022) 68–80, <https://doi.org/10.1002/bbb.2261>.
- [115] L. Zhang, et al., Greener production of cellulose nanocrystals: An optimised design and life cycle assessment, *J. Clean. Prod.* vol. 345 (Apr. 2022) 131073, <https://doi.org/10.1016/j.jclepro.2022.131073>.
- [116] M.-X. Ruiz-Caldas, et al., Citrated cellulose nanocrystals from post-consumer cotton textiles, *J. Mater. Chem. A Mater.* vol. 11 (13) (Feb. 2023) 6854–6868, <https://doi.org/10.1039/D2TA09456H>.
- [117] R.M. Leão, P. Câmara Miléo, J.M.L.L. Maia, S.M. Luz, Environmental and technical feasibility of cellulose nanocrystal manufacturing from sugarcane bagasse, *Carbohydr. Polym.* vol. 175 (2017) 518–529, <https://doi.org/10.1016/j.carbpol.2017.07.087>.
- [118] R. Katakajwala, S.V. Mohan, Multi-product biorefinery with sugarcane bagasse: Process development for nanocellulose, lignin and biohydrogen production and lifecycle analysis, *Chem. Eng. J.* vol. 446 (2022) 1385–8947, <https://doi.org/10.1016/j.cej.2022.137233>.
- [119] N. Rajendran, T. Runge, R.D. Bergman, P. Nepal, C. Houtman, Techno-economic analysis and life cycle assessment of cellulose nanocrystals production from wood pulp, *Bioresour. Technol.* vol. 377 (2023) 128955, <https://doi.org/10.1016/j.biortech.2023.128955>.
- [120] Z. Hao, W.Y. Hamad, P. Yaseneva, Understanding the environmental impacts of large-scale cellulose nanocrystals production: Case studies in regions dependent on renewable and fossil fuel energy sources, *Chem. Eng. J.* vol. 478 (Dec. 2023) 147160, <https://doi.org/10.1016/j.cej.2023.147160>.
- [121] O. Rosales-Calderon, B. Pereira, V. Arantes, Economic assessment of the conversion of bleached eucalyptus Kraft pulp into cellulose nanocrystals in a stand-alone facility via acid and enzymatic hydrolysis, *Biofuels, Bioprod. Bioref.* vol. 15 (6) (Nov. 2021) 1775–1788, <https://doi.org/10.1002/bbb.2277>.
- [122] T.J. Bondancia, et al., Production of Nanocellulose Using Citric Acid in a Biorefinery Concept: Effect of the Hydrolysis Reaction Time and Techno-Economic Analysis, *Ind. Eng. Chem. Res.* vol. 59 (25) (Jun. 2020) 11505–11516, <https://doi.org/10.1021/acs.iecr.0c01359>.
- [123] L. Tan et al., Combining ex-ante LCA and EHS screening to assist green design: A case study of cellulose nanocrystal foam, 2018, doi: 10.1016/j.jclepro.2017.12.243.
- [124] H. Gu, R. Reiner, R. Bergman, and A. Rudie, LCA study for pilot scale production of Cellulose Nano Crystals (CNC) from wood pulp, 2015.
- [125] K. Lan, et al., A modeling framework to identify environmentally greener and lower-cost pathways of nanomaterials, *Green. Chem.* vol. 26 (6) (2024) 3466–3478, <https://doi.org/10.1039/D3GC04036D>.
- [126] S. Zargar, J. Jiang, F. Jiang, Q. Tu, Isolation of lignin-containing cellulose nanocrystals: life-cycle environmental impacts and opportunities for improvement, *Biofuels, Bioprod. Bioref.* vol. 16 (1) (Jan. 2022) 68–80, <https://doi.org/10.1002/bbb.2261>.
- [127] C.A. de Assis, et al., Conversion Economics of Forest Biomaterials: Risk and Financial Analysis of CNC Manufacturing, *Biofuels, Bioprod. Bioref.* vol. 11 (4) (Jul. 2017) 682–700, <https://doi.org/10.1002/bbb.1782>.
- [128] L. Zhang, et al., Greener production of cellulose nanocrystals: An optimised design and life cycle assessment, *J. Clean. Prod.* vol. 345 (2022) 131073, <https://doi.org/10.1016/j.jclepro.2022.131073>.
- [129] R.M. Leão, P. Câmara Miléo, J.M.L.L. Maia, S.M. Luz, Environmental and technical feasibility of cellulose nanocrystal manufacturing from sugarcane bagasse, *Carbohydr. Polym.* vol. 175 (2017) 518–529, <https://doi.org/10.1016/j.carbpol.2017.07.087>.
- [130] T.J. Bondancia, et al., Cellulose Nanocrystals from Sugar Cane Bagasse Using Organic and/or Inorganic Acids: Techno-Economic Analysis and Life Cycle Assessment, *ACS Sustain. Chem. Eng.* vol. 10 (14) (Apr. 2022) 4660–4676, <https://doi.org/10.1021/acssuschemeng.2c00061>.
- [131] R. Katakajwala, S.V. Mohan, Multi-product biorefinery with sugarcane bagasse: Process development for nanocellulose, lignin and biohydrogen production and lifecycle analysis, *Chem. Eng. J.* vol. 446 (2022) 1385–8947, <https://doi.org/10.1016/j.cej.2022.137233>.
- [132] P. Gallo Stampino, L. Riva, G. Elegir, D. Bussini, G. Dotelli, Comparative Life Cycle Assessment of Cellulose Nanofibers Production Routes from Virgin and Recycled Raw Materials, *Molecules* vol. 26 (9) (Apr. 2021) 2558, <https://doi.org/10.3390/molecules26092558>.
- [133] J. Turk, P. Oven, I. Poljanšek, A. Lešek, F. Knez, K. Malovrh Rebec, Evaluation of an environmental profile comparison for nanocellulose production and supply chain by applying different life cycle assessment methods, *J. Clean. Prod.* vol. 247 (Feb. 2020) 119107, <https://doi.org/10.1016/j.jclepro.2019.119107>.
- [134] Q. Li, S. McGinnis, C. Sydnor, A. Wong, S. Renneckar, Nanocellulose Life Cycle Assessment, *ACS Sustain. Chem. Eng.* vol. 1 (8) (Aug. 2013) 919–928, <https://doi.org/10.1021/sc4000225>.
- [135] R. Arvidsson, D. Nguyen, M. Svanström, Life Cycle Assessment of Cellulose Nanofibrils Production by Mechanical Treatment and Two Different Pretreatment Processes, *Environ. Sci. Technol.* vol. 49 (11) (Jun. 2015) 6881–6890, <https://doi.org/10.1021/acs.est.5b00888>.
- [136] F. Piccinno, R. Hischer, S. Seeger, C. Som, Life cycle assessment of a new technology to extract, functionalize and orient cellulose nanofibers from food waste, *ACS Sustain. Chem. Eng.* vol. 3 (6) (Jun. 2015) 1047–1055, <https://doi.org/10.1021/ACSUSCHEMENG.5B00209>.
- [137] T. Krexner, et al., Environmental life cycle assessment of nano-cellulose and biogas production from manure, *J. Environ. Manag.* vol. 314 (Jul. 2022) 115093, <https://doi.org/10.1016/j.jenvman.2022.115093>.
- [138] C., O. M. B. D., S. P., P. T., L. H., K. J. and S. K., Hohenthal, Final assessment of nano enhanced new products, SUNPAP (Scale-up Nanoparticles in Modern Papermaking), Oct. 31, p.7th., 2012, Accessed: Apr. 21, 2024. [Online]. Available: https://scholar.google.com/scholar_lookup?title=Final+assessment+of+nano+enhanced+new+products&author=Hohenthal,+C.&author=Ovaskainen,+M.&author=Bussini,+D.&author=Sadocco,+P.&author=Pajula,+T.&author=Lehtinen,+H.&author=Kautto,+J.&author=Salmenkivi,+K.&publication_year=2012.
- [139] F. Foroughi, E. Rezvani Ghomi, F. Morshedi Dehaghi, R. Borayek, S. Ramakrishna, A Review on the Life Cycle Assessment of Cellulose: From Properties to the Potential of Making It a Low Carbon Material, *Materials* vol. 14 (4) (Feb. 2021) 714, <https://doi.org/10.3390/ma14040714>.
- [140] K.C. Teh, C.Y. Tan, I.M.L. Chew, Life cycle assessment on delignification and nanolignin synthesis pathways, *J. Environ. Chem. Eng.* vol. 9 (4) (Aug. 2021) 105381, <https://doi.org/10.1016/j.jece.2021.105381>.
- [141] D. Koch, M. Paul, S. Beisl, A. Friedl, B. Mihalyi, Life cycle assessment of a lignin nanoparticle biorefinery: Decision support for its process development, *J. Clean. Prod.* vol. 245 (Feb. 2020) 118760, <https://doi.org/10.1016/j.jclepro.2019.118760>.

- [142] V.D. Obasa, et al., A Review on Lignin-Based Carbon Fibres for Carbon Footprint Reduction, *Atmosphere (Basel)* vol. 13 (10) (Sep. 2022) 1605, <https://doi.org/10.3390/atmos13101605>.
- [143] A. Bengtsson, et al., Improved yield of carbon fibres from cellulose and kraft lignin, *Holzforchung* vol. 72 (12) (Dec. 2018) 1007–1016, <https://doi.org/10.1515/HF-2018-0028/MACHINEREADABLECITATION/RIS>.
- [144] Z. Lu, Review on the precursor preparation and carbon fiber manufacturing, *J. Phys.: Conf. Ser.*, IOP Publ. Ltd (Feb. 2021), <https://doi.org/10.1088/1742-6596/1798/1/012003>.
- [145] E. Tovar-Martinez, C.E. Sanchez-Rodriguez, J.D. Sanchez-Vasquez, M. Reyes-Reyes, R. López-Sandoval, Synthesis of carbon spheres from glucose using the hydrothermal carbonization method for the fabrication of EDLCs, *Diam. Relat. Mater.* vol. 136 (Jun. 2023) 110010, <https://doi.org/10.1016/j.DIAMOND.2023.110010>.
- [146] D.G. Kulas, M.C. Thies, D.R. Shonnard, Techno-Economic Analysis and Life Cycle Assessment of Waste Lignin Fractionation and Valorization Using the ALPHA Process, *ACS Sustain. Chem. Eng.* vol. 9 (15) (Apr. 2021) 5388–5395, <https://doi.org/10.1021/acssuschemeng.1c00267>.
- [147] M. Janssen, E. Gustafsson, L. Echaradt, J. Wallinder, J. Wolf, Life cycle assessment of lignin-based carbon fibres, *Mistra REES-Resour.-Eff. Effic. Solut. Based Circ. Econ. Think. View Proj.* (2019) [Online]. Available: <https://www.researchgate.net/publication/336553314>.
- [148] M. Xia, X. Zhang, Z. Xie, New Family of Hydrothermal Carbons with Super-High Surface Areas Derived from Nucleosides for Oxygen Reduction, *ACS Sustain. Chem. Eng.* vol. 10 (43) (Oct. 2022) 14330–14342, https://doi.org/10.1021/ACSSUSCHEMENG.2C04767/ASSET/IMAGES/LARGE/SC2C04767_0012.JPEG.
- [149] L. Yu, C. Falco, J. Weber, R.J. White, J.Y. Howe, M.M. Titirici, Carbohydrate-derived hydrothermal carbons: A thorough characterization study, *Langmuir* vol. 28 (33) (Aug. 2012) 12373–12383, <https://doi.org/10.1021/LA3024277>.
- [150] Y. Wang, et al., Biomass-Based Hydrothermal Carbons for the Contaminants Removal of Wastewater: A Mini-Review, *Mol. Sci.* (2023), <https://doi.org/10.3390/mjms24021769>.
- [151] M. Cossutta, V. Vretenar, T.A. Centeno, P. Kotrusz, J. McKechnie, S.J. Pickering, A comparative life cycle assessment of graphene and activated carbon in a supercapacitor application, *J. Clean. Prod.* vol. 242 (Jan. 2020), <https://doi.org/10.1016/j.jclepro.2019.118468>.
- [152] K.G. Roberts, B.A. Gloy, S. Joseph, N.R. Scott, J. Lehmann, Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential, *Environ. Sci. Technol.* vol. 44 (2) (Jan. 2010) 827–833, <https://doi.org/10.1021/es902266r>.
- [153] L. Lombardi, F. Tuci, M. Šlíz, K. Czerwińska, S. Fabrizi, M. Wilk, Life cycle assessment of the hydrothermal carbonization process applied to the wet fraction mechanically separated from municipal mixed waste, *Waste Manag.* vol. 166 (Jul. 2023) 181–193, <https://doi.org/10.1016/j.wasman.2023.04.043>.
- [154] F. Trotta, et al., A Comparative Techno-Economic and Lifecycle Analysis of Biomass-Derived Anode Materials for Lithium- and Sodium-Ion, *Batter., Adv. Sustain. Syst.* vol. 6 (6) (Jun. 2022), <https://doi.org/10.1002/ADSU.202200047>.
- [155] H. Moon, et al., Bio-Waste-Derived Hard Carbon Anodes Through a Sustainable and Cost-Effective Synthesis Process for Sodium-Ion Batteries, *ChemSusChem* vol. 16 (1) (Jan. 2023), <https://doi.org/10.1002/cssc.202201713>.
- [156] H. Liu, et al., A life cycle assessment of hard carbon anodes for sodium-ion batteries, *Philos. Trans. R. Soc. A: Math., Phys. Eng. Sci.* vol. 379 (2209) (Nov. 2021), <https://doi.org/10.1098/rsta.2020.0340>.
- [157] Z. Xu, et al., The Role of Hydrothermal Carbonization in Sustainable Sodium-Ion Battery Anodes, *Adv. Energy Mater.* vol. 12 (18) (May 2022), <https://doi.org/10.1002/aenm.202200208>.
- [158] S. Wickerts, R. Arvidsson, A. Nordelöf, M. Svanström, P. Johansson, Prospective life cycle assessment of sodium-ion batteries made from abundant elements, *J. Ind. Ecol.* vol. 28 (1) (Feb. 2024) 116–129, <https://doi.org/10.1111/JIEC.13452>.
- [159] J. Peters, D. Buchholz, S. Passerini, M. Weil, Life cycle assessment of sodium-ion batteries, *Energy Environ. Sci.* vol. 9 (5) (2016) 1744–1751, <https://doi.org/10.1039/C6EE00640J>.
- [160] H. Liu, et al., Life cycle assessment of bio-based hard carbon for sodium-ion batteries across different production scales, *Chem. Eng. J.* vol. 495 (Sep. 2024), <https://doi.org/10.1016/j.cej.2024.153410>.
- [161] S. Wickerts, R. Arvidsson, A. Nordelöf, M. Svanström, P. Johansson, Prospective life cycle assessment of sodium-ion batteries made from abundant elements, *J. Ind. Ecol.* vol. 28 (1) (Feb. 2024) 116–129, <https://doi.org/10.1111/jiec.13452>.
- [162] A. Li Borrión, M.C. McManus, and G.P. Hammond, Environmental life cycle assessment of lignocellulosic conversion to ethanol: A review, 2012, doi: 10.1016/j.rser.2012.04.016.
- [163] R.I. Muazu, A.L. Borrión, J.A. Stegemann, Life cycle assessment of biomass densification systems, *Biomass--Bioenergy* vol. 107 (Dec. 2017) 384–397, <https://doi.org/10.1016/j.biombioe.2017.10.026>.
- [164] M.J. Black, C. Whittaker, S.A. Hosseini, R. Diaz-Chavez, J. Woods, R.J. Murphy, Life Cycle Assessment and sustainability methodologies for assessing industrial crops, processes and end products, *Ind. Crops Prod.* vol. 34 (2011) 1332–1339, <https://doi.org/10.1016/j.indcrop.2010.12.002>.
- [165] O.M. Vanderfleet, E.D. Cranston, Production routes to tailor the performance of cellulose nanocrystals, *Nat. Res.* (Feb. 01, 2021), <https://doi.org/10.1038/s41578-020-00239-y>.
- [166] T. Ekvall, *Attributional and Consequential Life Cycle Assessment*, *IntechOpen, Sustain. Assess. 21st Century* (2019) doi: DOI: 10.5772/intechopen.89202.
- [167] European Union, *International Reference Life Cycle Data System (ILCD) handbook: Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment*. 2010. [Online]. Available: <https://ec.europa.eu/research/consultations/science-2.0/background.pdf>.
- [168] T. Ekvall, G. Finnveden, Allocation in ISO 14041-a critical review, *J. Clean. Prod.* vol. 9 (2001) 197–208. Accessed: Nov. 08, 2023. [Online]. Available: www.cleanerproduction.net.
- [169] D. Magalhães Do Nascimento, et al., A comprehensive approach for obtaining cellulose nanocrystal from coconut fiber. Part II: Environmental assessment of technological pathways, *Ind. Crops Prod.* vol. 93 (2016) 58–65, <https://doi.org/10.1016/j.indcrop.2016.02.063>.
- [170] M.C.B. de Figueirêdo, M. de, F. Rosa, C.M.L. Ugaya, M. de, S.M. de Souza Filho, A.C.C. da Silva Braid, L.F.L. de Melo, Life cycle assessment of cellulose nanowhiskers, *J. Clean. Prod.* vol. 35 (Nov. 2012) 130–139, <https://doi.org/10.1016/j.jclepro.2012.05.033>.
- [171] N. Thonemann, A. Schulte, D. Maga, How to conduct prospective life cycle assessment for emerging technologies? A systematic review and methodological guidance, *MDPI* (Feb. 01, 2020), <https://doi.org/10.3390/su12031192>.
- [172] J.A. Bergerson, et al., Life cycle assessment of emerging technologies: evaluation techniques at different stages of market and technical maturity, *J. Ind. Ecol.* vol. 24 (1) (Feb. 2020) 11–25, <https://doi.org/10.1111/jiec.12954>.
- [173] M.A.J. Huijbregts, W. Giljamse, A.M.J. Ragas, L. Reinjnders, Evaluating Uncertainty in Environmental Life-Cycle Assessment. A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling, *Environ. Sci. Technol.* vol. 37 (2003) 2600–2608, <https://doi.org/10.1021/ES020971>.
- [174] H.A. Baaqel, A. Bernardi, J.P. Hallett, G. Guillén-Gosálbez, B. Chachuat, Global SENSITIVITY ANALYSIS IN LIFE-CYCLE ASSESSMENT OF EARLY-STAGE TECHNOLOGY USING DETAILED PROCESS SIMULATION: APPLICATION TO DIALKYLIMIDAZOLIUM IONIC LIQUID PRODUCTION, *ACS Sustain. Chem. Eng.* vol. 11 (18) (May 2023) 7157–7169, <https://doi.org/10.1021/acssuschemeng.3c00547>.
- [175] C.A. de Assis, et al., Conversion economics of forest biomaterials: risk and financial analysis of CNC manufacturing, *Biofuels, Bioprod. Bioref.* vol. 11 (4) (Jul. 2017) 682–700, <https://doi.org/10.1002/bbb.1782>.
- [176] J. Steimel, M. Harrmann, G. Schembecker, S. Engell, Model-based conceptual design and optimization tool support for the early stage development of chemical processes under uncertainty, *Comput. Chem. Eng.* vol. 59 (Dec. 2013) 63–73, <https://doi.org/10.1016/j.compchemeng.2013.06.017>.
- [177] Y. Su, K. Kuipers, V. Hessel, T. Noël, A convenient numbering-up strategy for the scale-up of gas-liquid photoredox catalysis in flow, *React. Chem. Eng.* vol. 1 (1) (Feb. 2016) 73–81, <https://doi.org/10.1039/C5RE00021A>.
- [178] A. Azapagic, R. Clift, The application of life cycle assessment to process optimisation, *Comput. Chem. Eng.* vol. 23 (10) (Dec. 1999) 1509–1526, [https://doi.org/10.1016/S0098-1354\(99\)00308-7](https://doi.org/10.1016/S0098-1354(99)00308-7).
- [179] L.C. Dreyer, A.L. Niemann, M.Z. Hauschild, Comparison of three different LCIA methods: EDIP97, CML2001 and eco-indicator 99: Does it matter which one you choose, *Springer Verl.* (2003), <https://doi.org/10.1007/BF02978471>.
- [180] European Commission, Product Environmental Footprint Category, 2018.
- [181] M.A.J. Huijbregts, et al., ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, *Int. J. Life Cycle Assess.* vol. 22 (2) (Feb. 2017) 138–147, <https://doi.org/10.1007/s11367-016-1246-y>.
- [182] J.B. Guinee, et al., *Handbook on Life Cycle Assessment, Oper. Guide ISO Stand.* Vol. 1, 2a, 2b 3, *J. Clean. Prod.* vol. 6 (5) (2001) 311–313. Accessed: Nov. 11, 2023. [Online]. Available: <http://dx.doi.org/10.1016/j.jclepro.2015.04.109>.
- [183] J.C. Bare, G.A. Norris, D.W. Pennington, T. McKone, Tool. Reduct. Assess. Chem. Other Environ. Impacts vol. 6 (2003) 3–4, <https://doi.org/10.1162/108819802766269539>.
- [184] A. Azapagic, S. Perdan, *The International Journal of Sustainable Development & World Ecology, Integr. Sustain. Decis.-Support Framew. Part I: Probl. Struct.* (2009), <https://doi.org/10.1080/13504500509469622>.
- [185] M. Cinelli, S.R. Coles, and K. Kirwan, Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment, doi: 10.1016/j.ecolind.2014.06.011.
- [186] R.I. Muazu, R. Rothman, L. Maltby, Integrating life cycle assessment and environmental risk assessment: A critical review, *J. Clean. Prod.* vol. 293 (Apr. 2021) 126120, <https://doi.org/10.1016/j.jclepro.2021.126120>.