Renewable and Sustainable Energy Reviews 180 (2023) 113302

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Environmental impacts and techno-economic assessments of biobased products: A review

Seyed Hashem Mousavi-Avval [a,b], Kamalakanta Sahoo [a,b], Prakash Nepal [a], Troy Runge [b], Richard Bergman [a,*]

[a] United States Department of Agriculture Forest Service, Forest Products Laboratory, Madison, WI, 53726, USA
[b] Department of Biological Systems Engineering, University of Wisconsin-Madison, Madison, WI, 53706, USA

ARTICLE INFO

Keywords:
Bioproducts
Environmental impacts
Costs
Bioeconomy
Sustainable feedstock supply

ABSTRACT

Concerns over climate change and fossil resources depletion are drivers for increasing efforts to global transition from fossil-based to biobased products. The development of bioenergy and bioproduct systems, however, faces challenges in terms of resource use, environmental impacts, and production costs. Thus, identifying key areas to reduce costs and environmental impacts of biobased products is crucial. Based on the review of recent literature, this study aims to provide insights into the technical feasibility, costs, and environmental impacts of biobased products produced from different renewable biogenic resources, especially in reference to their fossil-based counterparts. Although biobased products are very diverse, this study focuses on the most promising set of biobased materials such as bio-chemicals, bioplastics, bio-adhesives, bicarbonates, nanocellulose, biochar, and activated carbon. By identifying the bottlenecks for reduction of costs and life cycle environmental impacts and the directions for future research needed in this area, this study would be useful for stakeholders of bioeconomy including researchers, policymakers, and producers who want to achieve the costs and environmental impacts reduction goals for sustainable development of biobased products.

1. Introduction

The global interest to improve energy security, prevent fossil resource depletion, and reduce greenhouse gas (GHG) emissions associated with the use of fossil-based products has led to significant research and industrial efforts toward the development of a biobased economy or bioeconomy [1–3]. A bioeconomy refers to replacing fossil resources with biobased resources to produce energy and materials; and it entails a wide range of low and high-value products, including but not limited to, energy and fuels, biochemicals, biomaterials such as bio-adhesives, carbon products, bicarbonates, and nanomaterials [4,5]. Although the definitions of bioeconomy and biobased products differ by country because of differing focuses, they share the same fundamental concept, i.e., "increasing utilization of biological products and processes across economic sectors for environmental and economic benefits" [6]. To encourage the production and use of sustainable biobased products, various countries have introduced certification programs where the producers of biobased products can certify their products via participation in available voluntary labeling initiatives, which requires measuring the biobased content of a product (via a third party) [7,8].

Biobased products have been gaining recent interest because of their numerous identified and perceived environmental, economic, and social benefits [9–13]. Because of such benefits, governmental and private sectors around the world have been increasing research and development efforts, developing long-term strategies, implementing policies and programs, and investing in developing the technologies to produce biobased products. For example, the European Union (EU) has declared the biobased products sector to be a priority area based on its potential for economic growth, reindustrialization, and addressing societal challenges [14]. Similarly, authorized by the US Farm Bill of 2002 and the Agriculture Improvement Act of 2018, the United States Department of Agriculture (USDA) has created the BioPreferred Program in the US, which focuses on increasing the purchase and use of biobased products to spur economic development, create new jobs, and provide new markets for rural commodities [7].

There are several challenges that need to be overcome for a feasible transition towards biobased products, including biomass availability, selection of suitable feedstocks, identifying the optimal location of

* Corresponding author. Forest Products Laboratory, 1 Gifford Pinchot Dr, Madison, WI 53726, USA
E-mail address: richard.d.bergman@usda.gov (R. Bergman).

https://doi.org/10.1016/j.rser.2023.113302
Received 14 August 2022; Received in revised form 22 February 2023; Accepted 14 April 2023
1364-0321/Published by Elsevier Ltd.

potential biorefineries, as well as numerous economic, environmental, and social constraints [15]. Design of a sustainable supply chain can help address some of these challenges [16–18]. At the same time, evaluating the technical feasibility, costs, and environmental impacts of different biobased products at the commercial scale are needed to identify the bottlenecks towards the sustainable development of biobased products [19–21]. Techno-economic analysis (TEA) and life cycle assessment (LCA) are two well recognized scientific tools for evaluating the sustainability of biobased products and making informed decisions [22].

The TEA methodology uses information derived from thermodynamic and material data for process development and technical optimization that allows us to understand the technical and financial feasibility of processes, products, or services [23]. This analysis allows us to understand the long-term economic impacts of technologies at various commercialization levels and to identify the hotspots for achieving the cost reduction targets [23].

In evaluating the techno-economics of biobased products, the system boundary usually covers the cradle-to-plant gate, and the reference include the unit mass of a product (e.g., kg of product) or unit mass of feedstock (e.g., kg of feedstock). Through process simulations and mass balance analysis, inputs and outputs (final products, coproducts, and emissions) are quantified. Some process parameters needed for process modeling of chemical reactions include temperature, pressure, efficiencies, residence time, etc. Process data are then used for equipment sizing and determining the required number of different equipment for the entire manufacturing plant [24]. The main parameters affecting the economics of bioproducts are then identified through sensitivity analysis.

LCA is an internationally standardized method that can be used to evaluate the environmental impacts of a product or service, throughout their life cycle, from raw material acquisition, through the production process, until use and disposal or end-of-life [25]. Following the ISO standards [26,27], the LCA methodology consists of four iterative methodological phases, namely goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [25,28].

Most of the recent studies on TEA and LCA of biobased products have reported high production cost of bioproducts from biobased feedstocks compared to the cost of producing their petroleum counterparts, which remains the main challenge towards commercialization of the biobased products. However, a comprehensive evaluation of the environmental impacts and costs associated with the bioproducts production is lacking. Thus, the main objective of this review study is to provide insights into the technical feasibility, costs, and environmental impacts of bioproducts from different biobased resources in comparison with their functionally equivalent fossil-based products. Additionally, this study evaluates the effects of various operating conditions and identifies the bottlenecks towards sustainable development of biobased products supply chain. Presenting the LCA and TEA performances of all types of biobased products in this review study is not feasible; so, the scope of this work is narrowed to the most promising set of biobased products such as bio-chemicals, bioplastics, bio-adhesives, bicarbonates, nanocellulose, biochar, and activated carbon.

2. Classification of biobased products

The list of currently identified biobased products is extensive. As of 2018, the USDA BioPreferred Program [7] has identified approximately 20,000 biobased products, excluding fuel, food, and feed. Because this list is yet to include additional forest products and textile fiber products, it has been suggested that a conservative estimate of the total number of existing bioproducts in the U.S. could be around 40,000 [12], which could be broadly categorized into different groups (Table 1). Golden and Handfield [11], categorized biobased products into 6 major groups based on their application types including: (1) chemicals, (2) co-products, (3) pharmaceuticals, (4) microorganisms and enzymes, (5) inks and dyes, and (6) consumer products. Biochemicals were further divided into five subcategories, including (i) non-plastic specific biopolymers, (ii) bioplastics, (iii) biolubricants, (iv) biosolvents, and (v) biosurfactants. The USDA BioPreferred Program [7] has identified 248 biobased product categories, which are grouped into 14 different headings based on end uses, suggesting a wide range of applications in consumer/household goods and services, such as household supplies, personal care and toiletries, and vehicle and equipment maintenance (Table 1).

Table 1
Grouping the biobased products by their types and end uses (excluding energy, livestock, food, feed, and pharmaceuticals sector).

Based on types [11]	Based on end uses [7]
A. Chemicals A.1 Biopolymers (non-plastics specific) A.1.1. Derived from polysaccharides, such as starch or chitin A.1.2 Produced from classical chemical synthesis using renewable, biobased monomers (e.g., polylactic acid (PLA)) A.1.3 Produced by microorganisms or genetically modified bacteria, (e.g., plyhydroxyalkanoates (PHAs) A.2 Bioplastics (e.g., polylactic acid (PLA), plyhydroxyalkanoates (PHAs), plant oils, fatty acids (FA) and fatty acid methyl esters (FAME), etc.) A.3 Biolubricants A.4 Biosolvents A.5 Biosurfactants A.6 Other biosynthetics B. Co-products (biofuel co-products) C. Biopharmaceuticals D. Microorganisms and enzymes E. Inks and dyes F. Consumer products	1. Baby and kids2. Construction 3. Custodial services 4. Films and packaging 5. Food services/cafeteria 6. Ground maintenance 7. Household supplies 8. Intermediates (feedstock) 9. Miscellaneous 10. Office supplies 11. Operations and maintenance 12. Personal care and toiletries 13. Safety equipment 14. Vehicle and equipment maintenance

The increased use of biobased products leads to reduced petroleum consumption by substituting petroleum-based products, leading to reduced dependency on fossil-based resources and providing an opportunity to reduce air pollutants and GHG emissions in the atmosphere [7,12,29,30]. For example, such avoided petroleum consumption and the GHG emissions reductions associated with the production of biobased products in the US in 2016 was estimated to be 9.40 million barrels, and 12.7 million metric tons (MT) CO_2e/yr, respectively [12]. Similarly, the annual GHG saving potential of 15 different biobased chemicals worldwide, using corn starch as feedstock, and assuming full substitution of the petrochemical equivalents, was estimated to be 512 million MT CO_2e/yr by 2030 [29]. In addition to carbon mitigation advantages, biobased products offer other benefits such as lower toxicity or environmentally friendly characteristics (e.g., biodegradable plastic materials) [8,10]. Similarly, increasing the use of fermentation and bio-catalysis to replace chemical synthesis can obtain higher process efficiency, leading to reduced energy, water consumption, and toxic waste generation [8].

Biomass feedstock is the precursor to the bioeconomy and plays a fundamental role in sustaining and accelerating the growth of the bioeconomy. Biomass feedstock is widely available, and it can serve as the precursor for a wide range of biobased products, depending on the production technologies [31,32]. Biomass can be supplied from different sources, including agricultural residues, forest and forest product residues, municipal solid waste, and energy crops [33,34]. However, biomass feedstock supply remains one of the biggest challenges for sustainable production of bioproducts, mainly due to the competition with food and feed production, and energy use [13,35]. In this regard, energy crops along with forest-related residues have some advantages over other feedstocks, including their capability of growing in marginal lands, less competition with cropland and resources required to produce food crops and reduces the negative environmental impacts associated with the production of bioproducts [36].

3. Global and US status of biobased industry

More than 50 countries around the world have either dedicated strategies or are actively working currently to develop relevant policies and programs related to biobased products [37,38]. The EU, the US, Brazil, Canada, China, and Malaysia are considered as the global leaders of the biobased industry, based on their currently installed production capacity, the planned production capacity, industrial innovation, and the availability of feedstock sources [39].

The world market size of the global biobased industry, including the food and feed sector, is estimated to be 10.33 trillion USD in 2018 (Table 2) [38]. Whereas, the market size of the global biobased industries, excluding the food and feed industries, is valued at 3.43 trillion USD, and is projected to increase to 5.05 trillion USD by 2030, representing an increase of about 50% [38].

The global biobased industry, excluding the food and feed sector, is estimated to require approximately 6.3 billion MT of biomass in 2018, which is projected to rise by 17% by 2030 (Table 2) [38]. More than 82% of current biomass feedstock is supplied by agricultural sector, with forestry supplying the rest [38]. The largest biomass-consuming sector is biorefinery, which is estimated to consume about 2.0 billion MT in 2018 [38]. However, the largest growth in biomass use is projected to occur in the global construction sector at a compound annual growth rate (CAGR) of 8.8%, from 361 MT in 2018 to 989 MT in 2030 (Table 2) [38].

While many biobased products and technologies are still at an early stage of commercialization, a significant number have already been adopted in the marketplace and their market share is projected to continue to grow several years ahead [11,14]. The specialty biobased chemicals (e.g., enzymes, inks and dyes, adhesives, lubricants) and biobased polymers (e.g., PLA, PHA) are expected to see most of the growth in the US [11]. In contrast, the biorefining industry, composed of the pulp and paper industry, constitutes the largest US biobased industry in terms of employment and total value-added, followed by biobased plastic and bottles, and forest products [12,20].

A recent assessment [40] estimated that EU bioeconomy provided jobs to 17.5 million people and added approximately 700 billion USD worth of value in 2017, which represented 8.9% and 4.7% of the EU labor force and gross domestic product (GDP), respectively. A similar study for the US [12] showed that biobased products industry (excluding energy, livestock, food, feed, and pharmaceuticals sectors) employed 4.65 million workers and contributed 459 billion USD to the US economy in 2016, representing increases of 16% and 24% relative to the 2013 levels, respectively (Fig. 1). Growths in employment and added value of such magnitudes suggest that the US biobased industry sector is growing at a faster rate than the aggregate economy and the GDP [12].

Plastics, with global production of 368 million MT, was a leading cause of negative environmental impacts in 2019 [41], and it is estimated that they will contribute to 20% of global annual oil consumption by 2050 [42]. The US Environmental Protection Agency (US EPA) has reported a total 7.65 million MT of plastic waste generated in the US in 2018, which was partially treated with recycling (2.4%) and combustion (19.0%), but mainly with landfilling (78.6%) [43], which causes several environmental impacts through leakage to the environment, especially to the water bodies [44,45]. In the same year, plastics contributed about 1.5% of total annual global emissions of greenhouse gases, i.e., 55.3 billion MT CO_2eq estimated by the International Panel on Climate Change (IPCC) [46]. These figures suggest that biobased and biodegradable plastics can play important role in reducing the use of high carbon intensive fossil-based plastics.

Bioplastics are plastic materials which are mostly or entirely produced from natural resources, such as vegetable oils, corn starch, woodchips, sugar cane, etc. [47]. For example, ethylene can be produced from sugar cane, and it can be further processed to manufacture polyethylene; or lactic acid can be produced from starch, and it can be further processed to manufacture polylactic acid (PLA), which can be used in packaging [48]. Bio-polyethylene (BPE), polyamide 11 (PA 11), polyhydroxyalkanoate (PHA) derived poly-3-hydroxybutyrate (PHB), polylactic acid or polylactide (PLA), and thermoplastic starch are different types of bioplastics [49]. The worldwide production capacity of bioplastic, is quite small, estimated to be at 2.1 MT in 2020 and projected to grow at a CAGR of around 17.5% until 2030 [50]. Among different types of bioplastics, polyethylene-terephthalate (PET), starch blends, PA, PLA, polyethylene (PE), and polytrimethylene terephthalate (PTT) made up more than half of the total bioplastic production volume [51].

Like bioplastics, biobased polymers are materials made from natural resources [52,53]. Similarly, the market share of biobased polymers in the current global market is very small; with a total production of 3.8 million MT, ~1% of the total production volume of fossil-based polymers in 2019 [54]. The total global production volume of biobased polymer industry is projected to grow from 4.6 million MT in 2020 to 6.7 million MT capacity in 2025, indicating an average CAGR of ~8% [55]. The global market for adhesives was estimated to be $53 billion in 2019, and it is expected to increase by 4.5% annually, from 2020 to 2030, to $85.7 billion by 2030 [56]. The market for adhesives can be categorized by adhesive production technology, type of resin, and flexibility and mode of application [57]. Fossil-based adhesives are usually produced as the co-products of petroleum-based processes; formaldehyde-based adhesives are usually used for the production of engineered wood

Table 2
Estimated bioeconomy market size and biomass use, 2018–2030 [38].

Industries	Market size			Biomass use		
	2018	2030	CAGR	2018	2030	CAGR
	Billion USD		%	Million MT		%
All biobased industries	10330	12819	1.8	23369	26613	1.1
All biobased industries, excluding food and feed	3430	5054	3.3	6259	7348	1.4
Major industries						
Pharmaceuticals	264	760	9.2	68	91	2.4
Textiles and wearing apparel	417	686	4.1	119	185	3.7
Building materials and construction	331	682	6.2	361	989	8.8
Packaging	375	544	3.2	161	352	6.8
Motor vehicles and components	255	526	6.2	255	520	6.2
Other forest products	133	201	3.5	206	310	3.2
Electronics and electrical products	117	217	5.1	37	67	7.2
Machinery and equipment	52	96	5.3	34	58	4.5
Biomass energy and biofuels	143	18	2.3	2011	2419	1.6
Food and feed losses and waste for composting purposes	2300	2590	1.0	5700	6400	1.0

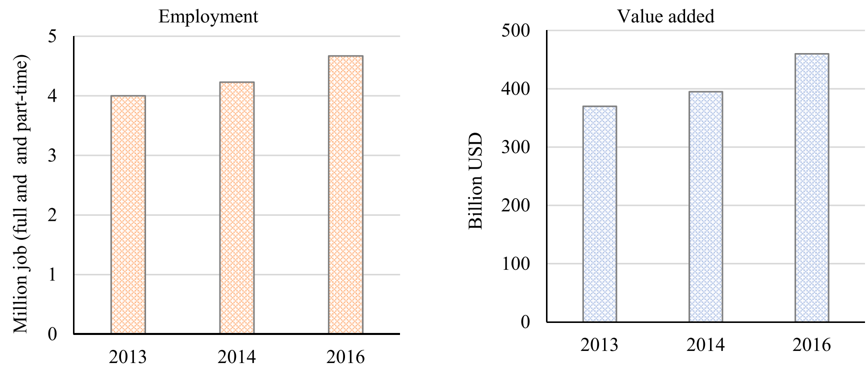

Fig. 1. Total employment and value-added contributions of US biobased products industry in 2013, 2014, and 2016 [12].

products such as wood panels using mainly urea-formaldehyde (UF), phenol formaldehyde (PF), and melamine-urea formaldehyde (MUF) [31]. These adhesives are known as resin and some of their features include low curing temperatures, excellent adhesion properties, water resistance, and low price [57,58]. In 2019, resin production in the U.S. reached nearly 55 million metric ton, on a dry weight basis [59].

Overall, it may be seen that there is great growth potential for biobased products. Their economic and environmental impacts may be investigated using LCA and TEA methodologies. This work will synthesize recent studies of biobased products studies to provide insight into this category.

4. Review methodology

This work comprises a literature review of the recent studies on LCA and TEA of biobased products published over the last 20 years (2003–2022). The review methodology included defining the review questions, identifying related work, selecting criteria, synthesizing the evidence, and interpreting the results [60]. A literature search of peer-reviewed journal articles in English language was performed in Scopus database. The search field of “Title, Abstract, Keywords” was selected for this work; and the search strings included “life cycle assessment” OR “techno economic analysis” OR “bio-chemicals” OR “bioplastics” OR “bio-adhesive” OR “bicarbonates” OR “nanocellulose” OR “carbon nanofibers” OR “biochar” OR “activated carbon”. From the search results, after review of the title and keywords of peer-reviewed publications, 290 research studies were selected for abstract screening; and then after abstract screening, 180 studies were selected for full text screening. Subsequently, 110 documents were selected as related works and included in this review study (Fig. 2). Among all journals, “Journal of Cleaner Production” and “Bioresource Technology” had the highest number of publications. Among all journal publishers, Elsevier contributed more publications. This study did not cover conference papers, book chapters, and non-English documents.

In this review of TEA and LCA of biobased products, some of the most common parameters representing the economic performance, e.g., minimum selling price (MSP), capital costs, and operating costs, as well as some environmental impacts, e.g., global warming impact, acidification, eutrophication, are reported. MSP represents the selling price required to reach the break-even point and make zero profit.

Table 3
Summary of techno-economic analysis (TEA) and life cycle assessment (LCA) publications on biobased products.

Biobased product	Number of TEA studies	Number of LCA studies
Biochemicals and bioplastics	12	25
Bio-adhesive	5	10
Biochar, activated carbon, carbon nanofibers and nanocellulose	23	38

5. LCA and TEA of bioproducts

In this section, we summarized a comprehensive review of the production technologies, key findings of LCA and TEA, and identified bottlenecks of commercial production of bioproducts including biochemicals, bioplastics, bio-adhesive, biochar, activated carbon, carbon nanofiber, and nanocellulose. Table 3 summarizes the number of publications in each category of biobased products focused in this study.

5.1. LCA and TEA of bio-chemicals and bioplastics

Different components of biomass, such as lignin, cellulose, and hemicellulose, can be processed through pyrolysis to produce mixtures of aromatics, olefins, CO, CO_2, water, and other products. Therefore, a wide range of chemical products has been identified which can be potentially produced from biobased feedstocks. This review, however, focuses on understanding costs and environmental impacts of few biochemicals, which are currently highly related to the global community and there is high interest towards their commercialization, including benzene, toluene, and xylene (BTX), and bioplastics.

5.1.1. Benzene, toluene, and xylene (BTX)

Catalytic fast pyrolysis (CFP) is the most common pyrolysis approach used to produce a mixture of aromatics, olefins, and a variety of other biochemicals (Fig. 3) [61]. The aromatics include hydrocarbon chemicals, such as BTX, and naphthalene, among other aromatics. The olefins

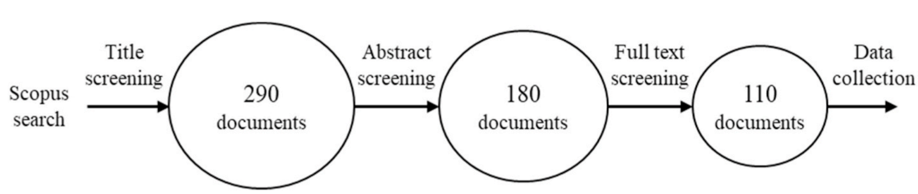

Fig. 2. Selection process for identifying related works.

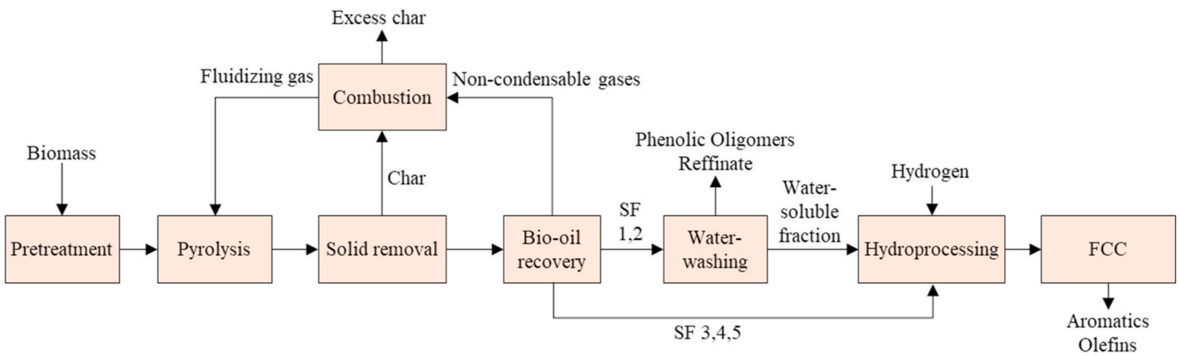

Fig. 3. Schematic overview of hydrocarbon chemicals (i.e., BTX) production through pyrolysis [61]. Stage fractions (SF), benzene, toluene, and xylene (BTX), fluidized catalytic cracking (FCC).

Table 4
Carbon yield and carbon selectivity in BTX production [61].

Process	Hydrogen consumption (g/100 g of carbon in feed)	Carbon yields and carbon selectivity (%)			
		Aromatics		Olefins	
Ru/H2+Pt/ H2+Zeolite	8.1	18.3		43.0	
		Carbon selectivity (%)			
		Benzene	27.0	Ethylene	32.0
		Toluene	49.3	Propylene	53.8
		Xylene	19.1	Butylene	14.2
		Ethyl Benzene	2.3	–	–

mainly include ethylene, propylene, and butylene [61]. Stage fractions (SFs) 1&2 go through water-washing process, in which the water-soluble fraction is separated, and proceed with a two-stage hydroprocessing and fluidized catalytic cracking (FCC) for the production of BTX and olefins. The temperature and pressure for the first and second hydrotreating stages are 398 Kelvin (K) and 100 bar, and 523 K and 100 bar, respectively (Fig. 3) [61]. Hydrotreating process is conducted at the presence of Ru/C catalyst [61]. Carbon yields and carbon selectivity for each product are presented in Table 4.

In a previous study [61] it was found that integrated bio-refineries, which produce biochemicals and BTX through fast pyrolysis of biomass had lower capital cost and operating cost. The minimum selling price (MSP) of BTX was estimated to be $1110/t, while it was reported as $0.82/L for biofuels and $461/t for biochemicals [61]. In addition, production of hydrocarbon chemicals showed a higher probability of being economically profitable compared to biofuels, due to higher revenue and less fluctuation in the market price [61].

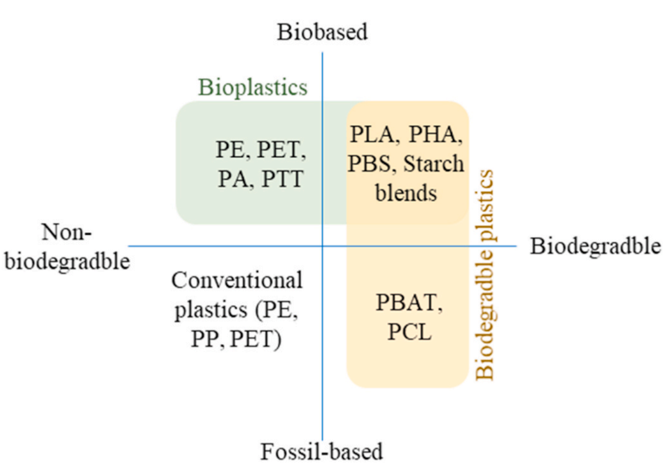

Fig. 4. Different types of plastics [64]. Polyethylene (PE), polyethylene terephthalate (PET), polyamide (PA), polytrimethylene terephthalate (PTT), polylactic acid (PLA), polyhydroxyalkanoates (PHA), polybutylene succinate (PBS), polypropylene (PP), polybutylene adipate terephthalate (PBAT), polycaprolactone (PCL).

5.1.2. Bioplastics

Bioplastics are alternatives to fossil-based plastics, which are manufactured from plants or other organic resources, thus, reducing fossil resource use such as petroleum [62]. Most biobased plastics are considered either biodegradable only under specific conditions or non-biodegradable [63]. Some biodegradable bioplastics include PLA, PHA, polybutylene succinate (PBS) and starch blends (Fig. 4) [64]. PHAs are biodegradable bioplastics that are conventionally produced from first-generation biomass [65], and they are expected to see the highest growth rate in the near future to be used mostly in flexible and rigid packaging [64].

Previous studies have demonstrated lower fossil fuel use and harmful health and environmental impacts of starch, PLA, and PHA biobased composites compared to fossil-based plastics [66]. However, some biobased plastics require additional processing for biological materials. For example, drying is needed for pretreatment of biobased feedstock before conversion processes, which can cause environmental impacts associated with electricity generation or natural gas combustion [67]. While replacing fossil-based plastics with bioplastics in different applications (e.g, packaging, construction, electronics, and household uses) have been shown to reduce global warming impacts, they are associated with increased eutrophication and acidification impacts [47]. Higher eutrophication and acidification impacts are mainly due to the use of agricultural inputs, especially chemical fertilizers for growing feedstock, which magnifies with the new production and recycling (aimed at reducing the cradle-to-grave environmental impacts) of bioplastics [47]. In some cases, there aren't any significant differences in environmental impacts of PLA composites, bioplastics from organic fillers, i.e., distiller's dried grains with solubles (DDGS)), flax, hemp, rice husks, and wood, compared to the environmental impacts and energy intensity of petroleum-based plastics from inorganic fillers, i.e., glass and talc (Fig. 5) [49].

In terms of production cost, bioplastics from organic fillers, i.e., DDGS, flax, hemp, rice husks, and wood, have shown comparable [49] or higher [47] production cost compared to petroleum-based plastics from inorganic fillers, i.e., glass and talc (Fig. 6). Higher production cost of bioplastics can be attributed to the high feedstock cost as well as smaller capacity of the production facility and the use of emerging or nascent technology for bioplastics compared to established technologies in the production of petroleum-based plastics [47].

The production cost of PHAs has been reported to be higher than other biopolymers, mostly due to the high cost of raw materials and chemicals used in PHA production [62]. To address these challenges, use of secondary residual feedstocks, e.g., biogas, wastewater, and sewage

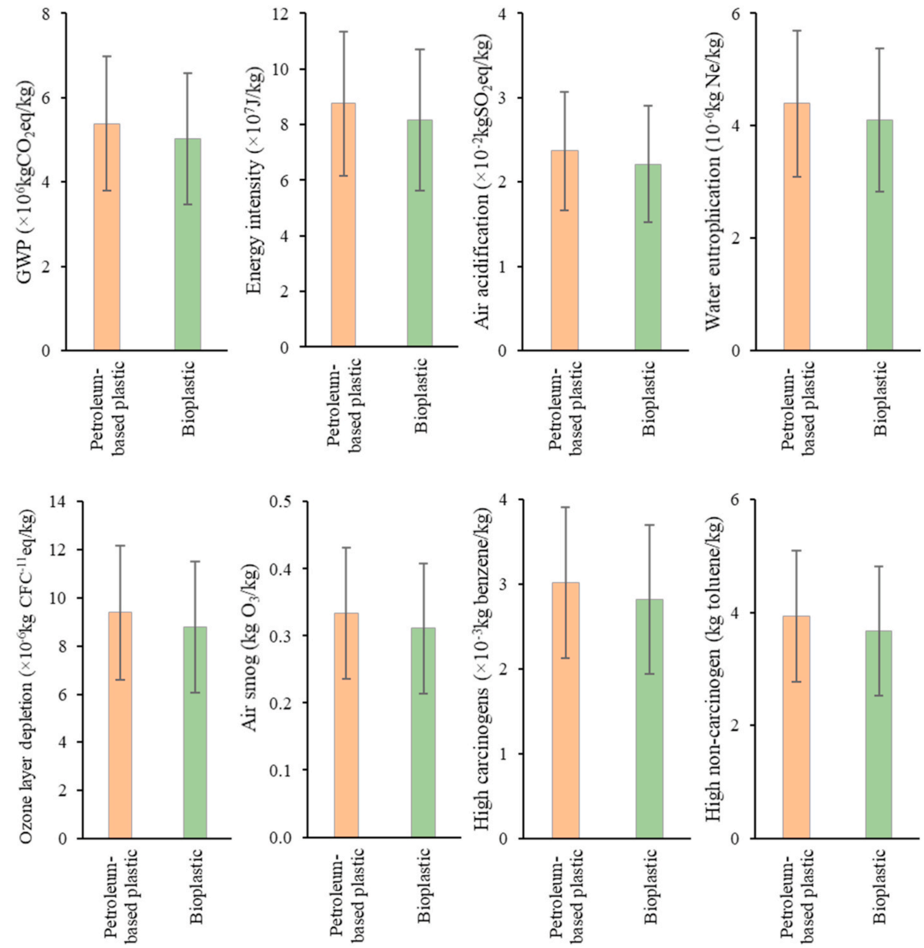

Fig. 5. Life-cycle environmental impacts of bioplastics compared to petroleum-based plastics [49].

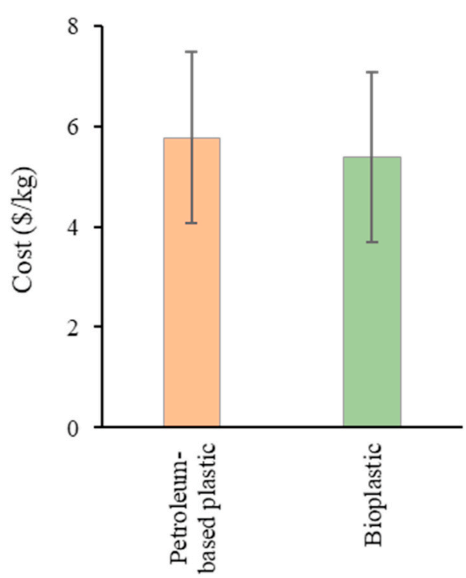

Fig. 6. Production costs of bioplastics compared to petroleum-based plastics [49].

sludge has been technically demonstrated to be feasible in the literature [68,69]. In this regard, production of PHAs from urban waste has shown better economic and environmental performances compared to PHAs from first-generation biomass [62]. Alternative management of waste and biorefinery residues are important factors affecting the economic and environmental performances of PHAs. In addition, use of sodium hypochlorite for PHA extraction, and CH_4 leakage from anaerobic digestion are the main opportunities for the reduction of costs and environmental impacts [62]. Davidson et al. [70] studied the environmental impacts and costs of producing hydroxymethylfurfural (HMF) and 2,5-furandicarboxylic acid (FDCA) and their derived biobased chemicals. They concluded that the production of HMF and FDCA and their derived products may offer lower CO_2emissions compared to their fossil counterparts; however, they are worse in other environmental impact categories. They are also less viable in terms of economic performance mainly due to higher production costs.

5.2. Bio-adhesives

Adhesives are chemicals that are being used as binding agents in different applications, such as the automotive, aerospace, and wood industries [71]. Adhesives are also important constituents for the manufacture of wood-based panels [58,72–74]. The release of volatile organic compounds (VOCs) and formaldehyde vapors from adhesives causes human health damage [58]. Bioadhesives compared to traditional adhesives, have improved mechanical and chemical properties [75]. Also, formaldehyde has been removed from their composition [76,77].

Bio-adhesives can be produced from different feedstocks, such as soy and corn proteins [78], starches [79], bio-glycerol, and lignin [73,80,81]. Soy protein-based adhesive is a widely used bio-adhesive in the wood panel sector [73,82], and some of its advantages include low cost, low pressing temperatures, as well as its capability for being used for wood with higher moisture content [31]. Lignin is a promising feedstock for the production of bio-adhesives, and a by-product of pulp manufacturing processes and cellulosic biofuel production process, with its composition widely changing depending on the composition of raw materials; thus, offering a wide range of applications [83]. The chemical structure of lignin is like that of phenol; so, it can be used as an alternative to phenol in the synthesis of phenol-formaldehyde (PF). Tannins are another potential feedstock for bio-adhesive production, which are currently used at industrial scale; however, production of tannin-based adhesive is limited due to supply constraints of tannins. Tannins are obtained from bark of pine, quebracho, oak, and chestnut, as well as leaves and fruits of plants, and some of the applications of tannin-based adhesives include the manufacture of inks and dyes [84]. Fig. 7 shows the production process of bioadhesives and petrochemical adhesives.

Despite the global interest and potential development of bio-adhesives, the technology is still in its infancy, and literature lacks a comprehensive review of bottlenecks for sustainable development of bioadhesives. Limited literature focuses on evaluation of environmental impacts and costs of composites from the timber industry, in which bioadhesives are considered as auxiliary materials [74,85]. Bioadhesive have demonstrated to have lower environmental impacts compared to petrochemical adhesives [80,86]; so, replacing PF with bio-adhesive will reduce the overall environmental profile of wood-based panel production [86]. Among different types of bioadhesives and fossil-based adhesives, soy and tannin-based bio-adhesives have demonstrated to have better overall environmental profile than fossil resins, while lignin-based adhesives tend to have a poorer environmental profile (Fig. 8) [31].

McDevitt and Grigsby [80] evaluated the environmental impacts and resources used during the life cycle of medium-density fiberboard (MDF) made from biobased adhesives (lignin-protein composite) compared with MDF made from the petrochemical adhesive (urea formaldehyde resin). The use of bio-adhesive reduced the single-score environmental impacts by 22% compared to the use of petrochemical adhesive. In addition, resource depletion of petrochemical adhesive was 40% higher than that of bio-adhesive [80]. Yang and Rosentrater [57] concluded that the production of structural adhesives from bio-glycerol had lower environmental burdens than those from petro-glycerol.

The MSP of structural bio-adhesive has been reported to be \$3.11/kg, primarily attributing to feedstock cost [87]. In addition, the unit production cost of structural bio-adhesives was estimated to be \$2.45/kg, which was comparable with the price of petrochemical adhesive available in the current market, and it showed a decreasing trend with an increase in plant scale. It was also noted that the addition of transportation and distribution costs after the biorefinery may increase the unit production cost.

In terms of the key factors affecting the environmental impacts and costs of bio-adhesive production, the glyoxalation stage was reported as the main contributor to the environmental burdens of bioadhesive production from lignin [31]; thus, optimization of process parameters for glyoxalation could significantly affect the environmental impacts of the system. In addition, use of local mineral resources has been identified as one of the main parameters affecting the overall environmental impacts of both petrochemical and biobased adhesives [80]. Electricity source and the product yield have also been identified as the key factors affecting the global warming impact of bioadhesives [57]. For example, use of electricity from coal has significantly increased the global warming impact of bioadhesive production compared to its production using biomass-based electricity (Fig. 9).

5.3. LCA and TEA of biochar

Biochar has different and diverse applications not limited to soil amendment in agriculture and horticulture, activated carbon filters for water treatment, cosmetics and medicines, environmental remediation, and construction materials. Biochar can be considered as a carbon-neutral or even carbon-negative solution when it is applied as soil amendment [88]. Biochar can be used as an alternative to conventional filler materials for producing lighter composites which can be used in the automotive industry, to help mitigate GHG emissions associated with fossil-based counterparts [89–91]. The environmental benefits achieved from renewable filler materials are mainly because of weight reduction resulting in fuel saving opportunity during the use phase of automotive components that incorporates renewable filler materials [89]. A wide range of feedstocks, including energy crops (e.g., switchgrass) [92], forest residues [93–97], miscanthus [98], poultry litter [99] and sewage sludge [100] have been identified as a promising candidate for biochar production.

Biochar can be produced from different thermochemical conversion technologies, such as conventional pyrolysis, microwave pyrolysis, and gasification [101]. Conventional pyrolysis is the most frequently used approach to produce biochar (Fig. 10). Pyrolysis involves thermal decomposition of dry biomass at a temperature ranging from 400 to 700 °C, with a partial supply of oxygen [102]. Based on the process conditions, the process is classified as slow pyrolysis (5–7 °C/min heating rate and the vapor residence time more than 1 h) and fast pyrolysis (more than 200 °C/min heating rate and vapor residence time less than 10 s) [103]. In addition to residence time and temperature, type of biomass and heating rate also affect the biochar quality and yield [104]. These pyrolysis process conditions affect the physicochemical properties and yield of biochar. In fast pyrolysis, compared with slow pyrolysis, biochar production yield and the surface area are both lower

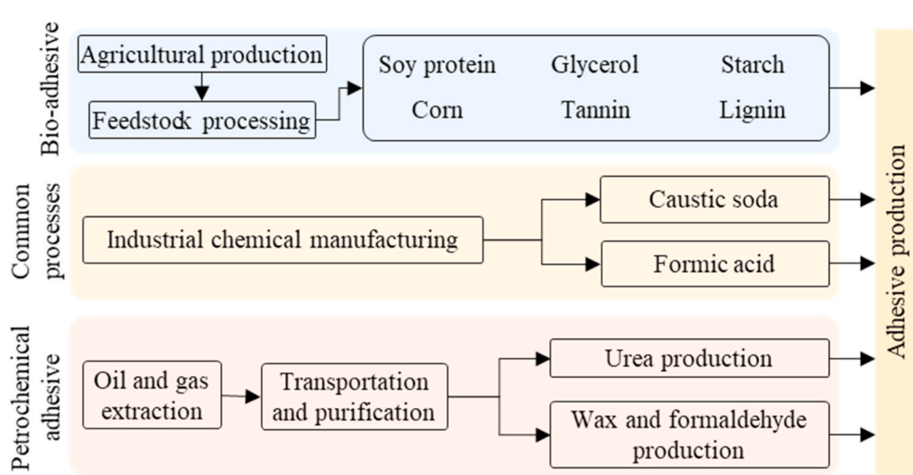

Fig. 7. System overview of bio-adhesive and petrochemical adhesive production.

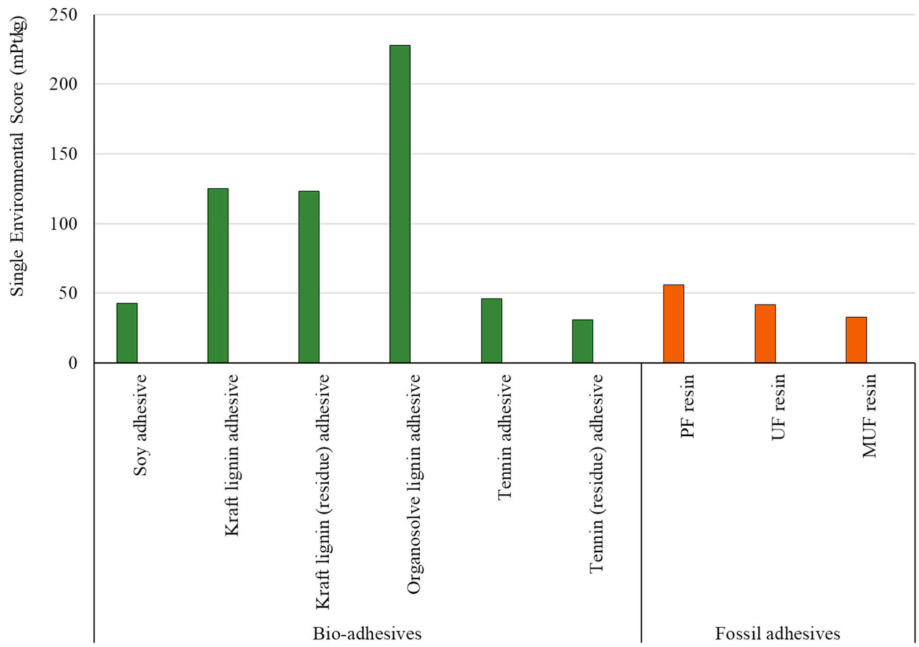

Fig. 8. Single score environmental impacts of bioadhesives from different feedstock types [31].

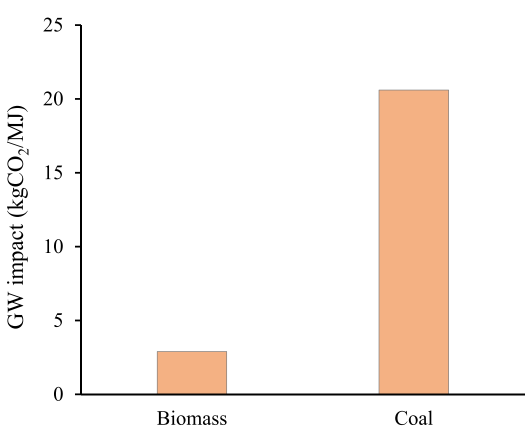

Fig. 9. GWP of bioadhesives with electricity supply from different sources [57].

[105].

Microwave pyrolysis is a relatively novel technology for production of biochar, which involves uniform penetration of microwave radiation throughout the treated biomass at a heating rate ranging from 0.1 to more than 1000 °C/s [108]. Some advantages of microwave pyrolysis compared to conventional approach include faster and more selective heat generation system [109], less pre-treatment needs, such as drying [110], as well as rapid and convenient start-up and shutdown [110]. Conversely, it has less flexibility of the input materials, and uncertainty of scale-up economics due to technological immaturity [110].

Gasification is used to produce biochar through thermochemical conversion technology, where biomass is partially oxidized at 600–900 °C or higher [105]. Gasifying agents that may be used include CO_2, air, oxygen, steam, or a mixture of these gases. The major product of gasification is syngas; thus, the biochar to feedstock mass ratio is quite low, i.e., 5–10% [111].

Considering different applications of biochar, use of biochar as an alternative to chemical fertilizer to cereal crops has shown to reduce the nitrate leaching and eutrophication potential by 63% compared to the use of chemical fertilizers [112]. Type of feedstock was identified as one of the main factors affecting the environmental impacts of biochar production [113]. In addition, variation in crop yield based on the region, land use efficiency, and crop lifetime considered for LCA studies in perennial crops are the main reasons for variation in the results [114]. In a 2014 study [115], GHG emissions and carbon cycling of biochar from different feedstocks (forest residue and corn stover) were evaluated and the results showed that emissions reduction from the use of corn fodder was higher than that from use of forest residue (Fig. 11). Stable carbon in the biochar was the main factor affecting the GHG emissions reduction for both feedstocks. It was found that optimization of pyrolysis system had a significant impact in sequestration of stable carbon in soil [115].

The driving force for GW impacts for biochar varied by feedstock source. GW impact of biochar production from miscanthus cultivated on marginal land, through slow pyrolysis, was estimated to be 118 kg CO_2/t, which was dominated by miscanthus cultivation (93 kg CO_2eq/t), followed by pyrolysis process (23 kg CO_2eq/t), and logistics operations (5 kg CO_2eq/t) [114]. GW impact was mainly affected by miscanthus yield and biochar yield. Miscanthus cultivation had also the highest contribution in acidification and non-carcinogenic potential impacts; while transportation and pyrolysis were the main contributors to the impact categories of eutrophication, smog and ecotoxicity, and carcinogenic potential, ozone depletion potential, and fossil resources depletion. It was shown that biochar production from switchgrass had higher net energy (4899 MJ/t dry feedstock) and GHG emissions (36 kg CO_2e/t dry feedstock), compared to its production from corn stover, and yard waste [98]. Net GHG emissions for both corn stover and yard waste were estimated to be −864 and −885 kg CO_2e/t dry feedstock, respectively. Higher GHG emissions of switchgrass was due to inputs used for feedstock cultivation, as well as land use change impact. A recent study [92] evaluated the GHG emissions and energy use for biochar production from switchgrass through pyrolysis technology in an auger reactor, by considering bio-oil and syngas as co-products. The system boundaries covered from cultivation of switchgrass on marginal lands, up to amendment of biochar in the field. Carbon sequestration and N_2O emissions reduction were also assessed. GHG emissions balance was estimated to be −2110 and −2561 kg CO_2e/t biochar for slow pyrolysis and fast pyrolysis, respectively, which indicates that biochar production from energy crop through pyrolysis can be a negative emission technology. GHG emissions reduction was dominant by carbon sequestration, which was mainly due to high carbon content and stability of carbon in biochar. Fast pyrolysis required more energy (13,563 MJ/t

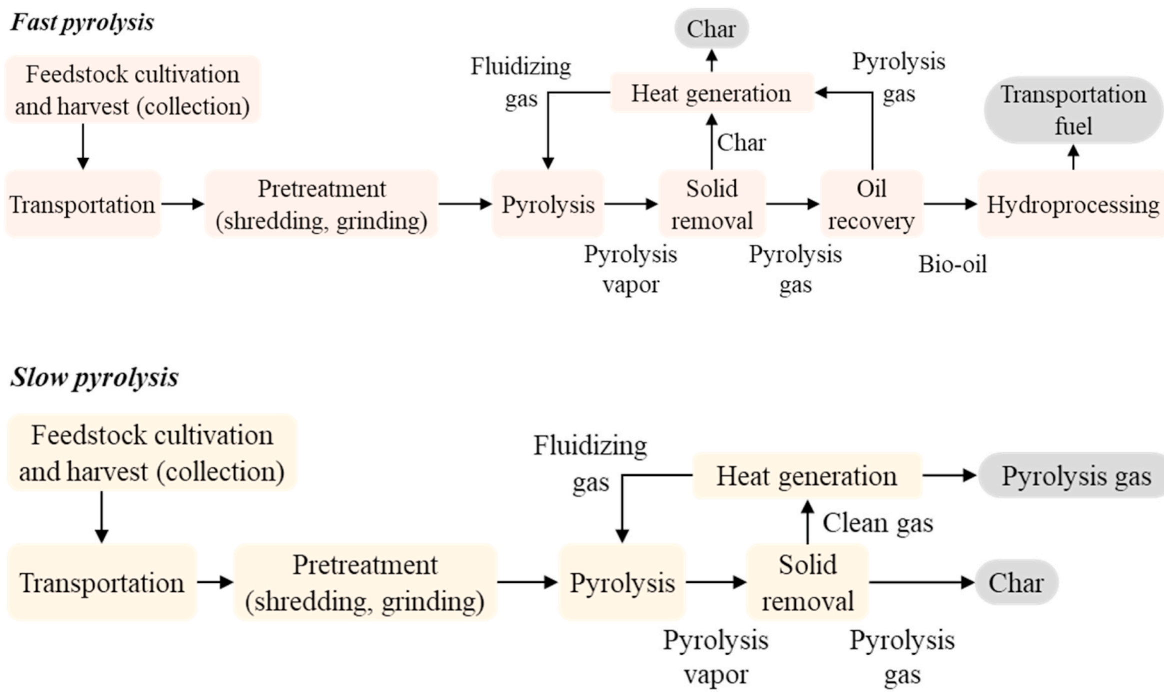

Fig. 10. Biochar production through fast and slow pyrolysis [106,107].

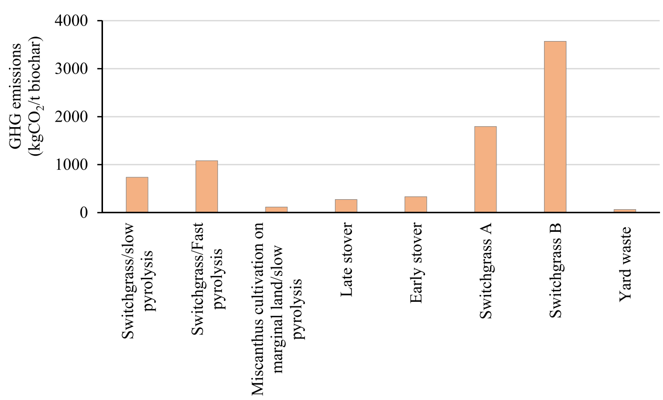

Fig. 11. GHG emissions of biochar production from different biobased sources [92,114,116].

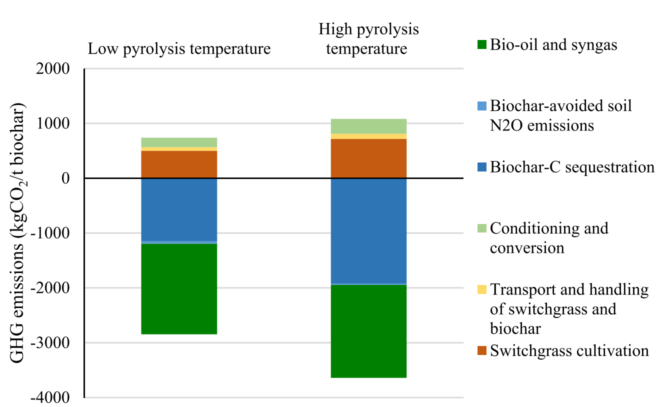

Fig. 12. GHG emissions of switchgrass-based biochar production and use in low and high pyrolysis temperature (adopted from Ref. [92]).

Table 5
Contribution of life cycle stages to the GHG emissions of pelletized biochar.

Life cycle stage	Contribution (kg CO_2eq/t dried feedstock)	Contribution (%)
Feedstock cultivation	199	−27
Pyrolysis	52	−7
Palletization	22	−3
Packaging	7	−1
Use in soil as a carbon sink	−368	50
Avoided use of heat	−252	34
Avoided use of electricity	−398	54
Total	−737	100

biochar) compared to slow pyrolysis (2925 MJ/t biochar) which translated to corresponding GHG emissions (Fig. 12), mainly due to energy consumption during the pyrolysis process.

GHG emissions in pellet biochar from miscanthus was found to be primarily from biomass cultivation, while GHG credit was dominated by carbon sequestration due to use of biochar and avoided use of electricity (Table 5) [114,117]. Optimization of agronomic inputs for miscanthus cultivation and improvement in yield is expected to significantly reduce the life cycle environmental impacts of biochar.

5.4. LCA and TEA of activated carbon

Activated carbon (AC) is a form of carbon processed with high surface area and porosity, which has high value-added applications in adsorption for water purification or other industrial processes [118]. It is mainly produced through pyrolysis of carbonaceous raw materials, such as coal, peat, nutshell, coconut husk, and wood, at a temperature lower than 1000 °C [119,120]. AC can be used to remove air or water pollutants. Some examples of its application include wastewater treatment, groundwater remediation, and air purification [121].

Biochar can be a precursor of AC while graphene can be extracted from the graphite fraction. However, currently, most AC is produced from coal. Some studies have evaluated substitution of coal-based AC with alternative bioproducts such as biomass-based AC and graphene [120,122]. Cossutta et al. [122] evaluated the environmental impacts of graphene and AC in production of supercapacitor. They stated that graphene-based devices had overall 14% (in fossil resources depletion) to 43% (in photochemical ozone formation) less environmental impacts than supercapacitor from AC. Graphene-based device also had 36% less GHG emissions. They concluded that with an improved technical performance, optimized production scale, and developed recycling technologies, graphene is a more-environment-friendly substitute for AC. The GW impact from manufacturing the supercapacitor from graphene was estimated to be ~2.5 times higher than that from AC (Fig. 13), mainly due to more active material requirement and higher GHG emissions of production of graphene compared to AC (~80 gCO_2eq/g vs 5 gCO_2eq/g).

Graphene-based supercapacitors with current material performance and energy mix-represent a greater environmental burden than conventional AC-based devices. A key factor in the poor environmental performance of the graphene supercapacitor is the high greenhouse gas intensity of primary graphene production, which dominates the production emissions. The inferior specific capacitance of graphene, when compared with AC, results in a larger and heavier device that requires more active material and greater material inputs, incurring greater use-phase impacts due to mass-induced fuel consumption.

Kim et al. [119] evaluated environmental impacts of AC production from wood waste, based on one tonne of feedstock, and compared them with those of coal-based AC. They found that AC from wood waste had 9.69 kg CO_2eq/kg less GW impact than from coal. Use of wood waste for production of AC, in addition to less GW impact during the production process of AC, has environmental benefits over landfilling wood waste, which was reported to have about 17 times higher GW impact (163 kg CO_2eq/t of wood waste). In production of AC, type of feedstock is one of the main parameters affecting the energy consumption (43.4–277 MJ/kg AC) and GHG emissions (3.96–22.0 kg CO_2eq/kg AC) [118]. This is mainly affected by the composition of biomass in terms of hydrogen and oxygen contents, and process parameters, such as activation temperature [118].

Evaluation of technical feasibility and costs of biochar production from different feedstocks have been the subject of several studies. Haeldermans et al. [123] compared the technical feasibility and costs of conventional and microwave pyrolysis technologies for biochar production from various residue streams. They estimated the MSP of biochar to be $510-1010/t in conventional pyrolysis, however it was in the range of $660-1150/t in microwave pyrolysis. Roberts et al. [98] estimated the production costs of biochar systems from different sources, including agricultural residues (corn stover), yard waste, and switchgrass energy crops. The results revealed that the economic competitiveness of the pyrolysis-biochar system was mainly affected by costs of feedstock supply, pyrolysis, and credit associated with carbon savings. Supply of feedstock (biomass) from sources that would otherwise need waste management, such as yard waste, has a great potential for economic competitiveness ($69/t dry feedstock when the credit from CO_2e emission reductions was $80/t CO_2e). In addition to feedstock type, transportation distance causes significant variations on overall economic profitability of biochar [98].

Evaluation of techno-economics of centralized biochar production utilizing woody biomass in Canada for establishing a 1 MWh biochar-based bioenergy plant revealed that the cost of pyrolysis section ($381,536/yr, 36% of cost of the production system) had the highest share in overall cost of plant, followed by storage and processing, i.e., pelletization ($237,171/yr) (Fig. 14). The costs were based on a 25-year

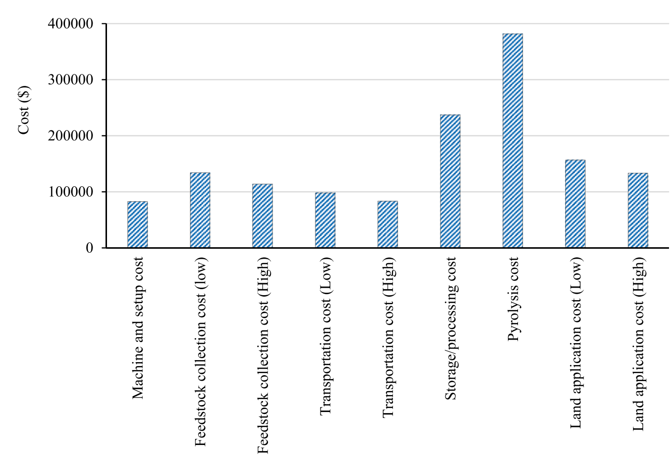

Fig. 14. Average annual cost of establishing a 1 MWh biochar-based bioenergy plant [93].

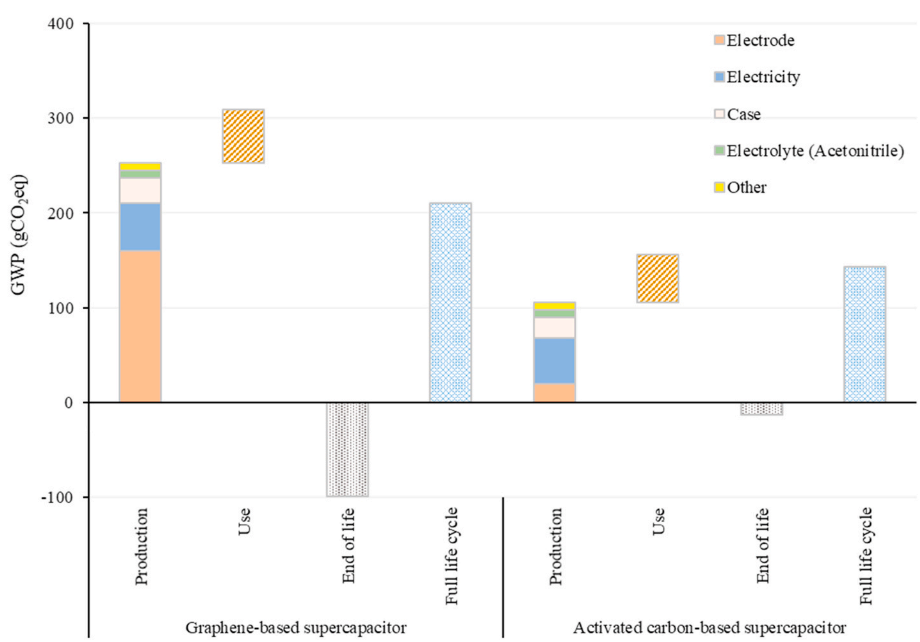

Fig. 13. Life cycle global warming potential (GWP) of supercapacitors using graphene and AC [122].

average annual cost. Costs of land application of biochar was estimated to be $156,739/yr and $133,228/yr for low and high availability of feedstock, respectively, which accounted for 14% of overall production cost. Feedstock collection cost was estimated to be ~$134,000/yr (low availability) and ~$114,000/yr (high availability), which accounted for 12% of overall production cost. Transportation costs for low and high availability were estimated to be $97,962/yr and $83,268/yr, respectively, which accounted for 9% of overall production cost. Overall cost of purchasing pyrolizer equipment, transport, installation, and associated cost of environmental burdens was estimated to be $82,727/yr [93].

Comparison of techno-economics of conventional and microwave pyrolysis technologies from residue streams revealed that MSP of biochar in conventional and microwave pyrolysis technologies was $510-1010/t and $660-1150/t, respectively. Thus, conventional pyrolysis was financially more viable than microwave pyrolysis [123]. By-product credit was also shown to be an important factor affecting the MSP of biochar. The impacts of credit from heat and power on overall techno-economics of biochar production from poultry litter through pyrolysis/gasification affected the MSP of biochar; so that the MSP was estimated to be ~$300/t with no credit from heat and power generation; while it could be reduced to ~$244/t, provided that electricity and heat be sold at ~$82/MW and ~$6.8/MWh, respectively [99]. The cost of handling and storing feedstock was $27.44/t. Feedstock cost and carbon content of biochar were identified as main factors affecting the techno-economics of biochar from poultry litter, while ash and moisture content were the main contributors to the quality of biochar. Lower ash content caused higher carbon content, which is one of the quality parameters of biochar.

5.5. *Carbon capture technology in production on biobased materials*

Development of bioproducts faces an important challenge, which is lower hydrogen to carbon ratio of biomass compared to petroleum, which causes production of a large amount of CO_2. Even though the source of carbon is biomass, carbon capture and utilization is an effective technology for the future biorefineries to further reduce the CO_2 emissions during the conversion processes [124]. Currently, carbon capture and storage technology is not economically competitive in most of its applications [125], and CO_2 valorization is an alternative technology to convert CO_2 into various forms of bioproducts, such as nanomaterials and bicarbonates.

6. Key drivers promoting growth of biobased industry

Currently, more than 50 countries have dedicated strategies in place, or they are in process of developing strategies to promote their bioeconomies [37,38]. Such strategies involving government mandate and supports and increasing investment in research and products/technologies development through public-private partnership have played a key role in developing and growing biobased products and industry worldwide. According to a survey conducted by the Joint Research Center in EU [39], the most important factors driving the development of biobased industry were product competitiveness, economic profitability, novelty of products, and environmental performance of the products [39]. Key drivers especially responsible for influencing bioeconomy in the US, based on the literature review by Golden and Handfield [11] include: 1) government drivers (policies and laws and regulations), 2) industry drivers (perceived competitive advantage in both costs and eco-friendly marketing to consumers), 3) consumer drivers (preferences towards biobased products relative to the petroleum-based products, 4) NGOs (campaign and awareness programs to promote biobased products). According to Lange et al. [126], some of the key drivers of biobased economy in the EU, most of which are also true for the US and other regions of the world, are: 1) abundant supply of biomass, 2) concern for climate change mitigation and focus on renewable, biobased fuels, 3) substitute for fossil-based chemicals and materials, 4) biorefineries stimulating rural development, livelihood, and jobs.

7. Main barriers and challenges hindering the growth of biobased industry

Although biobased products and related industries offer multitude of economic and environmental benefits and strengths and opportunities to expand further, they also face several challenges and barriers at present. Key barriers and challenges identified by companies and businesses engaged in biobased industry include: 1) potential high upfront capital costs; 2) higher production cost (especially feedstocks) of biobased products compared to their petroleum alternatives; 3) lack of available funds to invest in production capacity; 4) underdeveloped technologies or lack of viable technologies; 5) inadequate policy support; 6) ambiguous public perception about environmental benefits of biobased products; 7) fluctuating oil prices; 8) varying feedstock price and limited supply; and 8) sustainability concerns (e.g., indirect land use competition for food, feed, fuel, and feedstock for biobased materials [30,38,39,126–128]. It is worth mentioning that there are some limitations in TEA and LCA studies for bioproducts; for example, some of these products have not yet reached their commercial scales; therefore, there is a lack of data availability in terms of cost and life-cycle inventory. In addition, the environmental impacts associated with end-of-life of biobased products also has a contribution to overall products' life cycle impacts [129]. However, this review study did not take into consideration the end-of-life impacts because most of the literature studies fail to integrate the end-of-life option into a product's life cycle in a systemic perspective [130,131]. Most consumers are uncertain about the benefits of using biobased products as an alternative to petroleum-based products [11]. However, consumers in general are willing to pay 5–10% extra for biologically derived plastic alternatives [11,132]. Given the high cost of production and consumers' relatively low willingness to pay for green products, biobased products can compete on price with petroleum-based alternatives only if oil prices are high [132]. However, until recently, oil prices have been historically low in recent years thus threatening the market competitiveness of biobased products [132].

Although bioproducts typically offer reduced CO_2 emissions due to lower energy, water, raw material, and chemical consumption compared with fossil-based products, there are several concerns related to the sustainability of biomass-derived products, especially if feedstocks are produced using input-intensive agriculture [30]. The most common concerns about biobased products are that they: 1) contribute to indirect land use change through competition for land needed for food and feed production, 2) have negative impact on biodiversity (e.g., due to monoculture crops/plantations), 3) provide limited GHG benefit with relatively high cost, 4) contribute to higher food prices through competition for resources for the feedstock production [30,133]. Therefore, whether biobased products provide intended environmental benefits depends on the type of feedstock, region of production, technological level, and production scale [30]. Most of the potential negative impacts associated with input-intensive agriculture could be minimized, however, with increased use of residues and waste-based feedstock in the production process [30].

8. Conclusions

This study conducted a comprehensive review of recent literature on technical feasibility, costs, and environmental footprints of biobased products. It was found that substituting fossil-based products with biobased products has both environmental advantages and disadvantages. It reduces fossil resources use and GHG emissions, while it is detrimental in some other impact categories, such as acidification, and ecotoxicity. For energy crops, unlike residues, both environmental impacts and costs are mostly dominated by crop cultivation and logistics costs of feedstocks while environmental benefits of bioproducts over fossil-based products are attributed to CO_2 assimilation during the feedstock growth and carbon storage in the soil. The price of biobased products is primarily driven by costs of feedstock, logistics operations, capital investments, and scale of production. As a future direction for research in this area, implementation of integrated sustainability factors, including environmental impacts, costs, and social impacts, would provide more realistic solutions for development of biobased products. In addition, optimization of the production systems from environmental, social, and economic perspectives would guide sustainability-driven innovation in transition from fossil-based products to biobased counterparts. The outcomes of this study identified key drivers of techno-economic feasibility and environmental impacts of biobased products at the commercial scale. The outcomes will be useful for all stakeholders, including policymakers, investors, manufacturers, and farmers.

Credit author statement

Seyed Hashem Mousavi Avval: Methodology, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Kamalakanta Sahoo**: Conceptualization, Supervision, Methodology, Formal analysis, Investigation, Writing - Review & Editing. **Prakash Nepal**: Methodology, Investigation, Writing – Review and Editing. **Troy Runge:** Writing – Review and Editing, Project Administration, Funding Acquisition. **Richard Bergman**: Conceptualization, Writing – Review and Editing, Supervision, Project Administration, Funding Acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgement

This work is supported by Agriculture and Food Research Initiative Competitive Grant no. 2020-68012-31881 from the USDA National Institute of Food and Agriculture. Also, this work is supported by the USDA Forest Service (FS) Forest Products Laboratory, and University of Wisconsin-Madison. As some authors of this paper are employees of the USDA FS, the findings and conclusions in this report are those of the author(s) and should not be construed to represent any official USDA or U.S. Government determination or policy. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

References

[1] European Commission. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions—innovating for sustainable growth: A Bioeconomy for Europe. Brussels, Belgium, Available, https://opeuropaeu/en/publication-detail/-/publication/84e7a360-6970-4cb8-939d-8acbf33f0ae8/language-en. [Accessed 22 March 2022]. accessed.

[2] Ubando AT, Felix CB, Chen WH. Biorefineries in circular bioeconomy: a comprehensive review. Bioresour Technol 2020;299. https://doi.org/10.1016/j.biortech.2019.122585.

[3] Net zero by 2050 – Analysis - IEA n.d. https://www.iea.org/reports/net-zero-by-2050 (accessed May 21, 2022).

[4] Broeren MLM, Zijp MC, Waaijers-van der Loop SL, Heugens EHW, Posthuma L, Worrell E, et al. Environmental assessment of bio-based chemicals in early-stage development: a review of methods and indicators. Biofuels Bioprod Biorefining 2017;11:701–18. https://doi.org/10.1002/bbb.1772.

[5] Jakes JE, Arzola X, Bergman R, Ciesielski P, Hunt CG, Rahbar N, et al. Not just lumber–Using wood in the sustainable future of materials, chemicals, and fuels. JOM 2016;68(9):2395–404. https://doi.org/10.1007/S11837-016-2026-7.

[6] Birner R. Bioeconomy concepts. Bioeconomy Shap. Transit. To a Sustain. Biobased Econ.. Springer International Publishing; 2017. p. 17–38. https://doi.org/10.1007/978-3-319-68152-8_3.

[7] United States Department of Agriculture (USDA). BioPreferred program. Available at: https://WwwBiopreferredGov/BioPreferred/Faces/WelcomeXhtml. [Accessed 30 March 2021]. accessed.

[8] Euopean Commission. Bio-based producs. Available at: https://EcEuropaEu/Growth/Sectors/Biotechnology/Bio-Based-Products_en#:~:Text=Bio%2Dbased%20products%20are%20wholly,Geological%20formations%20and%2For%20fossilised. [Accessed 30 March 2021]. accessed.

[9] U.S. biobased products market potential and projections through 2025 - Meredith A. Williamson - google books n.d. https://books.google.com/books/about/U_S_Biobased_Products_Market_Potential_a.html?id=C22JPgAACAAJ (accessed March 30 2021).

[10] Ontario Ministry of Agriculture F and RA (OMAFR). Introduction to bioproducts. Available at: https://WwwOmafraGov.on.ca/English/Crops/Facts/10-013wHtm#2. [Accessed 30 March 2021]. accessed.

[11] Golden JS, Handfield RB. Why biobased? Opportunities in the emerging bioeconomy. 2014.

[12] Daystar J, Handfield RB, Golden JS, McConnell TE. A Report to the Congress of the United States of America. An Economic Impact Analysis of the U.S. Biobased Products Industry, vol. IV. A Joint Publication of the Supply Chain Resource Cooperative at North Carolina State University and the College of Eng; 2018.

[13] Isikgor FH, Becer CR. Lignocellulosic biomass: a sustainable platform for the production of bio-based chemicals and polymers. Polym Chem 2015;6:4497–559. https://doi.org/10.1039/C5PY00263J.

[14] European Commission. A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment. Available at: https://Knowledge4policyEcEuropaEu/Publication/Sustainable-Bioeconomy-Europe-Strengthening-Connection-between-Economy-Society_en. [Accessed 30 March 2021]. accessed.

[15] Wightman JL, Ahmed ZU, Volk TA, Castellano PJ, Peters CJ, DeGloria SD, et al. Assessing sustainable bioenergy feedstock production potential by integrated geospatial analysis of land use and land quality. Bioenergy Res 2015;8:1671–80. https://doi.org/10.1007/s12155-015-9618-x.

[16] Gronalt M, Rauch P. Designing a regional forest fuel supply network. Biomass Bioenergy 2007;31:393–402. https://doi.org/10.1016/j.biombioe.2007.01.007.

[17] Khan SAR, Yu Z, Golpira H, Sharif A, Mardani A. A state-of-the-art review and meta-analysis on sustainable supply chain management: future research directions. J Clean Prod 2021;278:123357. https://doi.org/10.1016/J.JCLEPRO.2020.123357.

[18] Seuring S, Müller M. From a literature review to a conceptual framework for sustainable supply chain management. J Clean Prod 2008;16:1699–710. https://doi.org/10.1016/J.JCLEPRO.2008.04.020.

[19] D'Amato D, Gaio M, Semenzin E. A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective. Sci Total Environ 2020;706:135859. https://doi.org/10.1016/j.scitotenv.2019.135859.

[20] Sahoo K, Bergman R, Alanya-Rosenbaum S, Gu H, Liang S. Life cycle assessment of forest-based products: a review. Sustain Times 2019;11(17):11. https://doi.org/10.3390/SU11174722. 30.

[21] Hong BH, How BS, Lam HL. Overview of sustainable biomass supply chain: from concept to modelling. Clean Technol Environ Policy 2016;18:2173–94. https://doi.org/10.1007/S10098-016-1155-6.

[22] Lo SLY, How BS, Teng SY, Lam HL, Lim CH, Rhamdhani MA, et al. Stochastic techno-economic evaluation model for biomass supply chain: a biomass gasification case study with supply chain uncertainties. Renew Sustain Energy Rev 2021;152. https://doi.org/10.1016/j.rser.2021.111644.

[23] Ögmundarson Ó, Sukumara S, Herrgård MJ, Fantke P. Combining environmental and economic performance for bioprocess optimization. Trends Biotechnol 2020;38. https://doi.org/10.1016/j.tibtech.2020.04.011.

[24] SuperPro Intelligen. Designer, user guide. New Jersey, USA: Intelligen, Inc. Scotch Plains; 2020. p. 597. Available at: https://www.intelligen.com/wp-content/uploads/2020/05/SuperPro_ManualForPrinting_v11.pdf. [Accessed 15 March 2022]. Accessed on.

[25] International Organization for Standardization. ISO 14040:2006 - environmental management – Life cycle assessment – Principles and framework. 2006. p. 20.

[26] ISO. EN. ISO 14044:2006 - environmental management: life cycle assessment; requirements and guidelines, vol. 46; 2006. https://doi.org/10.1136/bmj.332.7550.1107.

[27] ISO. ISO 14040:2006 - environmental management – life cycle assessment – principles and framework. 2006. p. 20.

[28] McLaren SJ. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. J Clean Prod 2017;140:399–409. https://doi.org/10.1016/J.JCLEPRO.2016.06.071.

[29] Hermann BG, Blok K, Patel MK. Producing bio-based bulk chemicals using industrial biotechnology saves energy and combats climate change. Environ Sci Technol 2007;41:7915–21. https://doi.org/10.1021/es062559q.

[30] Textile Exchange. Quick guide to biosynthetics. Texas: Lamesa; 2018. p. 28.

[31] Arias A, González-García S, González-Rodríguez S, Feijoo G, Moreira MT. Cradle-to-gate Life Cycle Assessment of bio-adhesives for the wood panel industry. A comparison with petrochemical alternatives. Sci Total Environ 2020;738:140357. https://doi.org/10.1016/j.scitotenv.2020.140357.

[32] Brown TR, Brown RC. Biorenewable resources: engineering new products from agriculture. John Wiley & Sons; 2013.
[33] Langholtz MH, Stokes BJ, Eaton LM. Billion-ton report: advancing domestic resources for a thriving bioeconomy 2016. 2016. https://doi.org/10.2172/1271651.
[34] U.S. Department of Energy. 2016 billion-ton report: advancing domestic resources for a thriving bioeconomy. In: Langholtz MH, Stokes BJ, Eaton (Leads) LM, editors. Volume 1: economic availability of feedstocks, vol. 1. Oak Ridge, TN: Oak Ridge National Laboratory; 2016. p. 448. ORNL/TM-2016/160.
[35] Mousavi-Avval SH, Shah A. Techno-economic analysis of hydroprocessed renewable jet fuel production from pennycress oilseed. Renew Sustain Energy Rev 2021;149:111340. https://doi.org/10.1016/j.rser.2021.111340.
[36] Lee H, Lautenbach S. A quantitative review of relationships between ecosystem services. Ecol Indicat 2016;66:340–51. https://doi.org/10.1016/j.ecolind.2016.02.004.
[37] Dietz T, Börner J, Förster JJ, von Braun J. Governance of the bioeconomy: a global comparative study of national bioeconomy strategies. Sustain Times 2018;10. https://doi.org/10.3390/su10093190.
[38] WBCSD. Circular bioeconomy: The business opportunity contributing to a sustainable world. 2020.
[39] Nattrass L, Biggs C, Bauen A, Parisi C, Rodríguez-Cerezo E, Gómez-Barbero M. The EU bio-based industry : results from a survey. 2016. https://doi.org/10.2791/806858.
[40] Ronzon T, Piotrowski S, Tamosiunas S, Dammer L, Carus M, M'barek R. Developments of economic growth and employment in bioeconomy sectors across the EU. Sustainability 2020;12:4507. https://doi.org/10.3390/su12114507.
[41] Statista. Annual production of plastics worldwide from 1950 to 2020. Available, https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/. [Accessed 22 March 2022]. accessed.
[42] Beckstrom BD, Wilson MH, Crocker M, Quinn JC. Bioplastic feedstock production from microalgae with fuel co-products: a techno-economic and life cycle impact assessment. Algal Res 2020;46:101769. https://doi.org/10.1016/j.algal.2019.101769.
[43] Environmental Protection Agency U, of Land O, Management E, of Resource Conservation O. Advancing sustainable materials management: 2018 fact Sheet assessing trends in materials generation and management in the United States. 2020.
[44] Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, et al. Plastic waste inputs from land into the ocean. Science (80-) 2015:347. https://doi.org/10.1126/science.1260352.
[45] Borrelle SB, Ringma J, Lavender Law K, Monnahan CC, Lebreton L, McGivern A, et al. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science (80-) 2020:369. https://doi.org/10.1126/SCIENCE.ABA3656.
[46] UN Environment Programme. Emissions gap report 2019. 2019.
[47] Koch D, Mihalyi B. Assessing the change in environmental impact categories when replacing conventional plastic with bioplastic in chosen application fields. Chem Eng Trans 2018;70:853–8. https://doi.org/10.3303/CET1870143.
[48] PlasticsEurope-Association of Plastics Manufacturers. Bio-based plastics. Available at: www.plasticseurope.org. [Accessed 19 March 2021]. accessed.
[49] Haylock R, Rosentrater KA. Cradle-to-Grave life cycle assessment and techno-economic analysis of polylactic acid composites with traditional and bio-based fillers. J Polym Environ 2018;26:1484–503. https://doi.org/10.1007/s10924-017-1041-2.
[50] Energy and Gold Ltd. Global bioplastics market predicted to grow 350%. Available at: https://energyandgoldcom/2016/03/10/an-enormous-investment-opportunity-in-a-rapidly-growing-space/. [Accessed 20 February 2023]. accessed.
[51] Europian Bioplastics. Bioplastics market data. Available at: WwwEuropean-BioplasticsOrg/Market/. [Accessed 30 March 2021]. accessed.
[52] Zhu Y, Romain C, Williams CK. Sustainable polymers from renewable resources. Nat 2016;540:354–62. https://doi.org/10.1038/nature21001. 5407633 2016.
[53] RameshKumar S, Shaiju P, O'Connor KE, P RB. Bio-based and biodegradable polymers - state-of-the-art, challenges and emerging trends. Curr Opin Green Sustain Chem 2020;21:75–81. https://doi.org/10.1016/J.COGSC.2019.12.005.
[54] Vanderreydt I, Rommens T, Tenhunen A, Mortensen LF, Tange I. Greenhouse Gas Emissions and Natural Capital Implications of Plastics (Including Biobased Plastics). Eionet Report-ETC/WMGE 2021/3. 2021. Available at: https://www.eionet.europa.eu/etcs/etc-wmge/products/greenhouse-gas-emissions-and-natural-capital-implications. Eur Top Cent Waste Mater a Green Econ Mol.
[55] PRESS RELEASE (EN/DE): for the first time: growth rate for Bio-based Polymers with 8 % CAGR far above overall polymer market growth. Nova-Institut GmbH Available, https://Nova-InstituteEu/Press/?Id=237. [Accessed 20 February 2023]. accessed.
[56] GlobeNewsWire. Adhesives market size is expected to reach us$ 85.7 billion by 2030, globally. Available at: https://www.globenewswire.com/news-release/2020/11/11/2125110/0/en/adhesives-market-size-is-expected-to-reach-us-85-7-billion-by-2030-globallyhtml. [Accessed 10 February 2021]. accessed.
[57] Yang M, Rosentrater KA. Cradle-to-gate life cycle assessment of structural bio-adhesives derived from glycerol. Int J Life Cycle Assess 2020:1–8. https://doi.org/10.1007/s11367-020-01733-9.
[58] Kim S. Environment-friendly adhesives for surface bonding of wood-based flooring using natural tannin to reduce formaldehyde and TVOC emission. Bioresour Technol 2009;100:744–8. https://doi.org/10.1016/j.biortech.2008.06.062.
[59] Statista. Total resin production in the United States from 2009 to 2020. Available, https://www.statista.com/statistics/203398/total-us-resin-production-from-2008/. [Accessed 22 March 2021]. accessed.
[60] Khan KS, Kunz R, Kleijnen J, Antes G. Five steps to conducting a systematic review. J R Soc Med 2003;96:118–21. https://doi.org/10.1258/jrsm.96.3.118.
[61] Hu W. Techno-economic, uncertainty, and optimization analysis of commodity product production from biomass fast pyrolysis and bio-oil upgrading Recommended Citation. Iowa State University; 2015.
[62] Andreasi Bassi S, Boldrin A, Frenna G, Astrup TF. An environmental and economic assessment of bioplastic from urban biowaste. The example of polyhydroxyalkanoate. Bioresour Technol 2021;327. https://doi.org/10.1016/j.biortech.2021.124813.
[63] Alaerts L, Augustinus M, Van Acker K. Impact of bio-based plastics on current recycling of plastics. Sustain Times 2018;10. https://doi.org/10.3390/su10051487.
[64] Bioplastics European. Bioplastic materials. Available at: https://www.european-bioplastics.org/bioplastics/materials/. [Accessed 10 January 2022]. accessed.
[65] Tsang YF, Kumar V, Samadar P, Yang Y, Lee J, Ok YS, et al. Production of bioplastic through food waste valorization. Environ Int 2019;127. https://doi.org/10.1016/j.envint.2019.03.076.
[66] Álvarez-Chávez CR, Edwards S, Moure-Eraso R, Geiser K. Sustainability of bio-based plastics: general comparative analysis and recommendations for improvement. J Clean Prod 2012;23:47–56. https://doi.org/10.1016/j.jclepro.2011.10.003.
[67] Gander B, Wehrli E, Alder R, Merkle HP. Quality improvement of spray-dried, protein-loaded d, l-PLA microspheres by appropriate polymer solvent selection. J Microencapsul 1995;12:83–97. https://doi.org/10.3109/02652049509051129.
[68] Bengsston S, Werker A, Visser C, Korving L. PHARIO - stepping stone to a sustainable value chain for PHA bioplastic using municipal activated sludge. Stowa; 2017.
[69] Bengtsson S, Karlsson A, Alexandersson T, Quadri L, Hjort M, Johansson P, et al. A process for polyhydroxyalkanoate (PHA) production from municipal wastewater treatment with biological carbon and nitrogen removal demonstrated at pilot-scale. N Biotech 2017;35. https://doi.org/10.1016/j.nbt.2016.11.005.
[70] Davidson MG, Elgie S, Parsons S, Young TJ. Production of HMF, FDCA and their derived products: a review of life cycle assessment (LCA) and techno-economic analysis (TEA) studies. Green Chem 2021;23. https://doi.org/10.1039/d1gc00721a.
[71] Yang M, Rosentrater KA. Life cycle assessment and techno-economic analysis of pressure sensitive bio-adhesive production. Energies 2019;12:4502. https://doi.org/10.3390/en12234502.
[72] Stark NM, Cai Z. Chapter 11: wood-based composite materials: panel products, glued laminated timber, structural composite lumber, and wood–nonwood composites. In: Wood handbook—wood as an engineering material. General Technical Report FPL-GTR-282. Madison, WI: U.S. Depart; 2021.
[73] Frihart CR, Hunt CG. Chapter 10: wood adhesives: bond formation and performance. In: Wood handbook—wood as an engineering material. General Technical Report FPL-GTR-282, vol. 23. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 2021.
[74] Bushi, Lindita Jamie Meil, Finlayson Grant. A cradle-to-gate life cycle assessment of north American wood products resin systems. 2022.
[75] Mathias JD, Grédiac M, Michaud P. Bio-based adhesives. Biopolym. Biotech admixtures eco-efficient constr. Mater. 2016:369–85. https://doi.org/10.1016/B978-0-08-100214-8.00016-6. Elsevier Inc.
[76] Pizzi A. Recent developments in eco-efficient bio-based adhesives for wood bonding: opportunities and issues. J Adhes Sci Technol 2006;20:829–46. https://doi.org/10.1163/156856106777638635.
[77] Siahkamari M, Emmanuel S, Hodge DB, Nejad M. Lignin-glyoxal: a fully biobased formaldehyde-free wood adhesive for interior engineered wood products. ACS Sustainable Chem Eng 2022;10:3430–41. https://doi.org/10.1021/ACSSUSCHEMENG.1C06843/ASSET/IMAGES/LARGE/SC1C06843_0010.JPEG.
[78] Langenberg K Van, Grigsby W, Ryan G. Green Adhesives: options for the Australian industry-summary of recent research into green adhesives from renewable materials and identification of those that are closest to commercial uptake. 2010.
[79] Moubarik A, Pizzi A, Allal A, Charrier F, Charrier B. Cornstarch and tannin in phenol-formaldehyde resins for plywood production. Ind Crop Prod 2009;30:188–93. https://doi.org/10.1016/j.indcrop.2009.03.005.
[80] McDevitt JE, Grigsby WJ. Life cycle assessment of bio- and petro-chemical adhesives used in fiberboard production. J Polym Environ 2014;22:537–44. https://doi.org/10.1007/s10924-014-0677-4.
[81] Van Nieuwenhove I, Renders T, Lauwaert J, De Roo T, De Clercq J, Verberckmoes A. Biobased resins using lignin and glyoxal. ACS Sustainable Chem Eng 2020;8:18789–809. https://doi.org/10.1021/ACSSUSCHEMENG.0C07227/ASSET/IMAGES/MEDIUM/SC0C07227_0018.GIF.
[82] Li K, Geng X, Simonsen J, Karchesy J. Novel wood adhesives from condensed tannins and polyethylenimine. Int J Adhesion Adhes 2004;24:327–33. https://doi.org/10.1016/j.ijadhadh.2003.11.004.
[83] Geng X, Li K. Investigation of wood adhesives from kraft lignin and polyethylenimine. J Adhes Sci Technol 2006;20:847–58. https://doi.org/10.1163/156856106777638699.
[84] Hemmilä V, Adamopoulos S, Karlsson O, Kumar A. Development of sustainable bio-adhesives for engineered wood panels-A Review. RSC Adv 2017;7:38604–30. https://doi.org/10.1039/c7ra06598a.

[85] Eisen A, Bussa M, Röder H. A review of environmental assessments of biobased against petrochemical adhesives. J Clean Prod 2020;277:124277. https://doi.org/10.1016/j.jclepro.2020.124277.
[86] González-García S, Feijoo G, Heathcote C, Kandelbauer A, Moreira MT. Environmental assessment of green hardboard production coupled with a laccase activated system. J Clean Prod 2011;19:445–53. https://doi.org/10.1016/j.jclepro.2010.10.016.
[87] Yang M, Rosentrater KA. Techno-economic analysis of the production process of structural bio-adhesive derived from glycerol. J Clean Prod 2019;228:388–98. https://doi.org/10.1016/j.jclepro.2019.04.288.
[88] Homagain K, Shahi C, Luckai N, Sharma M. Life cycle environmental impact assessment of biochar-based bioenergy production and utilization in Northwestern Ontario, Canada. J Res 2015;26:799–809. https://doi.org/10.1007/s11676-015-0132-y.
[89] Behazin E, Misra M, Mohanty AK. Sustainable biocarbon from pyrolyzed perennial grasses and their effects on impact modified polypropylene biocomposites. Compos B Eng 2017;118:116–24. https://doi.org/10.1016/j.compositesb.2017.03.003.
[90] Bergman R, Sahoo K, Englund K, Mousavi-Avval SH. Lifecycle assessment and techno-economic analysis of biochar pellet production from forest residues and field application. Energies 2022;15:1559. https://doi.org/10.3390/EN15041559.
[91] Han H-S, Jacobson A, Bilek EM, Ted), Sessions J. Waste to wisdom: utilizing forest residues for the production of bioenergy and biobased products. Appl Eng Agric 2018;34(1):5–10. https://doi.org/10.13031/AEA.12774.
[92] Brassard P, Godbout S, Pelletier F, Raghavan V, Palacios JH. Pyrolysis of switchgrass in an auger reactor for biochar production: a greenhouse gas and energy impacts assessment. Biomass Bioenergy 2018;116:99–105. https://doi.org/10.1016/j.biombioe.2018.06.007.
[93] Homagain K, Shahi C, Luckai N, Sharma M. Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application in Northwestern Ontario, Canada. For Ecosyst 2016;3:21. https://doi.org/10.1186/s40663-016-0081-8.
[94] Gu H, Bergman R. Life-cycle assessment of a distributed-scale thermochemical bioenergy conversion system | treesearch. Wood Fiber Sci 2016;48:129–41.
[95] Sahoo K, Upadhyay A, Runge T, Bergman R, Puettmann M, Bilek E. Life-cycle assessment and techno-economic analysis of biochar produced from forest residues using portable systems. Int J Life Cycle Assess 2021;26:189–213. https://doi.org/10.1007/s11367-020-01830-9.
[96] Puettmann M, Sahoo K, Wilson K, Oneil E. Life cycle assessment of biochar produced from forest residues using portable systems. J Clean Prod 2020:250. https://doi.org/10.1016/j.jclepro.2019.119564.
[97] Sahoo K, Bilek E, Bergman R, Mani S. Techno-economic analysis of producing solid biofuels and biochar from forest residues using portable systems. Appl Energy 2019;235:578–90. https://doi.org/10.1016/J.APENERGY.2018.10.076.
[98] Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environ Sci Technol 2010;44:827–33. https://doi.org/10.1021/es902266r.
[99] Huang Y, Anderson M, McIlveen-Wright D, Lyons GA, McRoberts WC, Wang YD, et al. Biochar and renewable energy generation from poultry litter waste: a technical and economic analysis based on computational simulations. Appl Energy 2015;160:656–63. https://doi.org/10.1016/j.apenergy.2015.01.029.
[100] Singh S, Kumar V, Dhanjal DS, Datta S, Bhatia D, Dhiman J, et al. A sustainable paradigm of sewage sludge biochar: valorization, opportunities, challenges and future prospects. J Clean Prod 2020;269:122259. https://doi.org/10.1016/j.jclepro.2020.122259.
[101] Xiong X, Yu IKM, Cao L, Tsang DCW, Zhang S, Ok YS. A review of biochar-based catalysts for chemical synthesis, biofuel production, and pollution control. Bioresour Technol 2017;246:254–70. https://doi.org/10.1016/j.biortech.2017.06.163.
[102] Kambo HS, Dutta A. A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. Renew Sustain Energy Rev 2015;45. https://doi.org/10.1016/j.rser.2015.01.050.
[103] Qian K, Kumar A, Zhang H, Bellmer D, Huhnke R. Recent advances in utilization of biochar. Renew Sustain Energy Rev 2015;42:1055–64. https://doi.org/10.1016/j.rser.2014.10.074.
[104] Zhang X, Zhang P, Yuan X, Li Y, Han L. Effect of pyrolysis temperature and correlation analysis on the yield and physicochemical properties of crop residue biochar. Bioresour Technol 2020;296:122318. https://doi.org/10.1016/j.biortech.2019.122318.
[105] Pandey A, Bhaskar T, Stöcker M, Sukumaran RK. Recent advances in thermochemical conversion of biomass. Elsevier Inc.; 2015. https://doi.org/10.1016/C2013-0-00403-3.
[106] Al-Rumaihi A, Shahbaz M, Mckay G, Mackey H, Al-Ansari T. A review of pyrolysis technologies and feedstock: a blending approach for plastic and biomass towards optimum biochar yield. Renew Sustain Energy Rev 2022;167:112715.
[107] Goyal HB, Seal D, Saxena RC. Bio-fuels from thermochemical conversion of renewable resources: a review. Renew Sustain Energy Rev 2008;12. https://doi.org/10.1016/j.rser.2006.07.014.
[108] Li J, Dai J, Liu G, Zhang H, Gao Z, Fu J, et al. Biochar from microwave pyrolysis of biomass: a review. Biomass Bioenergy 2016;94:228–44. https://doi.org/10.1016/j.biombioe.2016.09.010.
[109] Liew RK, Nam WL, Chong MY, Phang XY, Su MH, Yek PNY, et al. Oil palm waste: an abundant and promising feedstock for microwave pyrolysis conversion into good quality biochar with potential multi-applications. Process Saf Environ Protect 2018;115:57–69. https://doi.org/10.1016/j.psep.2017.10.005.
[110] Luque R, Menéndez JA, Arenillas A, Cot J. Microwave-assisted pyrolysis of biomass feedstocks: the way forward? Energy Environ Sci 2012;5:5481–8. https://doi.org/10.1039/c1ee02450g.
[111] Kumar A, Saini K, Bhaskar T. Advances in design strategies for preparation of biochar based catalytic system for production of high value chemicals. Bioresour Technol 2020;299:122564. https://doi.org/10.1016/j.biortech.2019.122564.
[112] González-Cencerrado A, Ranz JP, López-Franco Jiménez MT, Gajardo BR. Assessing the environmental benefit of a new fertilizer based on activated biochar applied to cereal crops. Sci Total Environ 2020;711:134668. https://doi.org/10.1016/j.scitotenv.2019.134668.
[113] Akhtar J, Saidina Amin N. A review on operating parameters for optimum liquid oil yield in biomass pyrolysis. Renew Sustain Energy Rev 2012;16. https://doi.org/10.1016/j.rser.2012.05.033.
[114] Tadele D, Roy P, Defersha F, Misra M, Mohanty AK. Life Cycle Assessment of renewable filler material (biochar) produced from perennial grass (Miscanthus). AIMS Energy 2019;7:430–40. https://doi.org/10.3934/energy.2019.4.430.
[115] Dutta B, Raghavan V. A life cycle assessment of environmental and economic balance of biochar systems in Quebec. Int J Energy Environ Eng 2014;5:1–11. https://doi.org/10.1007/s40095-014-0106-4.
[116] Kambo HS, Dutta A. Strength, storage, and combustion characteristics of densified lignocellulosic biomass produced via torrefaction and hydrothermal carbonization. Appl Energy 2014;135:182–91. https://doi.org/10.1016/j.apenergy.2014.08.094.
[117] Bartocci P, Bidini G, Saputo P, Fantozzi F. Biochar pellet carbon footprint. Chem Eng Trans 2016;50:217–22. https://doi.org/10.3303/CET1650037.
[118] Liao M, Kelley S, Yao Y. Generating energy and greenhouse gas inventory data of activated carbon production using machine learning and kinetic based process simulation. ACS Sustainable Chem Eng 2020;8:1252–61. https://doi.org/10.1021/acssuschemeng.9b06522.
[119] Kim MH, Jeong IT, Park SB, Kim JW. Analysis of environmental impact of activated carbon production from wood waste. Environ Eng Res 2019;24:117–26. https://doi.org/10.4491/eer.2018.104.
[120] Gu H, Bergman R, Anderson N, Alanya-Rosenbaum S. Life cycle assessment of activated carbon from woody biomass. Wood Fiber Sci 2018;50:229–43. https://doi.org/10.22382/wfs-2018-024.
[121] Kadirvelu K, Thamaraiselvi K, Namasivayam C. Removal of heavy metals from industrial wastewaters by adsorption onto activated carbon prepared from an agricultural solid waste. Bioresour Technol 2001;76:63–5. https://doi.org/10.1016/S0960-8524(00)00072-9.
[122] Cossutta M, Vretenar V, Centeno TA, Kotrusz P, McKechnie J, Pickering SJ. A comparative life cycle assessment of graphene and activated carbon in a supercapacitor application. J Clean Prod 2020;242:118468. https://doi.org/10.1016/j.jclepro.2019.118468.
[123] Haeldermans T, Campion L, Kuppens T, Vanreppelen K, Cuypers A, Schreurs S. A comparative techno-economic assessment of biochar production from different residue streams using conventional and microwave pyrolysis. Bioresour Technol 2020;318:124083. https://doi.org/10.1016/j.biortech.2020.124083.
[124] Sharifzadeh M, Wang L, Shah N. Integrated biorefineries: CO2 utilization for maximum biomass conversion. Renew Sustain Energy Rev 2015;47:151–61. https://doi.org/10.1016/j.rser.2015.03.001.
[125] Moch JM, Xue W, Holdren JP. Carbon capture, utilization, and storage: technologies and costs in the U.S. context. Available at: www.belfercenter.org/publication/carbon-capture-utilization-and-storage-technologies-and-costs-us-context. [Accessed 20 January 2022]. accessed.
[126] Lange L, Connor KO, Arason S, Bundgård-Jørgensen U, Canalis A, Carrez D, et al. Developing a sustainable and circular bio-based economy in EU: by partnering across sectors, upscaling and using new knowledge faster, and for the benefit of climate, environment & biodiversity, and people & business. Front Bioeng Biotechnol 2021;8:1456. https://doi.org/10.3389/fbioe.2020.619066.
[127] de Jong E, Higson A, Walsh P, Wellisch M. Bio-based Chemical: Value added Products from Biorefineries. IEA Bioenergy – Task 42 Report. 2012. Available, www.ieabioenergycom/blog/publications/bio-based-chemicals-value-added-products-from-biorefineries/. [Accessed 30 March 2021]. accessed.
[128] Moreno A, Sumozas A, Olivia JM, Negro MJ. Chapter 1- bio-based industries. In: Galanakis CM, editor. Biobased products and industries. Amstredam, The Netherlands: Elsevier; 2020.
[129] Spierling S, Venkatachalam V, Mudersbach M, Becker N, Herrmann C, Endres HJ. End-of-life options for bio-based plastics in a circular economy-status quo and potential from a life cycle assessment perspective. Resources 2020;9. https://doi.org/10.3390/RESOURCES9070090.
[130] Wang C, Liu Y, Chen WQ, Zhu B, Qu S, Xu M. Critical review of global plastics stock and flow data. J Ind Ecol 2021;25. https://doi.org/10.1111/jiec.13125.
[131] Hottle TA, Bilec MM, Landis AE. Biopolymer production and end of life comparisons using life cycle assessment. Resour Conserv Recycl 2017;122. https://doi.org/10.1016/j.resconrec.2017.03.002.
[132] Goldsberry C. Oil Prices and the fate of bioplastics in the marketplace. Available at: https://www.;plasticstodaycom/biopolymers/oil-prices-and-fate-bioplastics-marketplace. [Accessed 30 March 2021]. accessed.
[133] JCJ Bart, Gucciardi E, Cavallaro S. The transition from reliance on fossil resources to biomass valorisation. Biolubricants 2013:74–120. https://doi.org/10.1533/9780857096326.74. Elsevier.