15 Life Cycle Assessment of Lignocellulosic Waste Biorefinery

V. Venkatramanan, Shachi Shah, Ram Prasad, and Mrinalini Shah

Abstract

The twenty-first century is witnessing fossil fuel depletion, increase in the atmospheric concentration of greenhouse gases, industrialization, urbanization and global climate change. There is a growing need to switch over to renewable energy resources and move towards circular bioeconomy. Sustainable bioeconomy has been promoted to replace fossil fuels and to produce bioenergy, chemicals and high value-added products. Biorefineries play a pivotal role in circular bioeconomy. Adoption of biorefineries is a win-win proposition both from the perspective of energy security and waste management. "*Biorefining is defined as the sustainable synergetic processing of biomass into a spectrum of marketable food and feed ingredients, products (chemicals, materials) and energy (fuels, power, heat)*". Biorefinery system endeavours to maximize the production of useful products from the biomass. Biorefineries adopt technologies which aim to process the biomass into diverse building blocks. The building blocks are further processed to generate biochemicals and biofuels. The biorefineries are classified based on key features such as (a) feedstocks used in the biorefinery, (b) conversion processes, (c) platform or intermediary products and (d) targeted products. The feedstocks including its characteristics, availability and biodegradability is one of the pertinent factors deciding the sustainability of

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biorefinery system. The debate between food and fuel has led to the search for second-generation biorefineries, which thrives on non-food biomass. The second-generation biorefineries utilize feedstocks such as residual biomass, lignocellulosic biomass and waste streams. The alternative biomass resources have huge potential for energy generation and can minimize fossil fuel use. Lignocellulose is the most abundant source of unutilised biomass. The positive attributes of lignocellulose biomass are year-round availability of biomass, renewability, sustainability, and amenability to conversion. Nevertheless, lignocellulosic waste biomass requires pretreatment for augmenting the efficiency of the conversion process. Several pretreatment strategies and methods such as physical, chemical and biological methods are adopted to enable lignin deconstruction. The pretreated lignocellulosic biomass through thermochemical conversion (combustion, gasification, hydrothermal processing, liquefaction, pyrolysis) and biochemical conversion are converted into bioenergy, biofuels, speciality chemicals and value-added products. Nevertheless, it is important to assess the impacts of biorefinery on the environment from the perspective of feedstocks, product generation and economic returns. The sustainability of the biorefineries is assessed through the life cycle assessment methodology. Life cycle assessment of biorefineries gains currency on account of (a) technological advancement, (b) bioconversion of diverse feedstocks into value-added products, (c) evaluation of the environmental performance of the biorefineries and (d) validating the sustainable conversion processes. As per ISO 14040, LCA involves four important components, namely goal, scope and functional unit; inventory analysis; impact assessment and interpretation. It has been observed that LCA of lignocellulosic biorefineries is greatly influenced by the methodological attributes, namely the “functional unit”, “system boundaries”, “allocation methods”, LCA approach, etc. LCA studies on lignocellulosic biorefineries reveal that the accuracy and reliability of LCA study are influenced by factors, not limited to data inadequacy, certain assumptions in LCA study and site-specific or local conditions. Though there are challenges to LCA of lignocellulosic waste biorefinery, importance must be placed on the sustainable production of value-added products, efficient utilization of resources, biovalorization and energy efficiency of the biorefinery system. The future research can be directed towards (a) sustainable biorefineries; (b) waste valorization; (c) upscaling the production of value-added products; (d) optimisation of bioconversion processes; (e) sustainable design configuration of the biorefinery; (f) role of biorefineries in the circular economy and (g) contribution of biorefineries in climate change mitigation.

Keywords

Life cycle assessment (LCA) · Biorefinery · Lignocellulosic Biorefinery · Feedstocks · Biomass

15.1 Introduction

The twenty-first century is witnessing fossil fuel depletion, increase in the atmospheric concentration of greenhouse gases, industrialization, urbanization and global climate change (Venkatramanan et al. 2020, 2021a). The key issues in the domain of energy sector include switching over to renewable energy resources (Prasad et al. 2021), use of bio-based feedstocks, waste valorization and bioenergy generation (Venkatramanan et al. 2021b). The need to reduce greenhouse gases emissions, to increase the dependence on sustainable energy resources (Prasad et al. 2019a, 2020) and to upscale the production of biofuel (Prasad et al. 2019b; Shah and Venkatramanan 2019) demands the development of circular bioeconomy (Venkatramanan et al. 2021b). Sustainable bioeconomy has been promoted to replace fossil fuels and to produce bioenergy, chemicals and high value-added products (Palmeros Parada et al. 2016; Venkatramanan et al. 2021b). The alternative biomass resources particularly the lignocellulosic feedstocks, agro-wastes, and food wastes have huge potential for energy generation and can minimize fossil fuel use. The utilization of lignocellulosic waste for the production of value-added products downplays the concerns about fossil fuel use and also the consequences of the population growth (Bello et al. 2018). Further, across the world, countries have initiated steps to tap the potential of bioeconomy. Use of alternative bio-based resources through biorefinery concept and related technology influence environmental sustainability (Shah et al. 2019).

LCA study is prominently adopted in the sustainability assessment of the biorefineries. The biorefineries in the recent past are multifunctional and multiproduct based and also use a diverse group of feedstocks. In effect, the environmental profile of the biorefineries is greatly influenced by the feedstocks used, the bioconversion processes adopted and also the system design of the biorefineries. In this context, the role of LCA study in biorefineries is significant. As per ISO 14040, LCA involves four important components, namely goal, scope and functional unit; inventory analysis; impact assessment; and interpretation. LCA of lignocellulosic biorefineries is greatly influenced by the methodological attributes, namely the “functional unit”, “system boundaries”, “allocation methods”, LCA approach, etc. The accuracy and also the reliability of LCA study are influenced by factors, not limited to data inadequacy, certain assumptions in LCA study and site-specific or local conditions. The uncertainty in the environmental profile of lignocellulosic waste biorefinery calls for sensitivity analysis. The sensitivity analysis enables to quantify the influence of an input (Bezergianni and Chrysikou 2020). The challenges to LCA of lignocellulosic waste biorefinery demand LCA study to be systematic, comprehensive and well-designed. Nevertheless, in the LCA study of lignocellulosic waste biorefineries, importance must be given on the sustainable production of value-added products, efficient utilization of resources, biovalorization and energy efficiency of the biorefinery system.

15.2 Lignocellulosic Waste Biomass

"Lignocellulose is the most abundant source of unutilised biomass" (Menon and Rao 2012). Lignocellulosic biomass which includes agricultural waste, agro-industrial wastes and energy crops, due to positive features like year-round availability of biomass, renewability, sustainability and amenability to conversion are gaining significance in the era of global change (Bilal and Iqbal 2020). Important constituents of lignocellulosic biomass are cellulose (40 to 50%), hemicellulose (25 to 30%) and lignin (15 to 20%). However, the rate of cellulose, hemicellulose and lignin varies significantly based on the feedstock (Table 15.1) (De Buck et al. 2020). Cellulose is the prime component of the cell wall and they are made up of glucose units linked through β (1 → 4) glycosidic linkages. In other words, the cellulose is composed of cellobiose chains. The cellobiose is a disaccharide, which is formed by the condensation of a pair of glucose molecules. The cellulose chains through hydrogen bonds form microfibrils. These cellulose microfibrils are attached by hemicellulose and polymers (pectin) (Fig. 15.1) (Menon and Rao 2012). So, hemicellulose enables interlinking of cellulose fibres and also interlinking of cellulose and lignin. Hemicellulose is composed of C5 (xylose) and C6 (glucose, galactose, mannose). The composition of hemicellulose varies with the feedstocks. The hemicellulose in hardwood is mostly xylans. In the case of softwoods, the hemicellulose is made of glucomannans (De Buck et al. 2020). Lignin is a "polyphenolic polymer". It is made of paracoumaryl alcohol, coniferyl alcohol and sinapyl alcohol. Lignin is a polymerization product of paracoumaryl alcohol, coniferyl alcohol and sinapyl alcohol. Nevertheless, the ratio of these alcohol components varies with layers of the cell wall, tissues and plant parts. Lignin due to tightly linked aromatic polymer is resistant to the hydrolytic process.

15.3 A Primer on Biorefinery

The International Energy Agency (IEA) Bioenergy Task 42 defines "*biorefining as the sustainable synergetic processing of biomass into a spectrum of marketable food & feed ingredients, products (chemicals, materials) and energy (fuels, power, heat)*" (IEA 2014). Biorefinery system includes "*upstream (biomass production, transportation, pretreatment), midstream (biomass conversion to the targeted products) and downstream (product distribution) processing of bio-based feedstocks*" (Bezergianni and Chrysikou 2020). Biorefinery system endeavours to maximize the production of useful products from the biomass. Biorefineries adopt technologies which aim to process the biomass into diverse building blocks. The building blocks are further processed to generate biochemicals and biofuels (Fig. 15.2). Cherubini et al. (2009) attempted to classify or group the biorefineries based on key features such as (a) feedstocks used in the biorefinery, (b) conversion processes, (c) platform or intermediary products and (d) targeted products.

Table 15.1 Composition of representative lignocellulosic feedstocks

	Carbohydrate composition (% dry wt)			
Feedstocks	Cellulose	Hemicellulose	Lignin	References
Barley hull	34	36	19	Kim et al. (2008)
Barley straw	36–43	24–33	6.3–9.8	Garda-Aparicio et al. (2006) and Rowell (1992)
Bamboo	49–50	18–20	23	Alves et al. (2010)
Corn cob	32.3–45.6	39.8	6.7–13.9	Cao et al. (1997) and McKendry (2002)
Corn stover	35.1–39.5	20.7–24.6	11.0–19.1	Mosier et al. (2005)
Cotton	85–95	5–15	0	Kadolph and Langford (1998)
Cotton stalk	31	11	30	Rubio et al. (1998)
Douglas fir	35–48	20–22	15–21	Schell et al. (1999)
Eucalyptus	45–51	11–18	29	Pereira (1988) and Alves et al. (2010)
Hardwood stems	40–55	24–40	18–25	Howard et al. (2003) and Malherbe and Cloete (2002)
Rice straw	29.2–34.7	23–25.9	17–19	Brylev et al. (2001) and Prasad et al. (2007)
Rice husk	28.7–35.6	11.96–29.3	15.4–20	Allen et al. (2001) and Abbas and Ansumali (2010)
Wheat straw	35–39	22–30	12–16	Prasad et al. (2007)
Wheat bran	10.5–14.8	35.5–39.2	8.3–12.5	Miron et al. (2001)
Grasses	25–40	25–50	10–30	Stewart et al. (1997)
Newspaper	40–55	24–39	18–30	Howard et al. (2003)
Sugarcane bagasse	25–45	28–32	15–25	Alves et al. (2010) and Singh et al. (2009)
Sugarcane tops	35	32	14	Jeon et al. (2010)
Pine	42–49	13–25	23–29	Pereira (1988)
Poplar wood	45–51	25–28	10–21	Torget and Hsu (1994)
Olive tree biomass	25.2	15.8	19.1	Cara et al. (2008)
Jute fibres	45–53	18–21	21–26	Mosihuzzaman et al. (1982)
Switchgrass	35–40	25–30	15–20	Howard et al. (2003)
Grasses	25–40	25–50	10–30	Howard et al. (2003) and Malherbe and Cloete (2002)
Winter rye	29–30	22–26	16.1	Petersson et al. (2007)
Oilseed rape	27.3	20.5	14.2	Petersson et al. (2007)
Softwood stem	45–50	24–40	18–25	Howard et al. (2003) and Malherbe and Cloete (2002)
Oat straw	31–35	20–26	10–15	Rowell (1992)
Nut shells	25–30	22–28	30–40	Sinner et al. (1979)
Sorghum straw	32–35	24–27	15–21	Herrera et al. (2003) and Vázquez et al. (2007)

(continued)

Table 15.1 (continued)

Feedstocks	Carbohydrate composition (% dry wt)			References
	Cellulose	Hemicellulose	Lignin	
Tamarind kernel powder	10–15	55–65	–	Menon et al. (2010)
Water hyacinth	18.2–22.1	48.7–50.1	3.5–5.4	Nigam (2002) and Aswathy et al. (2010)

Source: With permission from Menon and Rao (2012)

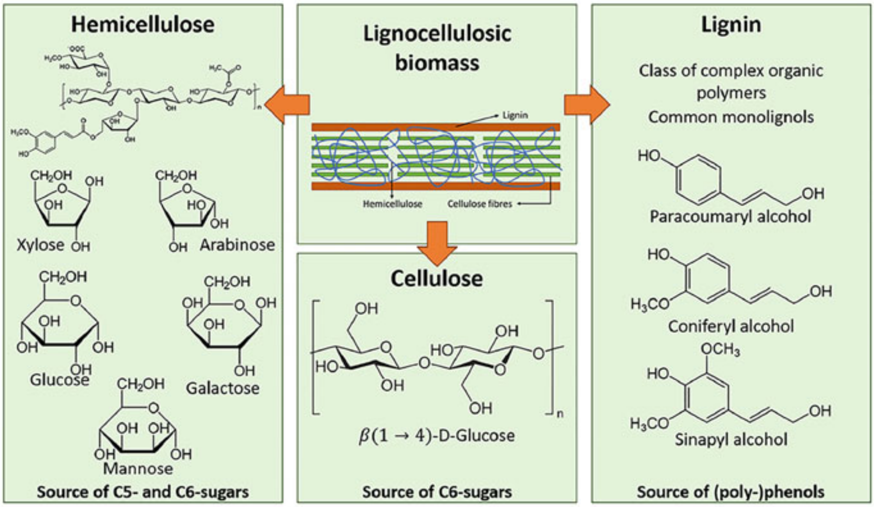

Fig. 15.1 Lignocellulosic biomass. (Source: Isikgor and Becer 2015; De Buck et al. 2020. "Modelling Biowaste Biorefineries: A review" by De Buck et al. 2020 is licensed under CC BY. Accessed at https://www.frontiersin.org/articles/10.3389/fsufs.2020.00011/full)

15.3.1 Biorefinery Generations and Associated Feedstocks

First-generation biorefineries utilize feedstocks such as food crops to produce biofuels and other value-added products (De Buck et al. 2020). Nevertheless, the sustainability of first-generation biorefineries is challenged by the debate on food versus fuel. It must be noted that crops such as corn, rapeseed, etc. contribute immensely to the production of bioethanol. For long-term sustainability and increasing food demand, the focus has been shifted towards other feedstocks that are rich in carbohydrates and available in plenty. Among the non-food crop-based feedstocks, lignocellulosic waste, municipal solid waste, agricultural wastes, food wastes, etc. are potential candidates. The second-generation biorefinery utilizes feedstocks such as residual biomass, lignocellulosic biomass and waste streams (De Buck et al. 2020). The waste normally used as feedstocks in the second-generation biorefineries include agricultural farm wastes/residues, forestry wastes, industrial wastes,

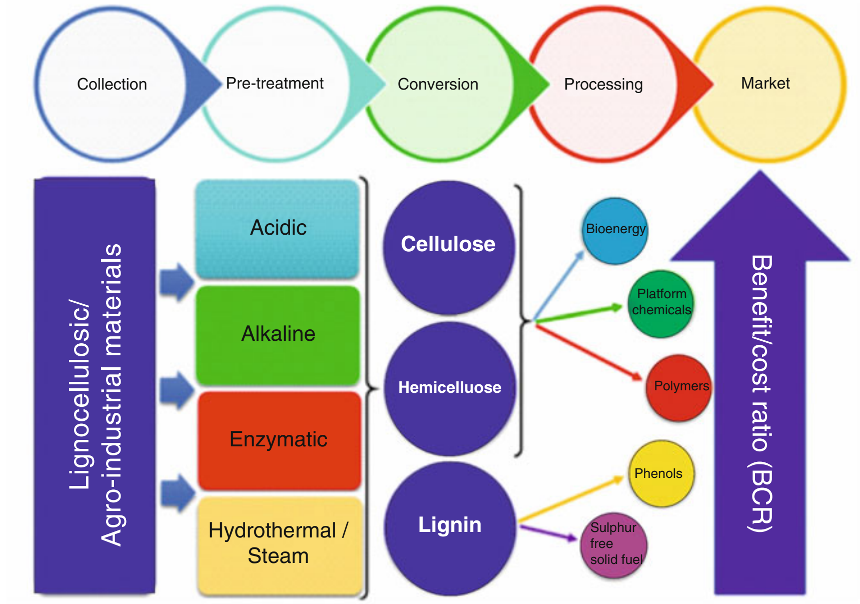

Fig. 15.2 Concept of biorefinery. (Source: With permission from Arevalo-Gallegos et al. 2017)

municipal solid wastes, kitchen wastes, etc. Biowaste refineries are prevalent widely and possess sustainability features as compared to the first-generation biorefineries. The third-generation biorefineries utilize feedstocks such as algal biomass (Bezergianni and Chrysikou 2020). These algal biorefineries are still under development and require research and development (De Buck et al. 2020).

15.3.2 Conversion Platforms

The conversion processes employed in biorefineries are significant, as they influence (a) economic and environmental feasibility of the biorefinery system, (b) process carbon efficiency and (c) environmental impacts like greenhouse gas emissions, eutrophication, acidification, etc. To better understand the conversion processes, Cherubini et al. (2009) grouped the conversion platforms into categories such as biochemical, thermochemical and hybrid processes (De Buck et al. 2020). The thermochemical conversion processes generally employ chemical processes such as pyrolysis and gasification for the conversion of feedstocks into valuable products. On the other hand, the biochemical processes use the action of microorganisms and enzymes for the bioconversion of feedstocks. In the case of hybrid processes, both the thermochemical and biological processes are employed in the conversion of biological feedstocks (De Buck et al. 2020).

15.3.3 Lignocellulosic Biorefinery

Sustainable bioeconomy provides a gateway to checkmate the global challenges including depletion of fossil fuels and climate change. “Bioeconomy involves the production and sustainable use of biological resources to further growth of the sustainable economy through generation of information, knowledge, bioproducts, ecosystem services and innovative processes” (Venkatramanan et al. 2021b). Bioeconomy has been encouraged as a strategy to replace fossil fuels and to produce bioenergy, chemicals and value-added products (Palmeros Parada et al. 2016). In this context, the concept of biorefineries is gaining currency. Lignocellulosic waste biorefineries are prominent due to the key characteristics of lignocellulosic waste feedstocks. The lignocellulosic feedstocks are known for its “sustainability, bio-renewability, availability round the year, recyclability” (Bilal and Iqbal 2020).

Lignocellulosic waste biomass requires pretreatment for augmenting the efficiency of the conversion process. Several pretreatment strategies and methods such as physical, chemical, and biological methods are adopted to enable lignin deconstruction (Fig. 15.3) (Menon and Rao 2012; Galbe and Wallberg 2019; De Buck et al. 2020; Bilal and Iqbal 2020). Through physical pretreatment, the lignocellulosic biomass is treated using methods like grinding, milling, irradiation and extrusion. The basic aims of physical pretreatment are size reduction, improving

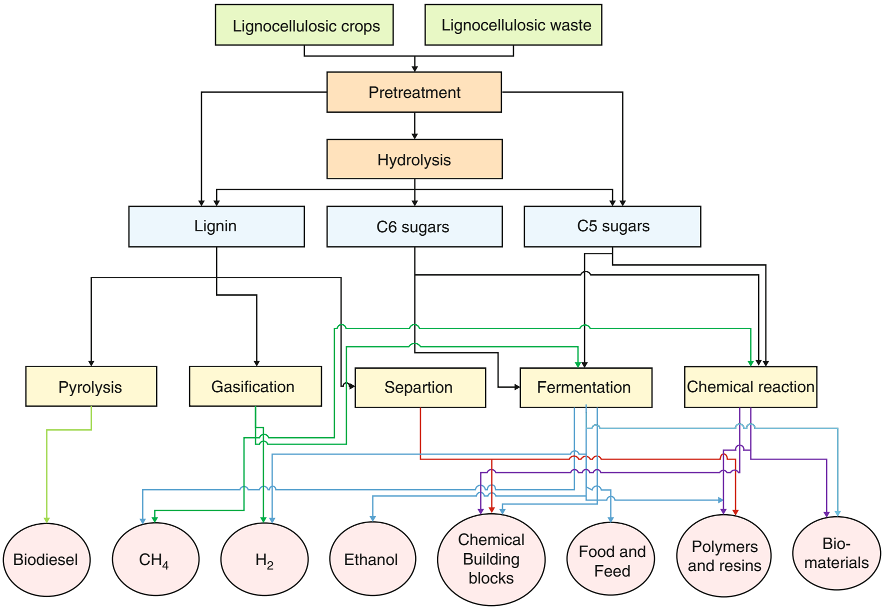

Fig. 15.3 A schematic representation of lignocellulosic biorefinery. (Source: Galbe and Wallberg 2019; “Pre-treatment for biorefineries: a review of common methods for efficient utilisation of lignocellulosic materials” by Galbe and Wallberg 2019 is licensed under CC BY. Accessed at https://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-019-1634-1)

enzymatic hydrolysis process, biodegradation of lignocellulosic waste and reducing crystallinity. Nevertheless, the physical pretreatment methods are energy-intensive and cost-intensive (Menon and Rao 2012; Galbe and Wallberg 2019; De Buck et al. 2020).

The physico-chemical treatment process integrates both physical and chemical process to increase the efficiency of the pretreatment process and enable degradation of lignocellulosic biomass. In this category, the common methods employed are steam explosion, ammonia fibre explosion (AFEX), ammonia recycle percolation (ARP), microwave-chemical pretreatment, liquid hot water pretreatment, etc. (Menon and Rao 2012). In case of steam explosion, the lignocellulosic waste biomass is treated with saturated steam (160–260 °C) (0.69–4.83 MPa) for a few minutes and subsequently, the pressure is reduced leading to explosive decompression. The water in the biomass explodes during the process of explosive decompression. The steam explosion pretreatment aims at hemicellulose hydrolysis and lignin degradation. In the case of liquid hot water treatment, the biomass is treated (cooked) in hot water at high pressure. This pretreatment process increases the "cellulose digestibility" and "sugar extraction". Concerning ammonia fibre explosion, the biomass is treated with liquid ammonia (1–2 kg of ammonia/kg of dry mass) at high temperature (90 °C) for about 30 min. This process enables the degradation of cellulose and hemicellulose and aids in augmenting the fermentation rate (Menon and Rao 2012; Galbe and Wallberg 2019; De Buck et al. 2020).

The chemical pretreatment methods are studied among the pretreatment methods. They include acid pretreatment, alkaline pretreatment, green solvents, etc. The basic purpose of chemical pretreatment methods is to improve the degradation of cellulose and to remove the lignin. In the case of acid pretreatment, acids (dilute or concentrated sulphuric acid/hydrochloric acid/phosphoric acid/nitric acid) are used to enable degradation of lignocellulosic waste. As regards the alkali pretreatment, bases such as sodium hydroxide and lime are used to treat the lignin-rich waste biomass (Menon and Rao 2012; Galbe and Wallberg 2019). Alkali pretreatment results in "*structural alteration of lignin, cellulose swelling, partial decrystallization of cellulose*" (Menon and Rao 2012).

Biological pretreatment methods employ the microorganisms and enzyme products for the treatment of lignocellulosic biomass. Interestingly, many microorganisms including fungi and bacteria are reported to degrade and to modify the chemical composition of lignocellulosic biomass. The rot fungi (basidiomycetes) are best known for the degradation of lignin. Particularly, the white-rot fungi like *Phanerochaete chrysosporium* are best known for lignin degradation. Nevertheless, the biological pretreatment process is time-consuming and demands controlled growth conditions for microbial activity (Menon and Rao 2012; Galbe and Wallberg 2019; De Buck et al. 2020).

The pretreated lignocellulosic biomass through thermochemical conversion (combustion, gasification, hydrothermal processing, liquefaction, pyrolysis) and biochemical conversion are converted into bioenergy, biofuels, speciality chemicals and value-added products. The products of pretreatment of lignocellulosic biomass are cellulose (C6), hemicellulose (C5/C6) and lignin. These intermediary compounds are transformed into biofuels and value-added chemicals (Fig. 15.4)

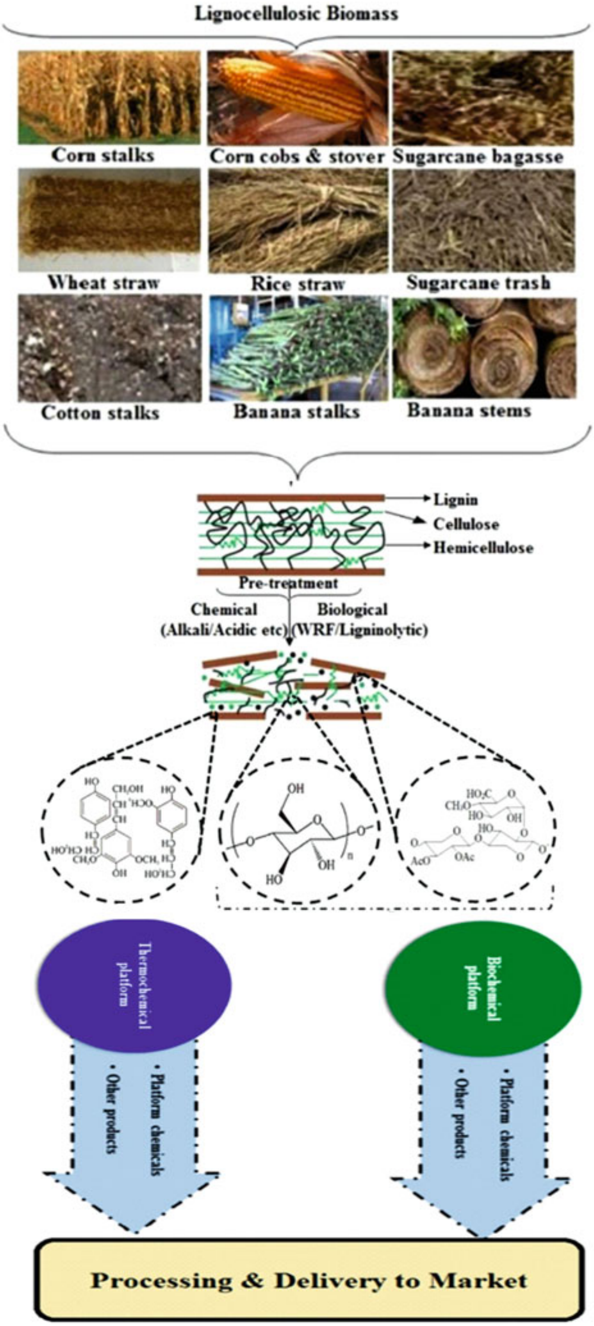

Fig. 15.4 Lignocellulosic waste bioconversion into platform chemicals. (Source: With permission from Arevalo-Gallegos et al. 2017)

Table 15.2 Value-added chemicals potentially derived from lignocellulosic biomass

Biomass	Constituents	Polymers	
Lignocellulosic biomass	Cellulose	Levulinic acid	Succinic acid, THF, MTHF, 1,4 butanediol, NMP, lactones
		Ethanol	Acrylic acid, acetaldehyde
		Lactic acid	2,3-pentanedione, Pyruvic acid
		3-hydroxypropionic acid	3-methyl THF, 3-methyl pyrrolidone
		Itaconic acid	2, methyl-1,4-butane diamine Itaconic diamide
		Glutamic acid Glucuronic acid Succinic acid	2-pyrrolidones, 1,4-butanediol, tetrahydrofuran
	Hemicellulose	Xylitol	
		Ethanol, butanol, 2,3-butanediol	
		Ferulic acid	Vanillin, vanillic acid, Protocatechuic acid
		Lactic acid	
		Furfural	
		Chitosan	
		Xylooligosaccharides	
	Lignin	Syngas	
		Syngas products	Methanol/dimethyl Ether, ethanol, mixed Liquid fuels
		Hydrocarbons	Cyclohexanes, higher Alkylates
		Phenols	Cresols, eugenol, Coniferols, syringols
		Oxidized products	Vanillin, Vanillic acid, DMSO, aldehydes, quinones, aromatic and aliphatic acids
		Macromolecules	Carbon fibres, Activated carbon, Polymer alloys, Polyelectrolytes, Substituted lignins, Thermosets, Composites, wood Preservatives, Nutraceuticals/drugs, Adhesives and resins

Source: With permission from Menon and Rao (2012)

(Table 15.2) (Menon and Rao 2012; Arevalo-Gallegos et al. 2017; Galbe and Wallberg 2019; De Buck et al. 2020; Bilal and Iqbal 2020).

15.4 Life Cycle Assessment

Growing population demands more food, feed and energy and consequently, there is a dire need to optimize the production of biomass and value-added products from the biomass. Generation of energy and high value-added chemicals and products from biomass provides a fillip to the bio-based economy and reduces the dependence on fossil fuels (Venkatramanan et al. 2021b). In this regard, technological developments like biorefineries are highly significant as they have the potential to use diverse feedstocks ranging from the food crops, non-food crops to lignocellulosic wastes, municipal solid wastes and food wastes (Parajuli et al. 2017). Nevertheless, the impact of biorefinery on the environment need to be assessed from the perspective of feedstocks, product generation and economic returns. The sustainability of the biorefineries is assessed through the life cycle assessment methodology. Life cycle assessment of biorefineries gains currency on account of (a) technological advancement, (b) bioconversion of diverse feedstocks into value-added products, (c) evaluation of the environmental performance of the biorefineries and (d) validating the sustainable conversion processes (Bezergianni and Chrysikou 2020).

Nevertheless, sustainable assessment of a biorefinery system should involve more than identification and quantification of environmental impacts. Multi-product biorefineries and integrated biorefineries need an assessment on eco-efficiency. Several studies have noted the significance of assessment of lignocellulosic biorefineries both from the environmental and economic perspectives. The LCA methodology and the eco-efficiency concept enable a comprehensive assessment of biorefinery sustainability. Further, extending the horizon of LCA methodology to incorporate the social dimensions through social life cycle assessments adds immense value and credibility to the assessment methodology. To gauge the social sustainability of the biorefineries, socio-economic indicators are widely used (Palmeros Parada et al. 2016). The integration of sustainability principles in the design of biorefineries is critical for the advancement of bioeconomy.

Life cycle assessment is a comprehensive and intensive approach that endeavours to assess the environmental impacts of products in its production process (Pant et al. 2011). An intensive assessment of the biorefinery system also aids in reducing or minimizing the negative impacts. Life cycle assessment methodology intents to figure out the environmental impacts related to a production process. Assessment of the production process through LCA methodology reveals the process subsystems that greatly influence the environmental consequence of a system. In other words, the LCA study of a biorefinery system provides a valuable output in terms of identification of "process hotspots" in the process value chain. Further, optimization of the process hotspots in the lignocellulosic biorefineries entails the optimization of the pretreatment process, technologies and production of value-added products (Bello et al. 2018).

Life cycle assessment of biorefineries reveals the "environmental profile of the biorefineries", "feedstock optimization" and "process configuration" (Bezergianni and Chrysikou 2020). Life cycle assessment studies can be grouped into attributional and consequential LCA study based on the processes that are included in the system boundary. The attributional LCA study identifies and quantifies the environmental impact of a product/system through a time-tested process. The attributional LCA study provides inputs regarding the hotspots in the production process. On the other hand, the consequential LCA study reflects on the potential impacts emanating from the future decisions that have significant influences on the study systems (Bezergianni and Chrysikou 2020).

15.4.1 Purpose of LCA in Biorefineries

Studies on LCA of biorefinery system (Uihlein and Schebek 2009; Bernstad Saraiva 2017; Julio et al. 2017; Van Hung et al. 2020; Bezergianni and Chrysikou 2020) throws light on the following purpose of undertaking LCA study.

(a) To optimize and efficiently use the feedstocks in a biorefinery system.
(b) To identify efficient conversion and recycling paths.
(c) To identify sustainable biorefinery system.
(d) To produce specific bioproducts (value-added products and chemicals) from the diverse group of feedstocks.
(e) To improve and upscale the production processes and generation of value-added products.
(f) To identify the negative impacts kindred with the biorefinery process.
(g) To identify the hotspots in the production process or the life cycle of biorefinery.
(h) To identify a sustainable pathway for feedstock conversion from the perspectives of technology, value-addition and eco-efficiency.
(i) To develop sound decision support tool and consequently to perform strategic planning and policymaking.

15.4.2 LCA Framework

As per ISO 14040, LCA involves four important components (Fig. 15.5). They are as follows (Van Hung et al. 2020):

- The goal, scope and functional unit.
- Inventory analysis.
- Impact assessment.
- Interpretation.

The first and foremost step in LCA is goal setting. The goal relates to the motivation and purpose of the LCA study. The goal also states the target audience and also the potential application of LCA study. In the LCA study on biorefinery producing bioenergy, bioethanol and value-added chemicals from switchgrass as feedstock,

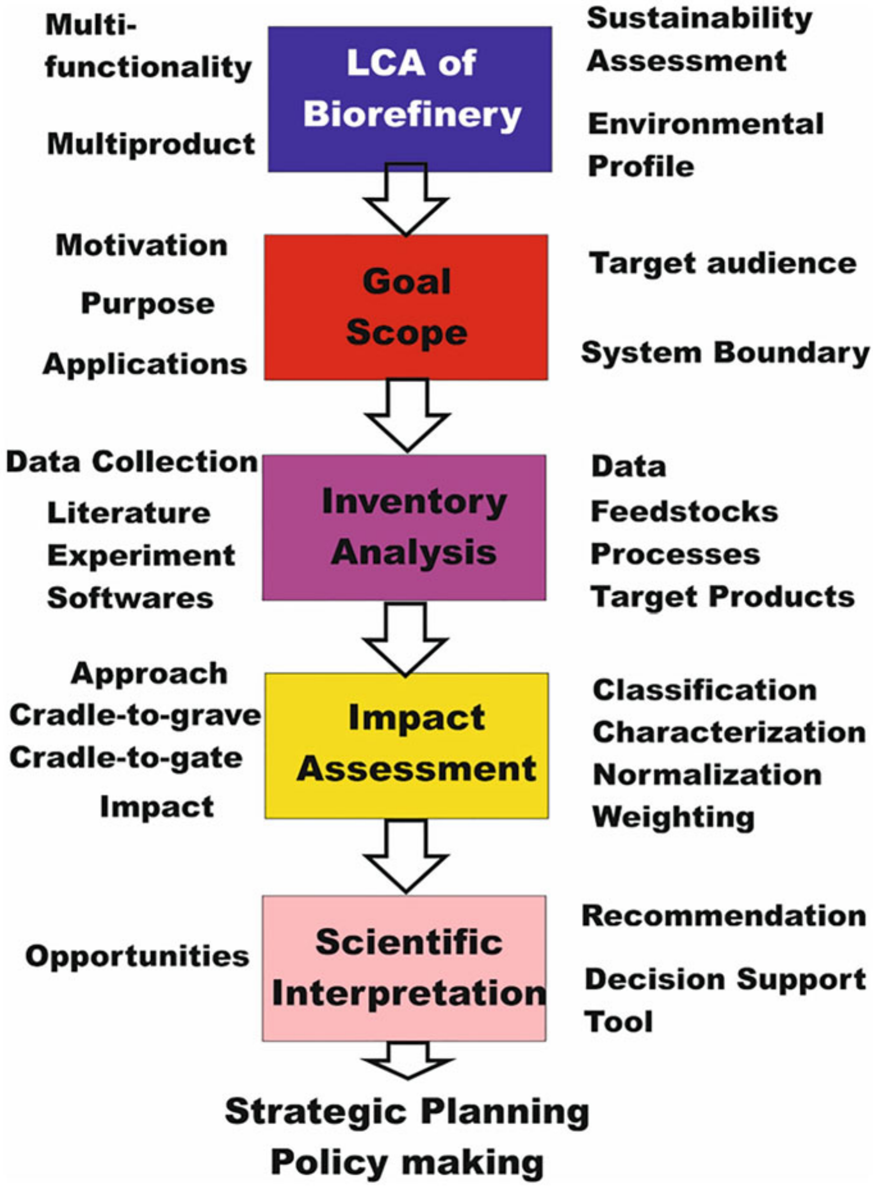

Fig. 15.5 LCA methodology and framework

Cherubini and Jungmeier (2010) stated the goal as a comparative analysis of fossil fuel-based system with the biorefinery system. The goal of the LCA study draws the broad contour of opportunities and scope of LCA study. The LCA study on biorefineries incorporates assessments related to greenhouse gas emissions, waste management, bioenergy, value-added chemicals and bioproducts (Gnansounou 2017). The goal of the LCA study defines the functional unit. The functional unit reflects the function of the system under study and also the targeted value-added products. Generally, in the LCA study, the functional unit can be the "mobility indicator" such as kilometre or energy unit (megajoules). Energy unit is adopted as a functional unit in case of comparative analysis of biorefineries adopting different pathways to produce bioethanol. In effect, approaches adopted to define the functional unit in case of integrated biorefineries include either biomass input or the targeted product. The goal and scope definition including the system boundaries and, functional unit decides the methodology of the LCA study (Bezergianni and Chrysikou 2020).

In the recent past, biorefineries are looked upon as a bio-based technology with an intent to produce multiple products. The multifunctionality of the integrated biorefineries calls for allocating the environmental impacts of the biorefineries among various outputs as well (IEA 2019). The multi-products generated from the biorefinery possess varied attributes and also diverse applications. Under such circumstances, the LCA of multi-product biorefinery is complicated. Similarly, in the case of multifunctional biorefineries wherein a single activity may have multiple functions. For instance, the lignocellulosic biorefineries involve in addition to waste management, generation of energy and high value-added products. In this case, as well, there is a need to allocate the burdens or environmental impacts between the production processes (Bezergianni and Chrysikou 2020). In the LCA of multi-product biorefinery, it is a great challenge to allocate the inputs and outputs between different products. However, ISO 14044 does not recommend allocation. Due to the multifunctionality of the integrated biorefineries, there is a need for a fool-proof allocation procedure. The procedures such as economic allocation, gross energy allocation and mass allocation are adopted to allocate the resource input and releases among the products of the biorefinery system. Allocation in the LCA of biorefineries can be applied either through system expansion or by partitioning method. In the former case, the functional unit is suitably reframed to incorporate the functions of all the co-products. In the latter case, the environmental impacts are allocated among the products based on their "mass, volume or energy content" or economic features like the market price of the products, etc. (Bezergianni and Chrysikou 2020). However, it must be noted that the methods of allocation should be implemented aptly.

Life cycle inventory analysis is a very significant step in the LCA study. Based on the goal of the LCA study, the LCA inventory analysis includes an intensive collection of data about the feedstocks or inputs, production processes and targeted value-added products. Data inadequacy is a challenge in the LCA study. In this regard, software such as SimaPro and GEMIS envisages simplification of the environmental assessment of biorefineries (Bezergianni and Chrysikou 2020). In the life cycle analysis, the system boundaries are specified. The system boundary states the biomass production, bioconversion process into value-added products and energy supply system. The system boundaries in case of LCA of biorefineries depend on the feedstocks (Bernstad Saraiva 2017). As regards the feedstocks for biorefineries, it can be either a dedicated biomass feedstock or lignocellulosic residues as in the case of lignocellulosic waste biorefineries. LCA of biorefineries involving dedicated biomass as feedstock, factor in the environmental impacts due to the inputs and also land-use changes. On the other hand, LCA of lignocellulosic biorefineries which uses lignocellulosic wastes as feedstock, allocate zero environmental burdens to the feedstock.

As regards the LCA approach, IEA (2019) recommends generally cradle-to-grave life cycle approach. Nevertheless, due to data inadequacy, a cradle-to-gate approach is also followed. While the cradle-to-gate approach involves life cycle of the study system until the production stage, the cradle-to-grave life cycle approach involves life cycle of the system including reuse and recycle of the products (Bezergianni and Chrysikou 2020). For instance, in the case of LCA of rice-based biorefinery, the cradle-to-grave life cycle approach incorporates the environmental impacts emanating from the rice cultivation stage to the ultimate consumption of the products by the consumers. In the case of cradle-to-gate approach, the LCA of rice-based biorefinery incorporates the environmental impacts from paddy cultivation, crop residue collection, transportation and final processing at the biorefinery plant (Sreekumar et al. 2020). In both the approaches, the consumption of resources or inputs and the emissions are quantified (Bezergianni and Chrysikou 2020).

The life cycle impact assessment follows the life cycle inventory analysis. In other words, the output of the life cycle inventory analysis forms an input to the life cycle impact assessment. The life cycle impact assessment involves steps such as classification, characterization normalization and weighting. The environmental impact categories considered in LCA study are “global warming”, “abiotic and biotic resource depletion”, “acidification”, “stratospheric ozone depletion”, “eutrophication”, “photochemical oxidation” and “human toxicity” (Gnansounou 2017; Bezergianni and Chrysikou 2020). Studies observe that the impact categories considered in the LCA of biorefineries should not be limited to the greenhouse gas emissions and energy balances (Finkbeiner 2009). Studies by Uihlein and Schebek (2009) on LCA of lignocellulosic biorefineries categorically included the impact categories like fossil fuel use, land use and human toxicity. As stated by Bezergianni and Chrysikou (2020), the LCA of biorefineries include impact categories such as “greenhouse gas emissions”, “acidification potential”, “ozone-depleting potential” and “photochemical ozone creation potential”. However, it must be noted that a comprehensive inclusion of impact categories provides a detailed environmental profile of the lignocellulose biorefinery.

Scientific interpretation follows the life cycle impact assessment. Scientific interpretation aids to figure out the opportunities and provides scope for improvement in the lignocellulosic waste biorefineries.

In the LCA study, for assessing the environmental profile of lignocellulosic biorefinery, there is a need for a reference system for comparative analysis. Since, most often, the main product of biorefinery is the biofuel, the reference system will be a fossil fuel-based refinery system. In such a case, it will be also beneficial to assess the sustainability of switching over from fossil fuel-based system to biorefinery (Bezergianni and Chrysikou 2020).

LCA of lignocellulosic biorefineries is greatly influenced by the methodological attributes, namely the “functional unit”, “system boundaries”, “allocation methods”, LCA approach, etc. The accuracy and also the reliability of LCA study are influenced by factors, not limited to data inadequacy, certain assumptions in LCA study and site-specific or local conditions. Uncertainties exist in the environmental assessment of lignocellulosic biorefineries, perhaps due to the methodological aspects of LCA study. The uncertainty in the environmental profile of lignocellulosic waste biorefinery calls for sensitivity analysis. Through sensitivity analysis, the variables that cause significant environmental impacts can be identified (Julio et al. 2017). In other words, the sensitivity analysis enables to quantify the influence of an input (Bezergianni and Chrysikou 2020).

15.4.3 Challenges

The LCA of the lignocellulosic waste biorefinery is indeed a complicated process. It involves detailed inputs from (a) types of lignocellulosic waste feedstocks; (b) amount of lignocellulose waste available; (c) characteristic features of lignocellulosic waste feedstocks; (d) bioconversion processes; (e) energy intensity; (f) co-products/value-added products, etc. The LCA methodology adopted in the study of lignocellulosic waste biorefinery endeavours to identify and quantify the environmental impacts. In the process, in addition to eliciting the environmental impacts of the lignocellulosic waste biorefinery, the LCA study figures out the hotspots in the production process/bioconversion process. Further, the challenges to LCA of lignocellulosic waste biorefineries are data inadequacy, the rigidity of the system boundary, diverse co-products generation, local environmental conditions, etc. The challenges to LCA of lignocellulosic waste biorefinery demand LCA study to be systematic, comprehensive and well-designed. Nevertheless, in the LCA study of lignocellulosic waste biorefineries, importance must be given on the sustainable production of value-added products, efficient utilization of resources, biovalorization and energy efficiency of the biorefinery system.

15.5 Conclusion

The biorefinery system is being promoted to replace a fossil fuel-based energy use. Further, adoption of biorefineries greatly aids in the utilization of a diverse group of renewable feedstocks, waste valorization and development of sustainable bioeconomy and circular economy. The biorefineries through the “thermochemical processes” and “biochemical processes” convert the biomass into bioenergy, chemicals and value-added products. The future research can be directed towards (a) sustainable biorefineries; (b) waste valorization; (c) upscaling the production of value-added products; (d) optimization of bioconversion processes; (e) sustainable design configuration of the biorefinery; (f) role of biorefineries in the circular economy and (g) contribution of biorefineries in climate change mitigation.

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