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Review

# Sustainable utilization of crop residues for energy generation: A life cycle assessment (LCA) perspective

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ABSTRACT

Modernization in the crop cultivation and development of high yielding varieties resulted in increased crop residues. A large portion of crop residues is not handled appropriately, which leads to environmental burden on society. The crop residues are rich in organic substances, which can be better utilized for various purposes, including energy generation. The utilization of crop residues for energy generation has partially contributed to resolve the inappropriate handling practices, thus reducing their environmental impacts. Life cycle assessment (LCA) is used as a tool to investigate environmental sustainability and can be explored to integrate with social and economic effects to quantify environmental impacts for energy generation from crop residues. This review will provide a comprehensive understanding on LCA inference for decision support to policy-makers and different relevant choices to various applications for sustainable energy generation from crop residues.

## 1. Introduction

Agricultural crops are playing a major role in feeding everyone on the globe. Increasing population triggered the cultivation of high yielding crop varieties and utilization of modern cultivation practices. However, the increased production of food grains also increased the production of crop residues in the form of stalks, stubbles, leaves, seed pods, etc. The crop residues are being used as animal feed and fuel for cooking purposes in rural areas (Prasad et al., 2018), and a considerable amount of the crop residues is left unutilized on the field/farms. The proper disposal of leftover crop residues is a significant challenge (Prasad et al., 2012; Kumar et al., 2016). The faulty management of surplus crop residue contributed huge environmental burden on society. The northern part of India, for example, suffers from extreme air pollution caused by the burning of the rice stalks (Sawlani et al., 2019; Tripathi et al., 2019).

Increasing energy demand, depleting fossil reserves, sustainable management of crop residues, and pollution from consumption of conventional fuels has created attention towards sustainable energy generation from biomass (Singh and Olsen, 2011; Prasad et al., 2014; Rathore et al., 2019). There is a great need to develop a renewable biofuel economy to reduce reliance on fossil fuels, reduce greenhouse gas (GHG) emissions, and enhance rural economies (McLaughlin et al., 2002). Lal (2005) stated that the main strategy for mitigation of the greenhouse effect is to reduce and off-set anthropogenic emissions of $CO_2$ and other GHGs, and there is a need to develop carbon–neutral renewable sources of energy. Crop residues are cellulosic material having high fixed carbon content, could be a potential source of feedstock for energy generation, and need to be critically and objectively assessed because of its positive impact on soil carbon sequestration, soil quality maintenance, ecosystem functions, etc.

Energy conversion, utilization and access underlie many of the great challenges associated with sustainability, environmental quality, security and poverty (Singh et al., 2011; Korres et al., 2010). A number of techniques are available to produce different biofuels such as bioethanol (Kumar et al., 2020; Prasad et al., 2020; Akbarian-Saravi et al.,

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2020), biomethane (Long and Murphy, 2019; Zhu et al., 2019), biohydrogen (Yang et al., 2019; Kannah et al., 2019), etc. using crop residue as raw material. The sustainability of energy generation from biomass depends on a precise assessment of the availability of biomass, planning of cost-effective logistics, and evaluation of expected environmental implications (Hiloidhari et al., 2017). The sustainability of various techniques in terms of cost-effectiveness, Net Energy Ratio (NER), and emission generation during production and consumption, which leads to the social, economic and environmental impact on the society, need to be explored before developing any policy. The influence of energy products and services on the environment has become an essential ingredient of decision-making processes for framing new policies.

Life cycle assessment (LCA) is a tool, which can effectively use for assessment of environmental burden of available technologies and to compare various techniques (Singh et al., 2013). LCA can also suggest alternative sub-processes to make the process sustainable.

The present review is an effort to provide comprehensive understanding based on LCA for decision support to policy-makers and different relevant choices to various applications for sustainable energy generation from crop residues.

## 2. Crop residues

Crop residues are the leftover material of harvested crops such as stalks, stubbles, husk, bagasse, seed pods, etc. (Sharma et al., 2018). In general, crop residues contain high amount of Carbon (C), Nitrogen (N), Phosphorus (P), Potassium (K), and other minerals depending upon the crop. Additionally, post-harvest losses contribute to a substantial proportion of the agricultural biomass loss, most of which happen at the farm before and during harvest, distribution, transportation, and wastage at the level of the consumer (Cardoen et al., 2015a).

### 2.1. Availability of surplus of crop residues

Globally, the production of crop residues is increasing as Cherubin et al. (2018) estimated the crop residues production for the USA, Asia, Africa, Europe and World for the year 2003 and 2013 and reported that about 3803 Million Tons (MT) crop residues were produced from different crops viz. cereals, legumes, oilseeds, sugar and tuber crops in the world during year 2003, which was reached to 5011 MT (31.7% higher than the year 2003) in the year 2013 (Table 1).

According to Hiloidhari et al. (2014), in India, the total dry biomass of 686.0 MT was generated annually from the various crops (Table 2). It was estimated that annually 234.5 MT is surplus crop residue available in India; this is being 34.2% of the total identified crop residue generation in India. It has been estimated that among the total agricultural field residues generated in India, about 75% of it utilized as fodder and other purposes in agriculture and households such as mulching, composting, fuel, thatch, etc. The remaining 25% of agricultural field residue can be considered as potentially available biomass for bio-based industry (Cardoen et al., 2015b).

**Table 2**
Gross and surplus crop residue potential in India (adapted from Hiloidhari et al., 2014).

| Crop group | Crop residue* (MT) | |
|---|---|---|
| | Gross potential | Surplus potential |
| Cereals | 367.7 | 90.1 |
| Oilseeds | 48.8 | 13.7 |
| Pulses | 17.9 | 5.1 |
| Sugarcane | 110.6 | 55.7 |
| Horticultural crops | 61.4 | 22.5 |
| Others crops | 79.8 | 47.3 |
| Total (MT) | **686.2** | **234.4** |

*dry weight basis.

Therefore, the vast amount of crop residues are available worldwide, which can be explored for the production of renewable energy with multiple benefits, such as enhancing indigenous energy sources, strengthening sustainable energy, and boosting the rural economy and environmental systems (Pant et al., 2019).

### 2.2. Current management of agricultural residues and their consequences to human health

According to Food and Agriculture Organization (FAO), in 2016, agriculture corresponded to about one-third of total world land area and sugarcane, maize, wheat, rice, potatoes, etc. are among the most cultivated plants (FAO, 2018). Deshavath et al. (2019), assessed around 181.8 MT of agricultural residues (derived from rice, wheat, corn, and sugarcane crops) were burnt in open-field in Brazil, China, India, and the United States in the year 2016, and the emissions were equivalent to 15.8 MT of $CO_2$ (Table 3).

#### 2.2.1. Crop residues burning and human health

Crop residues burning has now become a year-end event that turns most parts of north India into a gas chamber, putting the health of the citizens at risk. Open-field burning of crop residues has already banned in many countries, including India. The burning of crop residues on the field has emerged as an easy option for farmers to instantly clear their fields for the sowing of succeeding crop on time (Ahmed et al., 2015).

**Table 1**
The crop residue production and its energy potential in the world during 2003 and 2013.

| S. No. | Crop | Crop Residue production*# (MT) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | The USA | | Asia | | Africa | | Europe | | World | |
| | | 2003 | 2013 | 2003 | 2013 | 2003 | 2013 | 2003 | 2013 | 2003 | 2013 |
| 1 | Cereals | 655 | 828 | 1412 | 1865 | 172 | 230 | 468 | 630 | 2769 | 3608 |
| 2 | Legumes | 175 | 259 | 74 | 87 | 16 | 22 | 8 | 11 | 276 | 382 |
| 3 | Oilseed crops | 38 | 53 | 87 | 126 | 10 | 13 | 36 | 72 | 175 | 275 |
| 4 | Sugar crops | 202 | 310 | 189 | 233 | 28 | 32 | 40 | 42 | 472 | 626 |
| 5 | Tubers | 11 | 12 | 60 | 67 | 7 | 12 | 33 | 28 | 111 | 120 |
| **5** | **Total** | **1081** | **1462** | **1822** | **2378** | **233** | **309** | **585** | **783** | **3803** | **5011** |
| **Energy potential of total crop residue available$** | | | | | | | | | | | |
| 6 | MBTU | 17,296 | 23,392 | 29,152 | 38,048 | 3728 | 4944 | 9360 | 12,528 | 60,848 | 80,176 |
| 7 | Tonnes of oil equivalent (TOE) | 436.14 | 589.86 | 735.11 | 959.44 | 94.01 | 124.67 | 236.03 | 315.91 | 1534.37 | 2021.75 |

*dry weight basis.
#Data adopted from Cherubin et al. (2018).
$Calculated as per estimation made by Weisz (2004).

**Table 3**
Amount of crops residues burnt in open-fields in the year of 2016 and their $CO_2$ emissions (Adapted from Deshavath et al. (2019)).

| Countries | Agriculture crop residues burnt (MT/year) | | | | $CO_2$ emission (MT/year) |
|---|---|---|---|---|---|
| | Corn | Rice | Wheat | Sugarcane | |
| The United States | 35.11 | 0.07 | 7.10 | 0.24 | 3.73 |
| India | 10.20 | 23.63 | 12.09 | 3.22 | 4.25 |
| China | 38.98 | 16.75 | 9.74 | 1.09 | 5.75 |
| Brazil | 14.96 | 1.07 | 0.87 | 6.65 | 2.03 |
| Total | **99.25** | **41.52** | **29.8** | **11.2** | **15.76** |

However, the burning of crop residues is a cause of serious concern. It releases a massive amount of air pollutants and toxic gases (namely, CO, NO, $NH_3$, NOx, SOx, VOCs, etc.), aerosols, particulates/soot/elemental and black carbon smoke, which is causing adverse impacts on human health especially asthma and other respiratory disorders, etc. (Torigoe et al., 2000; Kumar et al., 2015). Crop residues burning also leads to GHG emission ($CO_2$, $CH_4$, $N_2O$), which is contributing to global warming and climate change. Crop biomass burning is also known as a vital comprehensive source of gaseous emissions, adding as much as 40% of gross $CO_2$ and 38% of the $O_3$ in the troposphere (Levine, 2011; Prasad and Dhanya, 2011; Bhuvaneshwari et al., 2019).

### 2.2.2. *Crop residues burning and nutrient loss*

The burning of crop residues not only adds to the pollution in the environment but also deteriorates the soil health (loss of nutrients and beneficial microbes). Norouzi and Ramezanpour (2013) studied the effect of fire on soil nutrient availability in the forest of North Iran. They reported that fire significantly increased sand, pH, electrical conductivity (EC), and base saturation (BS), while significantly decreased clay, organic carbon, and cation exchange capacity (CEC) of the soil. They also mentioned that fire significantly increased soluble K, Calcium (Ca), Magnesium (Mg), exchangeable K, and available P. The increased availability of nutrients would get loss by leaching with the water. The heat generated from burning crop residue increases the soil temperature, which adversely affects the population of beneficial soil microorganisms. Frequent burning of crop residues leads to complete eradication of the beneficial micro-organisms from the top layer of soil and reduces the nitrogen and carbon content in the soil. In India, the Ministry of Agriculture (2014) in 2014 during development of National Policy for Management of Crop Residues (NPMCR) estimated that burning of one tonne of rice straw accounts for loss of 5.5 kg Nitrogen (N), 2.3 kg phosphorus (P), 25 kg potassium (K) and 1.2 kg sulphur (S) besides, organic carbon. In general, 80% of N, 25% of P, 50% of S, and 20% of K available in crop residues get lost by burning of crop residues. The soil gets enriched by incorporating the crop residues in the soil itself, particularly with organic C and N (DAC, 2014). The apex policy making body in India, the NITI Aayog in 2019 has mentioned that burning of crop residues of rice, wheat and sugarcane alone created a loss of about 0.4 MT nitrogen, 0.01 MT phosphorus and 0.3 MT potassium (Table 4). The systematic utilization of residue can contribute to energy security, reduction of environmental pollution, and reduce nutrient loss and improve soil health.

**Table 4**
Nutrient loss due to burning of crop residues in India (adapted from NITI, 2019).

| Crop residue | Nutrient loss (MT/year) | | |
|---|---|---|---|
| | Nitrogen | Phosphorus | Potassium |
| Rice | 0.236 | 0.009 | 0.200 |
| Wheat | 0.079 | 0.004 | 0.061 |
| Sugarcane | 0.079 | 0.001 | 0.033 |
| **Total** | **0.394** | **0.014** | **0.294** |

### 2.3. *The energy potential of crop residues*

The production and use of bioenergy from crop residues, especially the blending of biofuels with conventional fuels, could prevent the over-exploitation of fossil fuel, which thereby cuts GHG emissions and helps to mitigate climate change (Hanaki and Portugal-Pereira, 2018). The energy content of crop residues varies among the type of residue such as stem, husk, stubbles, etc. and with the crop species. The energy content of rice straw is 3015 kcal/kg while, the energy content of hay is 3738 kcal/kg (Stout, 1990). The fuel value of one-tonne crop residue is estimated to 16 MBTU (Weisz, 2004). The energy potential of crop residues for the years 2003 and 2013 is calculated based on Weisz's (2004) estimation and presented in Table 1. The total energy potential of world residue is about 60,848 M BTU and 80176 M BTU for the years 2003 and 2013, respectively, which is equivalent to about 1534 tonnes of oil equivalent (TOE) and 2022 TOE, respectively. The corresponding values for surplus crop residue in India are 3747 MBTU, which is equal to 94.5 TOE.

### 2.4. *Energy generation from crop residues*

The non-woody biomass contains agro-industrial and agro-crops residues, these are biodegradable in nature, and it can be used for the energy need of the world. The woody and non-woody biomass can directly be used for industrial process heating, domestic cooking, and electrical power generation. In the modern era, the biomass gasification process used for small capacity power generation plants. In general, the solid fuel (biomass) is converted to the gaseous form by using a combination of thermo-chemical processes. The various technologies are listed in the brief that used for energy generation from various crop residues (Fig. 1).

Fig. 1 summarizes the various available technology used for energy generation by using crop residues. These technologies can be used in combination with each other for generating more energy with lesser input of energy and time. The conventional combustion was used to generate electricity from biomass as direct firing to produce high-pressure steam that can be used to start the turbine for electricity generation. The gasification techniques applied to the agricultural residues to convert it into the gaseous form, and it can be used for cooking, heating, mechanical work, and electricity generation. The solid biomass can also be converted to pyrolytic oil by using the process of pyrolysis, and later on, by combustion, heat can be generated. The wet biomass and different crop residues directly converted into biohydrogen and biogas by using fermentation and anaerobic digestion. The crop residues that contain higher sugar and starch are used to produce bioethanol, and these converted by using a series of biochemical processes such as enzymatic hydrolysis, saccharification, and fermentation. The biodiesel from agricultural residues is produced from oil crops (rape, sunflowers) by using refining and crushing techniques to generate vegetable oils. These primarily produced vegetable oils are converted to methyl ester (biodiesel) by the transesterification process. Table 5 summarized the recent studies for the production of energy from crop residues using bioconversion technologies mentioned in Fig. 1. Different crop residues such as rice, wheat bran, maize and almond shells are used as a primary substrate for bioenergy generation in different countries (Table 5). The highest biochemical methane potential (BMP) of 166.34 mL/g VS was generated by using corn stalk as a substrate in whole slurry anaerobic digestion (Wang et al., 2019).

Currently, more than 40 lignocellulosic biorefineries are operating across Europe (Hassan et al., 2019). In 2012, Beta Renewables set up the first operational industrial cellulosic ethanol plant in the world. By 2015, the 40 MMgy plant in Crescentino, Italy was reported to shipping cellulosic ethanol to Europe on a daily basis (Beta Renewables PROESA, 2016). After the success, Beta Renewables was planned to build more

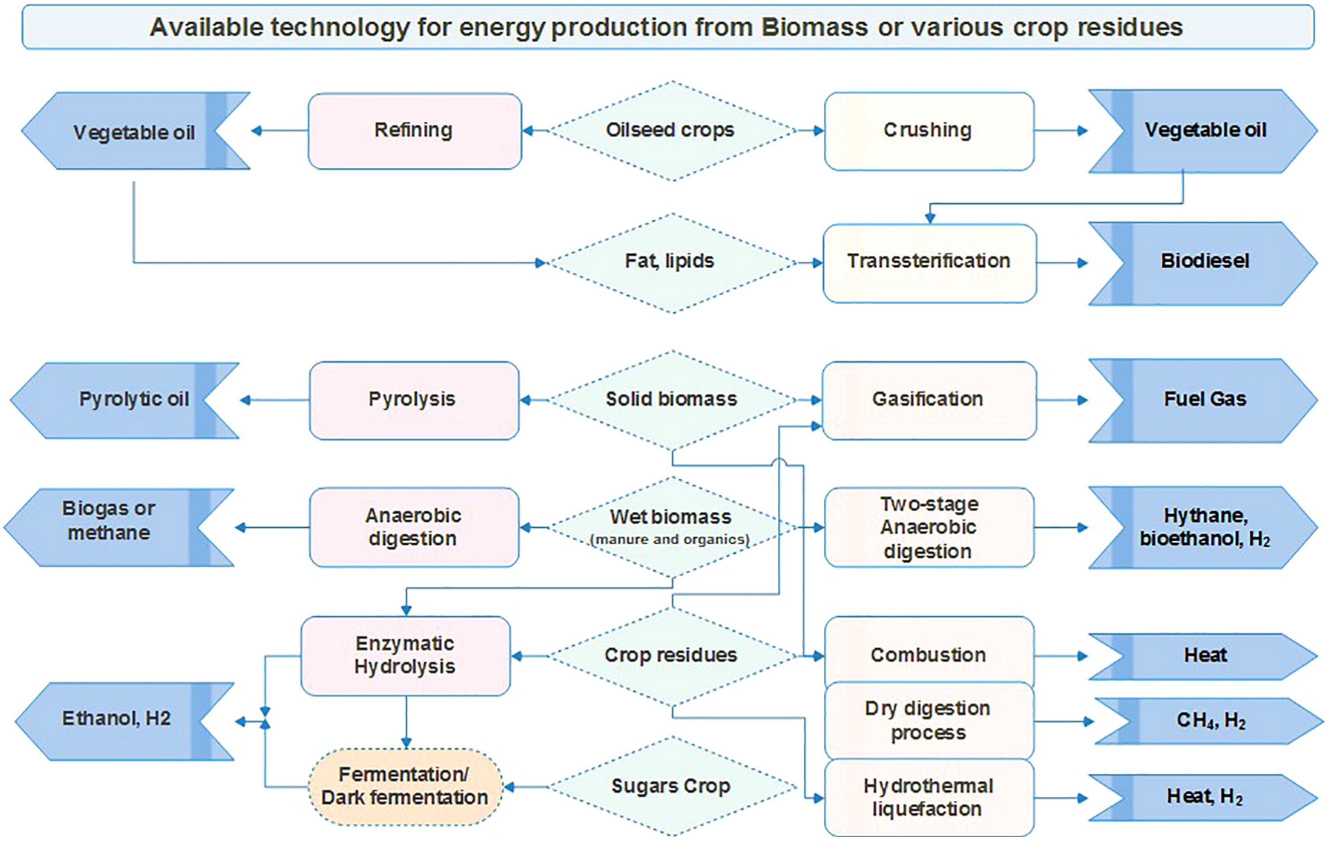

**Fig 1.** Basic flow chart shows the various technologies used for energy production from various crop residues.

cellulosic ethanol plants in India, the USA, Brazil, and China (Rosales-Calderon and Valdeir, 2019). In 2015, Abengoa opened a 25 MMgy cellulosic ethanol plant in Hugoton, Kansas, USA (Rosales-Calderon and Valdeir, 2019). Historically, cellulosic biofuel production levels have been low or incompetent. The industry has experienced significant progress in recent years. The commercialization of cellulosic ethanol, now became a reality because crop residues are low-cost and readily available substrates in all parts of the word (Lane, 2015; UNCTAD, 2016). For commercial use of crop residues for generating bioenergy, the conventional and new technologies should be used together for better efficiencies of the reactors. These would be real future energy sources and for them to more accessible for commercial use, new processes and technologies continue to develop.

### 2.5. Sustainability of energy generation from crop residues

Bioenergy played a significant role in the sustainability of human civilization. In the year 2012, about 2.6 billion people worldwide rely on the traditional use of biomass as a primary source of energy, which is estimated to about 33 to 43 exa-joules (EJ) (OEDC/IEA, 2014). In 2016, the global use of bioenergy was about 50 EJ (World Energy Congress, 2016). Bioenergy sources are rarely accounted for national energy statistics despite their long history and increased interest in bioenergy research (Bentsen et al., 2014; OEDC/IEA, 2014). The sustainable utilization of bioenergy is in line with global strategies to mitigate GHGs emissions (IPCC, 2011; United Nations Framework Convention on Climate Change, 2015). According to the International Energy Agency (IEA), biofuels used in transport are expected to enable a 6% global GHG reduction.

Sustainable energy generation is the major challenge of the 21st century. Sustainability deals explicitly with the role of bioenergy in ensuring the well-being of the planet, economy, and society both today and tomorrow. The potential environmental benefits that can be attained from bioenergy obtained from renewable crop residue sources are the foremost driving forces for promoting the production and use of bioenergy (SanzRequena et al., 2011).

First-generation biofuels, produced from crops, compete with food availability. Whereas, second-generation biofuels created from wastes or crop residues is a sustainable route to solve “food vs. fuel” issue (Cassman and Liska 2007) with a significant environmental and economic gain (Schenk et al., 2008; Havlík et al., 2011; Piemonte et al., 2014).

Compared to vegetable oil as feedstock, lignocelluloses material such as crop residue is cheaper, available in abundance, not competing with food and also not requiring land to cultivate for energy purposes; making it most promising feedstock for energy generation without any debate such as food vs. fuel competition, land-use change, resource utilization, pollutants released in the environment, impact on biodiversity and ecosystem, etc. by production of feedstock. However, because of the complex structure of lignocellulose, the conversion process is relatively complicated. Energy generation from crop residue meets the standards for sustainable biofuels set in the Roundtable for sustainable biofuels released in 2008 which focused on especially to follow international treaties and national laws regarding air quality, water resources, agricultural practices, etc.; GHGs reduction in comparison to fossil fuels; contribute to the social and economic development; shall not impair food security; avoid adverse impacts on biodiversity, ecosystems, and areas of high conservation value; promote practices that improve soil health and minimize degradation, optimized use of ground water and reduce the contamination or depletion of water resources; reduction in air pollution; cost-effective production and improving production efficiency and socio-environmental performance; and shall not violet land rights (Roundtable on Sustainable Biofuels, 2009; Pavlovskaia, 2015).

**Table 5**
Various technologies for the production of energy from crop residue.

| S. No. | Crop residue | Technology | Energy type | Energy yield | Country of study | References |
|---|---|---|---|---|---|---|
| 1 | Rice Crop Residue | Bioconversion, Enzymatic saccharification, Fermentation | Bioethanol | 4 g/L ethanol with fermentation efficiency 55–66% | India | Sharma et al. (2019) |
| 2 | Almond shells | Two-stage anaerobic digestion | Hythane and ethanol | Substrate degradation (91.3%) | India | Kaur et al. (2020) |
| 3 | Corn stalk | Whole slurry anaerobic digestion | Biochemical methane potential (BMP) | Highest BMP (166.34 mL/g VS) | China | Wang et al. (2019) |
| 4 | Cob corn waste | Densification, Pelletizing treatments & grinding | Thermal use | A total specific energy of 0.1 kWh $kg^{-1}$ | Spain | Miranda et al. (2018) |
| 5 | Agricultural crops, Agricultural waste and residue | Biochemical conversion | Second-generation biofuels | About 0.35, 3.84, 1.07 biodiesel, bioethanol, biobutanol respectively can be produced | Iran | Alavijeh and Yaghmaei (2016) |
| 6 | Residual biomass | Bioenergy (utilizing forest and agricultural residues) | To produce bioheat in a rural area in Portugal, Estremoz | 53 $t/km^2$/year of residual biomass is produced in the given area | Montado area, Southwestern Europe | Malico et al. (2016) |
| 7 | Agricultural residues | Bioenergy | Direct combustion | Potential nearly 141 TWh/year generation(bio) | Brazil | Portugal-Pereira et al. (2015) |
| 8 | Biomass | Renewable energy source | Fuel wood and biomass energy | 17 Mtoe (Million tonne of oil equivalent)/year | Turkey | Toklu (2017) |
| 9 | Banana biomass | Biomass to energy | Combustion, supercritical water gasification and digestion to produce thermal energy and biogas | 950 MW/Year | Malaysia | Tock et al. (2010) |
| 10 | Agricultural residues | Sustainable biomass quantification | Biomass Energy | 5.3 TWh (Tera Watt) | Bolivia | Morato et al. (2019) |
| 11 | Microalgae and rice residue | Co-fermentation | Biohydrogen& volatile fatty acids generation | Highest $H_2$ yield of 201.8 mL/g VS | China | Sun et al. (2018) |
| 12 | Cocoa residues | Anaerobic Digestion | Bioenergy | Methane yield 193 (dry) L $kg^{-1}$ volatile solids fed | Ecuador | Acosta et al. (2018) |
| 13 | Sugarcane bagasse | Ozonation, anaerobic digestion and enzymatic hydrolysis | Biogas and ($CH_4$ and $H_2$) ethanol production | 2.6 $Nm^3$ of $CH_4$ and 0.18 $Nm^3$ of $H_2$ per kg of total organic carbon | Brazil | Adarme et al. (2017) |
| 14 | Wheat Bran and maize effluents | Dark Fermentation | Production of biohydrogen | highest hydrogen 648.6 and 320.3 mL $L^{-1}$, respectively with wheat bran and maize effluents | Italy | Corneli et al. (2016) |

## 3. Life cycle assessment (LCA) of energy generation from crop residues

Life cycle assessment (LCA) is a tool to assess the environmental burdens from a process or activity or product by identifying and quantifying energy and materials usage, as well as impacts on the environment due to waste generation and its discharge. LCA allows the identification of the opportunities to improve the process for environmental sustainability over the whole life cycle (Hiloidhari et al., 2017; Singh et al., 2010; Singh and Olsen, 2012). Rubio Rodríguez et al. (2011) concluded in an LCA study on the valuation of alternative energy routes that LCA based indicators might be an efficient tool to compare alternative energy routes in terms of direct environmental impact and indirect natural resource costs towards different services and commodities.

The LCA study is consists of four steps, viz. the first step is goal and scope definition, which defines the goal and scope of the study, system boundary, and functional unit. The second step is life cycle inventory (LCI), modeled product's life cycle by analyzing all inputs and outputs of the product. The third step is known as life cycle inventory analysis (LCIA), where the eco-friendly relevance of entire inputs and outputs of a product is assessed. In the fourth step, Interpretation, the results of the study are interpreted and concluded by suggesting the possible measures to reduce the burden on the environment (Rathore et al., 2013). The various phases of the LCA study are displayed in Fig. 2. The different stages of LCA are discussed in detail by Singh et al. (2010) and concluded that LCA results should be expressed in output based on final energy associated with reference system (per kWh or per km) and recommended to adopt cradle to the grave system for bioenergy studies.

The primary aim of the LCA study is to minimize the environmental burden by replacing the processes/sub-processes, which are generating a higher impact on the environment with the alternate process/sub-process to increase the acceptability of the product (Hiloidhari et al., 2017). A generalized flow diagram of an LCA study is produced (Fig. 3), which shows various processes, inputs and outputs for product manufacturing. The availability of choices for inputs and processes and their selection decides the sustainability of the product, which can be achieved by using the LCA.

### 3.1. Challenges in the implementation of LCA

The environmental performance of energy generation from biomass/crop residues based on their GHG savings and energy balances depend on several factors such as feedstock types, conversion technologies, special and temporal variations, land-use and land-use changes, substituted products like electricity, transportation fuel, fate of co-products, impact allocation, assumptions and data used, inventory development, impact assessment, etc. (Rathore et al., 2016; Menichetti and Otto, 2009). Therefore, the selection of appropriate/right combination of all processes in very important to find out the sustainable approach for energy generation from crop residues or other biomass.

### 3.1.1. Selection of crop residue and technology for energy conversion

Different crop residues have varied quantity and form of carbon, nitrogen, phosphorus, and other elements. The availability and type of the element, primarily carbon, affect significantly energy generation and emissions, which decides the acceptability of the energy produced. The applicability of conversion technology also needs to choose very cautiously because the production of bioethanol from one crop residue could be a better option than the production of biomethane of other energy types, while another crop residue could be best suited for the production of biogas. In a study, Soam et al. (2017) stated that electricity production from rice straw has a higher reduction of GHGs as compared to biogas production. Shafie et al. (2014) also reported that rice straw-based power generation emits less GHGs in comparison with coal or natural gas.

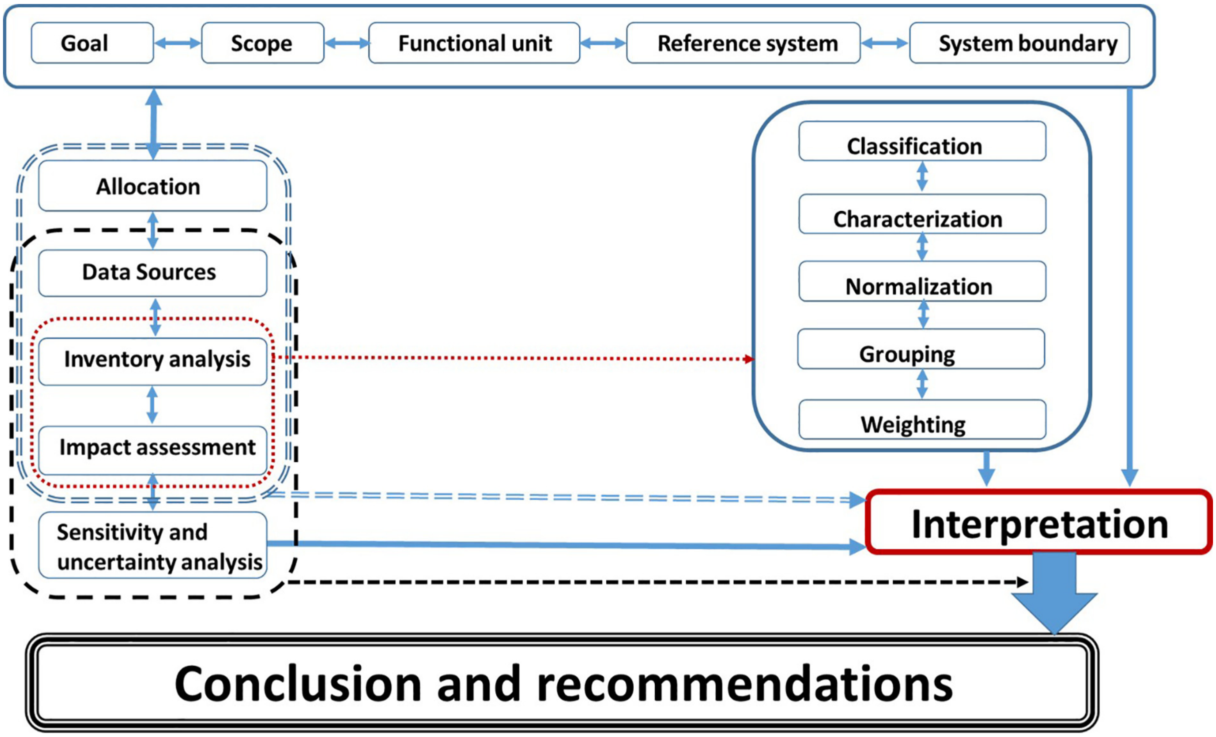

**Fig.2.** A generalized layout of LCA methodology.

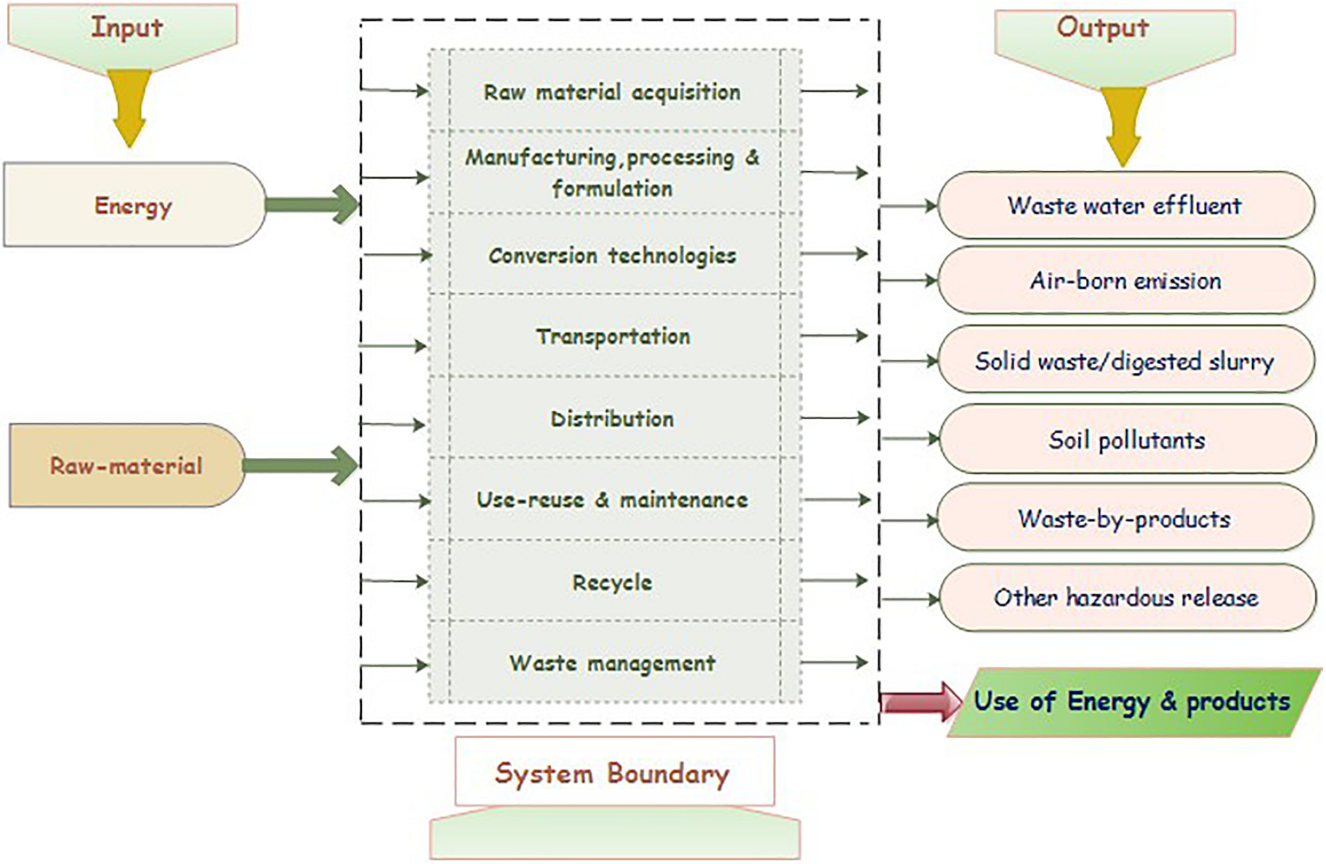

**Fig. 3.** A generalized flow diagram of product manufacturing for a Life Cycle Assessment (LCA) study.

Tonini et al. (2016) concluded in a study of consequential LCA of twenty-four biomasses (from dedicated crops to residues of different origin) for the production of bioelectricity, biomethane, and bioethanol that biofuel production from agro-residues without involving land-use change is a promising emissions reduction option. Sanscartier et al. (2014) found that the use of corn cob pellets for electricity generation could reduce about 40% and 80% GHGs emissions compared to coal and natural gas combined cycle (NGCC), respectively. They also mentioned that the removal of agricultural residues from fields contributed to increased erosion and adversely affected soil fertility due to the loss of soil organic carbon and nutrients. Therefore, sustainable use of crop residue should be considered to maintain soil fertility over a long period.

Cherubini et al. (2009) reported that heat and electricity production from biomass has higher GHGs emissions reduction and energy-saving benefits than the production of biofuel. The residue biomass shows the most reliable environment-friendly performance since they avoid both the impacts of the production of an energy crop and emissions from biowaste management. Muench (2015) recommended that the deployment of both dedicated and non-dedicated lignocellulosic biomass for energy production with thermo-chemical conversion can reduce higher GHGs emissions than direct combustion of that lignocellulosic biomass. The energy generation from crop residue has several environmental benefits over conventional fuels if utilized in a sustainable way (Hiloidhari et al., 2017). However, since the energy from crop residues can be produced through different energy conversion routes, such as heat, electricity, bioethanol, biomethane, etc., therefore, identification of the most sustainable path of energy generation is the most important.

### 3.1.2. Selection of LCA model

The variations among results obtained from different LCA tools have challenged the credibility of the assessments, policy development, and progress towards or compliance with GHG mitigation targets (Pereira et al., 2019). Pereira et al. (2019) and IEA (2019) has studied the accuracy of leading LCA models used for sustainability assessment of biofuels, to identify their main differences and commonalities and to examine how their various assumptions, as well as methodologies, influence carbon intensity (CI) estimates, to improve understanding and confidence of the LCA practitioners (Table 6). IEA Bioenergy Taskforce 39 (jointly with Taskforce 38) summarized that there are number of reasons for the obvious lack of agreement between the various LCA models, such as the assumptions made in every model are not same, e.g., field location, amount and type of fertilizer, etc. used for agricultural production practices, choice of crop residue, conversion technique, etc. Different models have also made different assumptions about the CI of non-feedstock inputs such as energy, nutrients, etc. The variation in the assumptions made in different models leads variable results in terms of GHG emissions per Mega Joule (MJ) of biofuel produced when using the default values. In addition, there are several key differences between the various model's calculation methodologies that also exist, like the substitution method used to handle co-products in the GHGenius model compared to the allocation method used by the other LCA models. They concluded that primarily the default values within the models and the related assumptions lead to the apparent discrepancies if harmonized these assumptions, the models estimated similar CI values for a particular biofuel (IEA, 2019). Pereira et al. (2019) concluded that variation in the results among models suggest that modeling tools should provide transparent data sources and assumptions used in LCA calculations, which will facilitate the understanding of effects in terms of geographical locations of production of biomass and biofuels consumption.

### 3.1.3. Allocation of environmental burden

In the energy generation from biomass, agricultural practices of farming stage result in significant GHGs emissions and other environmental impacts due to use of energy for intensive farm machinery, irrigation, land preparation, sowing, harvest, collection, and transportation activities. The use of fertilizer, pesticides, and other chemicals also contributed significant amount of emissions and impacts on soil, air and water (Hiloidhari et al., 2017).

The allocation step is one of the crucial steps that determine how much of the environmental burden created by a multi-functional process should be apportioned to every product or function (Singh and Olsen, 2012). Inappropriate allocations can lead to incorrect LCA results (Hiloidhari et al., 2017). Allocation is a procedure of appropriately allocating the environmental burdens of a multi-functional process among its functions or products (Reap et al., 2008). Plevin et al. (2014) cautioned that LCA results should refrain from using unsupported claims, such as "using product X results in a Y% decrease in GHG emission compared to product Z" because such claims are valid only in rare cases.

In the energy generation from crop residues, the way of allocation of emissions is very important, because the crop was produced for some other purpose, not for the energy generation purpose. Therefore, all emissions could not be accounted for energy generation. The impact of land-use change may not be considered for energy generation from crop

**Table 6**
Some of the main attributes of the biofuels LCA models (Adapted from IEA (2019) and Pereira et al. (2019)).

| | LCA Models | | | | |
|---|---|---|---|---|---|
| | BioGrace | GHGenius | GREET | New EC | Virtual Sugarcane Biorefinery (VSB) |
| Model version | 4d (2015) | 5.0a (2018) | 2017 | 2017 | 2018 |
| Developed for regulatory use | Yes | No | Yes | Yes | No |
| IPCC GWP method | 2001 | 1995, 2001, 2007, 2013 | 2013 | 2013 | 2013 |
| Default global warming gases | $CO_2$, $CH_4$, $N_2O$ | $CO_2$, $CH_4$, $N_2O$, CO, VOC, NOx, fluorinated compounds | $CO_2$, $CH_4$, $N_2O$ | $CO_2$, $CH_4$, $N_2O$ | $CO_2$, $CH_4$, $N_2O$ |
| Lifecycle data | JRC (2008) | Internal | Internal | JRC (2017) | Ecoinvent |
| Functional unit | MJ | km, MJ | km, mile, Btu, MJ | MJ | km, MJ |
| Default allocation | Energy | Mostly substitution | Variable (substitution/energy) | Energy | Economic |
| Land use change | C stocks | Internal model | CCLUB/GTAP | C stocks | – |
| Type of LCA | Attributional | Attributional | Attributional | – | Attributional |
| Functional unit | Energy (MJ) | Service (km)<br>Energy (MJ) | Service (km, mile)<br>Energy (Btu, MJ) | – | Service (km)<br>Energy (MJ) |
| Heating value | LHV | HHV or LHV | HHV or LHV | – | LHV |
| Gasoline baseline (g CO2eq per MJ) | 83.8 | 95.0 | 90.2 | – | 87.5 |
| Impact categories | GHG | GHG, Energy, Cost effectiveness | GHG, Energy, Water use, Air pollutants | | Energy, Ozone depletion and others |

residue. Also, during energy generation, some byproducts are generated. Therefore, the environmental burden caused during the production of energy also needs to allocate between energy and byproduct. The allocation of emissions and inputs for the production of crop residues may be done on the basis of mass or economic value or carbon content. The allocation based on carbon content is the best way for the environmental impact related studies, and economic value is the least accepted because the market fluctuates with several factors, so the economic value is not constant. Allocation on the basis of mass is also not the preferred method because it could not be an accurate measure of energy factor (Singh et al., 2010; Gnansounou et al., 2009).

Sechhi et al. (2019), in an LCA study of lignin as fuel co-product, studied various allocation techniques (no allocation, allocation based on energy content, mass and economic value basis) and found that impacts on various products are shifting significantly by changing the allocation technique. DeRose et al. (2019) reported that a baseline emission results of conversion of distiller's grains to renewable fuels and high-value protein emitted 17 g $CO_2$-eq per MJ fuel product and 10.3 kg $CO_2$-eq per kg protein product and they found a dramatic impact of sensitivity to allocation methods with results ranging between − 8 to 140 g $CO_2$-eq per MJ fuel product and − 0.3 to 6.4 kg $CO_2$-eq per kg protein product.

### 3.1.4. Impact assessment

The life cycle impact assessment is the phase of LCA in which potential human health and environmental impacts are identified; all possible ecological and human health effects along with resource depletion are included (Korres, 2013). During this phase, the associations between the product or process with possible environmental impacts, midpoints are established. Midpoint environmental impact categories include global warming potential, eutrophication and acidification, photochemical oxidants, existence of various particles, and finally, energy balance (Borjesson et al., 2011). Global warming potential refers to increases in the average temperature caused through increases of global warming potential as an effect of anthropogenic emissions of global warming gases such as $CO_2$, $CH_4$, $N_2O$, CFCs, HCFCs, and others. Acidification is the accumulation of acidifying substances such as $H_2SO_4$, HCl in the water or suspension in the atmosphere; these are deposited onto the ground by rains exhibiting a wide variety of impacts on soil, ground and surface waters along with biotic e.g., biological organisms, ecosystems, or abiotic materials, e.g., buildings. Eutrophication is a process whereby water bodies enriched by nitrogen or phosphorus-based compounds that stimulate the growth of algae. Fertilizers, from agricultural operations, N deposition from the atmosphere, soil erosion are typical resources of nutrients that cause eutrophication (Wenisch and Monier, 2007). Life cycle impact assessment provides a systematic procedure for classifying and characterizing these types of environmental effects. GHGs emissions, for example, are classified according to their global warming potential. Carbon dioxide ($CO_2$), for example, assumes the value of 1, whereas methane ($CH_4$) and nitrous oxide ($N_2O$) billed with a value of 23 and 296, respectively (IPCC, 2001). Midpoint impact assessment approaches reflect the relative potency of the stressors at a common midpoint between the stress and its consequence. Analysis at a mid-point minimizes the amount of forecasting and effect modeling incorporated into the LCIA, and thereby lessening the complexity of the modeling and often simplify communication (Bare et al., 2003). Endpoints, on the other hand, belong to a broader, more generic impact category for example "skin cancer" or "cataract" describe a condition of human health, "marine life damage" describes a condition of natural environment whereas "crop damage" describes a condition related with an anthropogenic biotic environment or even natural resources.

### 3.1.5. Uncertainties and sensitivity analysis

The LCA studies of energy generation from crop residue/biomass depicted lesser environmental burden in comparison to conventional energy sources, but there are some uncertainties in the application of LCA. Liska (2015) discussed in details eight principles of uncertainties for LCA of biofuel system, which includes complexity of biofuel system (cultivation, logistics, conversion technology, distribution, end-use, etc.), variability of LCA methods/models, data deficiencies, spatial and temporal variability, impact categories, indirect impacts (land-use change, emission, etc.), transparency and reference system. The variations in the results occurred mainly due to choice of crop residue/raw materials, energy conversion technologies, end-use, consideration of land-use change (LUC), data authenticity, temporal and special variations, allocation technique, and LCA methodologies (consequential/attributional/hybrid) adapted for the study (Cherubini et al., 2009; Muench and Guenther, 2013; Singh et al., 2013; Muench, 2015; Hiloidhari et al., 2017).

Muench (2015) suggested that the uncertainties of LCA results of energy generation from biomass could be reduced by accounting for heterogeneity among biomass systems, considering the strong influence of small differences in biomass systems, transferability of LCA results between similar systems, avoiding the adoption of assumptions from other systems and inclusion of additional environmental, economic and social impact categories.

Sensitivity analysis aims to assess the consistency of assumptions, to identify the parameters or sub-process/stage of production system contributing the most considerable influence on results, and to evaluate possible improvement options by replacing the process contributing significant impact with the alternate process. The impact of energy generation from biomass varied with specific commodity, country of origin, agricultural practice, and regional or country-specific background data (Fritsche and Wiegmann, 2009). Sharma et al. (2020) in an LCA study of the conversion of lignocellulosic biomass into fuel and chemicals using different using chemical or conversion pathways reported that uncertainty for human toxicity and marine aquatic toxicity is mainly due to variation in data inventories for the use of toxic chemicals, in different electrical grids of different regions. They concluded that the feedstock used during the process makes the process efficient in terms of better yield, low energy input, and higher product conversion with an acceptable range of environmental emissions.

### 3.1.6. Other challenges

The lack of uniformity in selection of functional units creates difficulty in comparison to LCA results. There are a number of ways to define functional units such as input basis, output basis, areas basis, or based on the year. The functional unit may play an important role, especially with allocation issues for systems with multiple co-products and also have an impact on the interpretation of final results (Cherubini and Strømman, 2011).

In the energy generation from crop residue studies, the possible impacts of residue removal from the field need to be estimated with a reference used for agricultural residue because it affects the soil organic turnover, soil erosion, or crop yields (Cherubini and Strømman, 2011). Spatari et al. (2010), in their study on Life cycle evaluation of emerging lignocellulosic ethanol conversion technologies, considered 50% removal of the residue for ethanol production and 50% left in the field for maintenance of fertility.

McKone et al. (2011) reviewed grand challenges for the life-cycle assessment of biofuels. They mentioned that LCA results depend on a large number of input elements, and these elements are often based on data of varying quality. The variable quality of data inputs influences the quality and robustness of the outcome. Therefore, the quality of data inputs deserves more attention in LCA. They suggested that reducing the uncertainty and variability, and there is a need to understand and separate the "doable" and "knowable" assumptions. McKone et al. (2011) also mentioned that a strong challenge for LCA in addressing uncertainty is to provide and track metrics of data quality with respect to data acquisition (measurements, assumptions, expert judgment, etc.), extent of the data validation or corroborated, and the data capture technological, spatial, and temporal variations. They list out seven grand challenges, namely, (1) understanding farmers, feedstock options, and land use, (2) predicting biofuel production technologies and practices, (3) characterizing tailpipe emissions and their health consequences, (4) incorporating spatial heterogeneity in inventories and assessments, (5) accounting for time in impact assessments, (6) assessing transitions as well as end states and (7) confronting uncertainty and variability and suggested that by confronting listed challenges will recognize some issues that have not been well articulated among practitioners of LCA.

### 3.2. LCA for decision support to policy-makers

The development and application of new technologies are contingent upon the approval of them by policy makers, and for researchers developing those technologies and their applications, it has always been a challenge to make their technologies and their impact on policy makers. In addition to the obvious benefits of the newly developed technology, there exist few concerns associated with the design (reduction of the reaction period, simplification of the product recovery process) and economic feasibility (high cost of up-scaling and full-scale implementation) of using this new technology. As a consequence, identifying the full range of factors determining acceptance or rejection of using technologies converting crop residues into biofuels is important if effective regulation and exploitation of technology are to occur. The LCA then becomes a handy tool for demonstrating the full impact of the new technologies and show them a total impact of the whole value chain right from the feedstock to the final product and even its post-use fate. Both cradle to cradle and cradle to grave approaches can be used for this purpose.

Worldwide, bioenergy/biofuels are promoted with a variety of policy objectives along with the condition that a certain amount of GHG emission savings should be achieved. Therefore, legislation is required for a standardized GHG accounting procedure and encompassing the inclusion of indirect emissions in the life cycle of bioenergy (Cherubini and Strømman, 2011). There are concerns that the bio-based economy may undermine the sustainability of the transition, which can be addressed by adopting life-cycle-based tools, such as LCA, to review environmental impacts, economic indicators through life cycle costing (LCC) and social indicators throughout the lifecycle using social life cycle assessment (SLCA) (Martin et al., 2018). However, Kloepffer (2008) suggested that the combination of LCA, LCC, and SLCA will provide a much needed tool for the sustainability assessment of products. Recently Prasara-A et al. (2019) studied LCA and SLCA to examine the environmental, socio-economic and social performances of the various sugarcane-based products in Thailand and found that some problems such as cane crash burning and overuse of chemical fertilizer and agrochemicals were the leading causes not only of negative environmental performance but also of socio-economic and social performances.

Pierobon et al. (2018), in an LCA study, revealed that residual woody biomass recovered from slash-piles serves a more sustainable alternative to petroleum for the generation of jet fuel with a lower impact on global warming and local pollution. They have also suggested focusing more on the optimization of chemical processes of the bio-refinery to reduce the effects on the ‘Acidification’ and ‘Eutrophication’ impact categories in future.

Rajagopal and Zilberman (2008) reported that LCA could be used to develop policies as a regulatory tool to permit fuels below a threshold value for net carbon emissions to be sold in a market. The Low-Carbon Fuel Standard (LCFS) in California is a first-of-a-kind policy adopted in the world, which stipulates GHG emissions per unit of fuel to be below a maximum value, which is set to decline over time. They suggested that further methodological development, such as the inclusion of price effects, emission dynamics, technological development, and a distinction between marginal and average effects, is required before it is employed as a decision-making tool by policy makers. They further suggested considering non-GHG environmental impacts that would result from biofuels, which has not received much attention in the LCA literature and concluded that LCA is a construct that is valuable but prone to misuse and errors. Hellweg and Canals (2014) suggested that LCA practitioners should require to explain to the decision-makers that LCA is not a tool to provide a single answer. Still, it gives a comprehensive understanding of a problem and its possible solutions.

### 3.3. Bio-refinery concept

The biofuels produced from various crop residues are viewed as clean and eco-friendly fuels because of their non-GHG emitting nature and therefore help in conservation of the environment (Prasad et al., 2012). The conversion of crop residue to renewable energy is complex and expensive, which restrict it to compete with fossil fuels. The production of renewable energy using crop residue along with the production of high-value biochemicals and biomaterials such as benzene, micro-fibrillated cellulose, toluene, xylene, styrene, or cumene) could be a promising strategy to lower down the production cost (Parsell et al., 2015; Rosales-Calderon and Valdeir, 2019). Some biorefineries complex and non-conventional biomass energy industries are already competitive in the market, and several pilot and demonstration plants are working worldwide. Many of them are running to optimize the production efficiency of ethanol and chemicals from lignocellulosic biomass resources (Cherubini and Jungmeier, 2009). The biorefinery produces fuels, solvents, plastics, and food for human beings. For the biorefinery, various hybrid techniques were developed from diverse fields, such as bioengineering, agriculture, polymer chemistry, and food science (Ohara, 2003). The leading bio-based products are obtained from the conversion of biomass to essential commodities like cellulose, starch, and oil or lipids. A wide range of chemicals such as 1,3-propanediol, acetone, n-butanol, itaconic acid, or xylitol can be produced from the sugars formulated during the pretreatment of biomass and enzymatic hydrolysis of pretreated biomass (Rosales-Calderon and Valdeir, 2019). At present, various liquid biofuels are produced from biomass, such as ethanol and biodiesel. In addition, chemicals like lactic acid and amino acids are produced, which are mainly used in the food industry (Kamm and Kamm, 2004).

The investigations of integrated biorefinery (IBR) concepts are being explored to co-produce hydrocarbon fuels and high-value bio-based chemicals to enhance the economic viability of IBRs. It will increase the co-product utilization efficiency and reduce GHG emissions (Cai et al., 2018). The GHG results of biofuel LCA are highly sensitive to the nature of the co-product. Emission profile of the energy (biofuel) produced and other co-products vary significantly with different methods that distribute the total biorefinery emissions, and the resulting emission reduction benefits differently to the fuel product and non-fuel products. Cai et al. (2018) concluded that IBRs with co-production of biofuels and bio-chemicals present a challenge in allocating the GHG emissions of each product due to their distinct nature and utilities.

A super-structure framework for the techno-economic optimization of an integrated algae biorefinery is studied by Galanopoulos et al. (2019) and defined the integration concept by the use of the wastewater and $CO_2$ emissions from a wheat-straw biorefinery as feed to the algal biorefinery. The resulted algal wastes are recycled back to the wheat-straw biorefinery to generate value-added chemicals. Ajao et al. (2018) proposed integrated forest biorefineries as a viable option for the conversion of lignocellulosic biomass into a broad spectrum of profitable products for the pulp and paper industry. The extracted hemicelluloses from a Kraft pulping process prior to chemical pulping can be used for the production of biofuels, biochemicals, and biomaterials using chemical and biochemical processes.

Several new concepts for a bio-refinery have been developed. One such example is the dual purpose microalgae-bacteria based systems for treating wastewater and production of biofuels and chemical products, which significantly contribute to a substantial saving in the overall cost of microalgae biomass production (Olguín, 2012).

## 4. Conclusion

Crop residues are readily available and can be valorized for energy generation in a useful manner, which otherwise leads to environmental pollution and causes health problems. LCA provides commendation to evaluate the ecological, social, and economic sustainability of energy generation from crop residues. Since energy from agricultural residues can be generated from several routes, LCA can be explored for sustainable energy generation by evaluating the type and route best suited to the feedstock and geography. The LCA approach over the whole value chain has been covered for crop residue valorization as a policy support tool for policymakers and end-users.

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## 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.

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