Fuel 307 (2022) 121859

Contents lists available at ScienceDirect

Fuel

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

Bioenergy and bio-products from bio-waste and its associated modern circular economy: Current research trends, challenges, and future outlooks

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A R T I C L E I N F O

Keywords:
Modern circular economy
Biowaste
Bioproducts and bioenergy
Sustainable models
Challenges
Lignocellulose

A B S T R A C T

The generation of bioenergy and bioproducts from biowaste streams has piqued global interest in achieving a cutting-edge circular economy. The integration of biowaste into the cutting-edge circular economy has the potential to significantly increase the production of sustainable bioproducts and bioenergy. The potential for advanced forms and innovations to transform complicated, natural-rich biowastes into a variety of bioproducts and bioenergy with an advanced circular economy has been demonstrated in this article. It is described to emphasise the critical nature of research into improving biowaste conversion into circular economies and the impact that bioeconomy has on various societal sectors. The present study examined how microbial profiles have transformed treasured bioenergy and bioproducts aspirations into mechanical bioproducts marvels discovered through cutting-edge microbial analyses of biowaste. Additionally, the article discussed contemporary experiences with the developing circular economy of biowaste as a resource for numerous bioproducts and bioenergy businesses, as well as the emanant biowaste biorefinery methods that could be used to evaluate industrial-scale maintainable financial models for updated bioproducts and other generation-related issues.

1. Introduction

Limiting dependency on fossil-fuel assets and reducing the amount of solid biowaste are two of the most essential challenges confronting contemporary society. As a biowaste, lignocellulosic biomasses – including mash and paper, horticulture, nourishment, forestry, and municipal solid waste – are viewed as the most capable renewable resources, as they are generally accessible to the world and enable us to avoid the strife associated with the use of consumable crops [1]. Biowaste accounts for a significant portion of municipal waste, particularly in rural areas and developing countries [2]. Biowaste is frequently comprised of food-related biowaste from family cafeterias, industrial biowaste, decomposable plants, and waste from botanical gardens [3] Wijekoon et al. [4]. Additionally, the period of increased trash, which is projected to double between now and 2030, is motivating folks to consume more efficiently and recycle waste materials [5]. Both improvements and developments in cleaner biomass production and processing may contribute to the global transition to post-carbon fossil societal regimes [2]. Thus, researchers have been concentrating their efforts recently on developing bioproducts and bioenergy from a cost-effective renewable resource derived from industrial and agricultural biowaste [6]. Microalgae have captured researchers' attention as the alternative feedstock for various bioenergy production such as biodiesel, biohydrogen, and bioethanol [7]. Additionally, transitioning to a circular economy (CE) is crucial for achieving a sustainable, low-carbon and resource-efficient culture. A circular economy, for example, reuses, reprocesses, repairs, and refurbishes assets to maximise asset effectiveness in both use and output [5,8].

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https://doi.org/10.1016/j.fuel.2021.121859
Received 11 April 2021; Received in revised form 17 August 2021; Accepted 27 August 2021
Available online 3 September 2021

As one of the largest producers and users of environmental resources in industrialised and developing countries, biological products have developed into a vocal division in the development of a circular modern economy [9]. Developing biological products results in environmental and economic benefits, such as the substitution of chemically synthesised or fossil-fuel produced biomaterials, which is critical for the circular economy concept [10]. The advancement of the circular economy places a premium on product life cycles, design, and generation strategy, as well as on resource utilisation and biowaste generation across the full life cycle of a bioproduct. The circular and bioeconomy structures are complementary in terms of maintainability and resource efficiency objectives. The global bioeconomy plans place a premium on sustainable management of organic resources to ensure asset viability and biomass sustainability. Such a circular bioeconomy will demand the development of biorefineries in addition to enhanced sustainability measures [11]. The life cycle assessment (LCA) is a user-friendly technique for determining the impact of the energy consumed, harmful chemicals released, and natural resources consumed at all phases of the life cycle of a product or activity. The application of system dynamics (SD) to biowaste management arrangements can aid in forecasting future trends and characterising the scheme. SD has proven to be extremely beneficial in recent years in areas relating to biowaste management [12].

The conversion of biomass to biological products and biofuels provides a sustainable way to manage degradable biowaste (agriculture and cattle waste, food waste, kitchen waste, green waste, seaweed, algae, sewage sludge, agro industries, forestry residues, and other organic industrial waste, for example) [13]. The CE's backbone is comprised of coordinated biorefineries that utilise the complete biomass waste components to generate energy, vitality, and chemicals. On the other hand, processed solid and liquid waste streams such as pomace, peels, seeds, and byproduct streams are biomass-dense and include a variety of vital components such as proteins, carbohydrates, and minerals. These wastes have the potential to be an excellent cost-effective raw material for the creation of value-added products such as enzymes, pigments, bioactive chemicals, and biofuels with a wide range of industrial and therapeutic applications [14].

Biobased treatment is gaining significant attention for the growth of the bioproducts refinery industry since it is viewed as a viable alternative to physico-chemical techniques for extending the recovery of organic products from wastes and obtaining significantly higher bioproduct yields while certain biowaste can be directly combustible for fuel, the combustion process produces air pollution [15]. Therefore, valorisation of biowaste into other value-added products such as biofuel is essential. Circular economy progression is precise and includes green product planning, strategy changes, extending the life of user products, waste management, and expanding the market for auxiliary materials such as basic crude materials, food, pulverisation and development, organic products, and biomass such as biohydrogen [1]. This review has given a more profound understanding of the modern circular economy, which has provided an outline of realistic biorefinery chemicals derived from biowaste and summarises the final progress in biobased processes for lignocellulosic waste utilisation, as well as the significance of the most recent restrictions and projections to dazed their associated circular economy progress. Additionally, this study is to evaluate several scenarios of natural waste management using a life cycle assessment (LCA) technique.

2. Global scenario of biowaste, bioenergy and bioproducts

Each year, a massive volume of municipal biomass waste is distributed throughout the world as a result of population growth, urbanisation, industrialisation, and changes in consumption habits. According to World Bank statistics, 2.01 billion tonnes of municipal solid waste was supplied globally in 2016, and the global generation of MSW per year is expected to increase to 2.2 billion tonnes in 2025 and 3.40 billion tonnes in 2050 [16]. This trash-derived biomass is the largest component of solid waste, accounting for 44 percent, although it decreases as income levels rise: it accounts for around 32 percent in high-income countries and 53–56 percent in middle-and low-income countries [17]. Within the 35 Organization for Economic Cooperation and Development (OECD) member countries, which generate 44% of all MSW, this proportion varies significantly, ranging from 14% to 56% of total biowaste [18]. Currently, only a small portion of this amount (37% in OECD nations, or 66 million tonnes) is delivered to biobased therapies. This indicates an enormous possibility of recovering bioresources from biowaste, as illustrated in Fig. 1 [19].

In Europe, there are about 17,000 methane units, especially in Germany (where over 50% of methane is generated), the United Kingdom, and Italy (with 14 percent each). Nearly 1000 of these units are fueled by biomass [3]. The pursuit of control over the transformation of non-food biomass assets has resulted in the modification of thermochemical transformation technologies such as pyrolysis and gasification combustion. Extraordinary gasification forms for syngas have been developed by combining coal, hydrogen, combustible biowastes, petroleum cokes, and biomass [20]. There are numerous biochemical and thermochemical processes for converting biomass to biofuel. Thermochemical transformations include burning, gasification, pyrolysis, and liquid catalytic cracking, whereas biochemical transformations have consolidated anaerobic digestion and other processes such as esterification and maturation [13]. Each year, the extraction process generates around 15,000 tonnes of exhausted coffee biowaste (ECB) in Portugal, which contains organic components and hence is appropriate for energy recovery [21].

Bacillus thuringiensis delivers biopesticides via biowaste digestate. For the development of such biobased products, solid form fermentation is used to replace chemically delivered pesticides with biosurfactants, hydrolytic compounds, and biopesticides (Fig. 1) [10]. The yield of bioethanol from agro-residues was increased from 0.29 to 0.45 g/g. The selection of an appropriate reactor configuration is critical when developing a modern solid-form fermentation process, even more so when dealing with substrates such as biowaste digestate for biopesticide preparations [22]. The production of high-value biopolymers such as biocosmetics, bionutrients, biofertilizers, biopharmaceuticals, biochemicals, and biomaterials by exploiting biomass breakdown via combustion, gasification, and ageing. The forms are beneficial for advanced consideration of critical mechanical breaches, limiting extended use with caution, and facilitating consumption of higher-quality bioproducts [23]. Joanna et al. [24] described chemical pretreatments prior to hydrolysis, such as ammonia pressurization/depressurization (APD) or acid base pretreatment, in order to lower the cost of the enzymes. Elalami et al. [25] discussed the pyrolysis, combustion, and gasification processes, as well as combined digestion. Pecorini et al. [26] described anaerobic digestion and dark fermentation for the production of biological hydrogen via a constant stimulated tank reactor in conjunction with an internal combustion engine and molten carbonate energy cell (Table 1) [27].

3. Significance of circular economy of bioenergy and bioproducts

The term 'circular economy' (CE) refers to the fusion of the circular economy and bioeconomy agendas, with varied degrees of emphasis on bioproducts and bioenergy. Its recent definition in research papers, policy documents, and industrial practices has resulted in the marginalisation of several critical social, ethical, and ecological components, endangering the circular bioeconomy's viability [28]. The circular economy concept has garnered substantial regional and worldwide appeal. The major obstacles are as follows: (1) significant environmental and social impacts of landfilling operations; (2) national economies' heavy reliance on extractive industries and resource recovery; and (3) rapid development of business models for the urban population that

Fig. 1. A framework of possible source of bio-waste, treatment approaches and its bio-products and bioenergy.

Table 1
Recent status of bioenergy and bio-products development through bio-waste feed-stocks.

Year	Region	Feedstock	Adopted methods	Characteristics features	Bioproducts	Advantages	References
2019	Barcelona	Biowaste digestate	Solid state fermentation	Biopesticides produced by *B. thuringiensis*; Maximum spore production of 8.15 ± 0.04 (10^7) CFU g $^{-1}$ DM and 2.85 ± 0.22 (10^7) CFU g^{-1} DM	Hydrolytic enzymes, biosurfactants, biopesticides	Contribute to the substitution of chemically produced pesticide	[10]
2019	Spain	Biowaste digestate	Solid-state fermentation	Bioethanol production ranged from 0.29 to 0.45 g/g	Bioethanol	The selection of a proper bioreactor configuration is important for the development of a new SSF process	[19]
2019	France	Organic solid sludge	Thermochemical process, Biological treatment, Anaerobic digestion	Organic fraction of municipal solid waste, fatty waste, lignocellulosic and algal biomassPyrolysis, combustion, gasification, Sludge pre-treatment and co-digestion	Biogas	Rich nutrients supplements for agriculture	[25]
2018	China	Lignocellulosic biomass	Strain development, genome lumbering and Fed batch fermentation	Alter biowaste to bioproducts; enhanced cellulose yield	Bioproducts	Produce high yield of bioproducts	[122]
2018	Lodz, Poland	Sugar Beet Pulp waste	Chemical pre-treatments, such as ammonia pressurization/ depressurization (APD) or acid base pre-treatment, Prior to hydrolysis	Harvesting and storing the beet, Beets are flumed, washed, and sliced into thin slices, diffused with hot water	Pure sugar	Produce pure sugar from the sugar beet at the least cost	[24]
2018	Italy	Food waste	Anaerobic digestion, dark fermentation	Used biochemical hydrogen potential, Continuous stirred tank reactor, internal combustion engine molten carbonate fuel cell	Biogas and other bio-degradable substrates	Produced bio-degradable substrates that recovers energy	[26]
2017	Poland	Biowaste	Combustion, gasification, and fermentation	Yield high value biopolymers like Biopharmaceuticals, Biocosmetics, Bio-nutrients, Biochemicals, Biofertilizers, Biomaterials from biowaste	Biorefinery, Bioproduct, Bioenergy,	Better considerate of chief technological gaps, preventive prolonged economics, feasible exploitation of high quality bioproducts	[23]
2017	Brazil	Coconut residues	Pretreatment of biowaste, enzyme hydrolysis, fermentation and bioproduct recovery	Hotspot analysis of medium-density fibreboard (MDF) and high-density fibreboard (HDF)	Bio-products	Improve MDF and HDF environmental performance	[123]

compete with traditional recycling businesses. The notion of a biowaste refinery has gained considerable interest in recent years as a viable alternative to the biorefinery, utilising biowaste to produce high-value bioproducts and bioenergy [29]. Biomass is critical in a circular economy, both in terms of material outputs and energy provision. To develop a circular bioeconomy, stakeholders across the value chain, from product design to waste management, must understand the practical implications of biomass use [30].

Environmental tax revenues were found to have a beneficial effect on the model. GDP (gross domestic product) growth is anticipated to increase by 11.69 units with a one-unit increase in environmental tax receipts (EU28). In other words, environmental tax revenues are a critical indication of economic growth because they have a positive and strong correlation with it. Municipal garbage recycling rates were shown to be considerable for the EU28 and had a favourable effect on GDP per capita. This variable was chosen as a proxy for both social and economic consequences. Thus, we established that both the social and economic components of the circular economy are statistically significant and extremely vital for economic growth [31]. The biorefinery circular economy concept has demonstrated enormous significance in the progress of the global economy, with the biowaste circular economy being the most suitable for the impending demand for environmental organic material handling [32]. Bagheri et al. [33] emphasise the importance of biowaste's high energy content based on its basic makeup. According to Flynn et al. [34], social science commitments to the CE literature are typically relegated to guiding approach disputes. There is certainly a need to bring together the work being done on circular economy administration moves and policies in order to assess how such measures might facilitate a sustainability transition [34,35]. The subjective evaluation was conducted to ascertain the imperatives and impediments to the recognition of a viable supply chain within the territorial bioproducts CE. Certainly, technical novelty, permissible restrictions, funding, and user preferences all contribute to the issues associated with accessible CE benefits and shift the carbon strength of manufacturing processes. Circular economy ethics and policies require the involvement of multiple firms, citizens, and collaborative approaches [36].

The circular economics of biowaste conversion demonstrates that seasonal and local constraints on digestates are becoming significant hurdles to AD intake and digestate utilisation [37]. Additionally, China and other countries continue to face impediments to an efficient and effective transition to a circular economy. Thus, it is worthwhile to investigate the hurdles to implementing bioenergy and bioproducts systems from biowaste [19]. Biofuels (for example, biomethane, cellulose, bioplastics, and biochemicals) can be classified as mixtures of intermediate value. Separately, compost and solid digestate are generated via oxygen-consuming and anaerobic digestion processes. These fundamental perspectives have provided insight into the value of these commodities to the global marketplace, when obtained through a financially viable and environmentally friendly manufacturing process [3].

Technological statistics demonstrate that anaerobic digestion is the most cost-effective and environmentally friendly method of managing the natural fraction of MSW. It enables the reduction of greenhouse gas (GHG) emissions, the elimination of offensive odours and bioaerosol emissions, the reduction of surface use, and the recovery of control powers from a low-cost biogas [3]. Bioenergy produced from biomass is used as a fuel for gasification or combustion gasification and can be used to generate heat, electricity, or chemicals. Additionally, biomass resources can be used to produce biofuels such as biodiesel or bioethanol. Bioethanol has the potential to be an extremely beneficial energy source that can partially replace gasoline [20]. Vaporous outflows of unstable natural molecules such as methane (CH_4), nitrogen oxide (N_2O), and ammonia (NH_3) are regarded as the primary source of the composting process's consequences, as well as its energy use [38]. Reconsidering financial frameworks and modernising circular asset management frameworks would aid in mitigating the pressing issue of urban biowaste management and limited access to sources. The future will see a rise in resource scarcity. The ability to motivate superiors and manage these assets will become critical for a sustainable global economy [29].

4. Biowaste refining process advancement and technologies for bioenergy and bioproducts development

Numerous industrial products were manufactured from biowaste during the twentieth century. Biowaste refining is a method of converting waste into bioproducts and will need to be used more in the future as fossil fuels are non-renewable resources. Several biobased and thermal transformation technologies can be used to convert biowaste into biofuels. Recent data is known for the creation of bioethanol (2–83 g/L) and biobutanol (0.29–0.45 g/g) via the energised yield of various biowaste-consuming microbes [29,39–41]. Banu et al. [42] demonstrated the increased value of biopolymers such as polyhydroxy butyrates, polyhydroxy alkonates, and polyurethane via maturation and biocatalysis strategies (*Pseudomonas putida, Rhodococcus jostii, Cunninghamella echinulate*, and *Aspergillus fumigatus*) using agricultural waste, whereas Rodrguez et al. [22] provided additional insight. Budzianowski [23] described novel economic approaches for the presentation of higher-quality bioproducts. These are critical for enterprises operating in the bioeconomy to be financially viable. The sugar industry generates a large amount of biowaste, such as sugar beet pulp, leaves, and molasses, which can be used to promote microbial growth and the production of cellular proteins, proteins, organically significant auxiliary metabolites, natural acids, prebiotic oligo saccharides, and other critical products [24]. Dynamic synergistic activity of organisms and their thermophilic proteins is achieved through a variety of methods, including genetic modification and enzyme saccharification [43], bio-based treatments [44], solid fermentations [45], thermotolerant enzyme saccharification [46], and stirred, solid, and fed batch fermentation [47].

The integrated biorefinery offers us a unique opportunity to revitalise an entire manufacturing division by utilising a renewable resource to generate large product streams in the form of chemicals, vitality, medicines, and energy [48]. Chitosan was previously obtained from shrimp shells, which are a byproduct of seafood restaurants [49]. Numerous commercially viable processes are available, but they are not always compatible with specific forms of biowaste, such as biomethane from anaerobic digestion (AD), ethanol fermentation, fatty acid methyl esters (FAME) biodieselterification, and hydrotreated herbal oil. With reference to the biowaste-to-biomethane process and technologies, the existing fine infrastructure of methane in a number of countries has made the production of methane from carbon dioxide (CO) rich gases a significant component of modern economies, due to its beneficial effect on reducing global warming potential (GWP) and non-renewable energy resource consumption [17]. We evaluated the tactics and state of anaerobic digestion/co-digestion, composting/co-composting, and thermochemical and hydrothermal technologies in this part [50].

4.1. Bioenergy production by anaerobic digestion/ co-digestion

Recently, the production of sustainable biogas, such as biohydrogen and biomethane, via anaerobic fermentation has attracted global attention [51]. The solid-state anaerobic digestion of biowaste in conjunction with yard waste (YW) has been demonstrated to be a viable technique for bioenergy generation. The co-digestion of biowaste with microwave pretreatment YW at an food/microorganism (F/M) ratio of 1.5 resulted in a significant methane generation (of 431 mL/gV) [52]. Hydrolytic chemicals (cellulases and proteases derived from the autochthonous microbiome), biosurfactants (sophorolipids derived from Starmellabombicola), and biopesticides (derived from Bacillus thuringiensis) are all targeted bioproducts [10]. According to Carvalho et al. [21], adding co-biomass significantly increases CH_4 generation and biogas production (12 percent), which may be a reasonable approach for a sustainable plant. Thiriet et al. [53] established a plan for decentralised and micro-scale Anaerobic Digestion (msAD) systems to be installed in *peri*-urban and urban areas. Cobalt chloride ($CoCl_2$) at a concentration of 1 g/m3 has the lowest greenhouse gas emissions of all other trace metals examined, when calculated in CO_2-equivalent terms [54].

The attapulgite expansion boosted methane yield by 8.9–37.3 percent and had an effect on the energy used to generate methane. Attapulgite, when combined with a 10 g/L expansion stacking, results in a greater methane delivery of 210.4 mL/g volatile solids. As demonstrated by increases in the activities of beta-glucosidase, dehydrogenase, protease, and coenzyme F420, attapulgite accelerated acetogenesis, hydrolysis, and methanogenesis. Additionally, the abundance of acetogenic and hydrolytic microbes (*Clostridiales, Fibrobacterales*, and

Syntrophobacterales) is enhanced, as is the abundance of methanogenic small-scale organisms (*Methanomicrobiales*) [55]. During acidogenic fermentation of dairy products, a three-day hydraulic retention time (HRT) is required to avoid instability owing to lactate aggregation, but a six-day HRT results in the highest hydrogen production of 0.676 mol H_2 mol^1 carbs consumed. Pasteurization of slaughterhouse waste had no significant effect on the anaerobic digestion process, but increasing the nutrient ratio of dairy products increased methane generation in individual schemes (34.7–37.6 percent growth). Surprisingly, even at the greatest ammonia concentration (about 4 g L^1), AD was not inhibited [56].

Biowaste digestion demonstrated dynamic framework instability due to methanogen inhibition, resulting in unsteady fatty corrosive aggregation and process failure at the lower natural loading rate. Alternatively, by co-digesting waste with waste-activated sludge (WAS), a steady state methane production rate of up to 0.27 Nm^3 kg1VSfed is reached for OLR = 1.7 gVS L^{1}d^1 [57]. Under constant digestion circumstances, the mixture of dairy manure and switchgrass (DM:SG) in an 80:20 ratio produced the highest methane yield of 138 mL/g added up to solids (TS) loading. The combination of DM:SG and dairy manure and corn stover (DM:CS) in a 60:40 ratio resulted in the highest VS drop of 25.8 percent. This 60:40 mixture resulted in the greatest decreases in cellulose and xylan, respectively, of 40.4 and 40.7 percent [58]. Valenti et al [59] investigation showed that anaerobic digestion generates methane at a rate of 229 Nm^3CH_4/tVS. Microbes are most intricate during hydrolysis and the earliest stages of anaerobic digestion [60].

4.2. Composting/co-composting

Composting biowaste has a number of advantages, including the valuing, sterilising, stabilisation, and reduction of waste biomasses. [61]. The addition of biochar to composting and vermin composting of biowastes increased the physico-chemical characteristics of the compost mixture, whereas natural matter biodegradation and microbial workouts reduced nitrogen loss and greenhouse gas (GHG) emissions [16]. Koliastasi et al. [62] suggested that the collapse of the olive remnants during composting results in superior interfacial covering materials. Regulated expansion of fluid to solid manure compost advanced it much toward the compost moisture level, efficiently controlled the thermophilic stage, and reduced leachate generation [63]. Co-composting with biochar accelerated the composting process, resulting in a more complex material with less odour, a more neutral pH, increased development, and increased moisture retention than compost [64]. It is determined that a single turn every week results in the lowest product quality, regardless of the co-substrate and mixing ratio [65]. Composting at the laboratory level is successfully conducted inside an air pack bioreactor with an oxygen concentration of 14–21 percent and a carbon dioxide concentration of 0–7 percent. Ammonia recycling is effective within the air bag bioreactor, resulting in an increase in the nitrate concentration from 62 to 1157 mg/kg, but the ammonia concentration declines periodically due to erratic pumping and waste gas fatigue [66].

The black soldier fly, Hermetiaillucens, is gaining growing interest as a viable approach for converting biowaste into protein and fat-ironic biomass suitable for animal nutrition. The technique is to supplement fly larvae with biowaste. This reduces the amount of biowaste by close to 50% to 80% and enables the development of larvae that may be collected after about 14 days with a biowaste transformation rate of up to 20% (on a solid premise). Additionally, larvae can be controlled and used as a substitute for fishmeal in unusual animal feed, and the residue can be composted for soil modification [67]. Manyapu et al. [68] discussed the synergistic effect of using fly ash in a co-composting process with biomass and kitchen garbage. The majority of organic degradation research is experimental in vessels with rates of 0.550 d^1. Mandpe et al. [69] described fly ash as an addition for enhancing the microbiological and enzymatic activity of natural wastes in-vessel composting. Lerch et al. [70] shed light on how chemical changes to plant leftovers throughout the composting process reduce their mineralization in soil. Composting decreased the labile pool of plant residue (from 29 to 9 percent) and increased the residence period of both labile and more protected pools from 21 to 34 days and 1.5–5.5 years, respectively. Compost has been shown to significantly limit the growth of plant diseases, including *Fusarium* sp., *Rhizoctonia* sp., *Pythium* sp., and *Trichoderma longibrachiatum*, among others [71–73].

4.3. Thermochemical and hydrothermal technologies

Hydrothermal carbonization (HTC) combined with gasification is a well-known method for generating hydrogen ironic syngas from trash. Syngas H_2 and CH_4 concentrations are increased, whereas gasifier tar from hydrochars is reduced to half of its unique value from biowastes [74]. Meanwhile, this transformation of "biowaste-to-fuel" advances gasification and enables the development of similar improvements in several areas, including enhanced syngas quality given by hydrochars and decreased arrangement of gasified tar from hydrochar. As aromaticity increases in the HTC technique, the top of the change value is shifted to a higher temperature [74]. Currently, two methods are gaining prominence: hydrogenation, or hydrogasification, which utilises hydrogen expansion for carbon to produce fuel with a higher hydrogen to carbon (H/C) ratio; and extremely perilous water gasification, which uses water as a response solvent and eliminates the requirement for biomass drying [13]. After HTC, the energy qualities of biowastes improved to the point that they were similar to lignite or even bitumite. The conversion of "–C–H/C–O to aromatic –C–C/CC" proved beneficial for stabilising their combustion performance by combining two stages of biowaste (devolatilization and combustion) into a single phase of hydrochars (combustion phase) [75]. The carbon conversion value of co-gasification increases as the biomass content of a fuel increases. The overall hydrogen volume and gas capacity produced by co-gasification are more than those predicted from the gasification results of the fuels analysed [76]. The other findings indicated that HTC did not improve the fuel quality of feedstock but did appear to improve its aromatic structures, despite the fact that each biowaste had diverse components. When HTC temperatures were increased from 120 to 300 °C, the carbonaceous assembly in hydrochars gradually transformed into bitumite or even anthracite [77]. Paladino and Neviani [78] conducted a comprehensive exploratory campaign on the integrated process at both the laboratory and pilot stage. The cetane number of biodiesel was increased from 47.7 to 58.4 and the lower heating value was increased from approximately 36080 kJ/kg to 36992 kJ/kg.

5. Circular life cycle assessment route and tools for biowaste utilization approaches

Life cycle assessment (LCA) is a flexible tool for quantifying the impact of resource and process selection decisions. However, there is a wide variety of techniques available for doing pavement life cycle assessments [79]. A life cycle assessment approach for assessing the environmental implications of viticultural technical management routes (TMRs) at the plot level. The VTTI/UC asphalt pavement life cycle assessment tool was developed to quantify the environmental loads associated with resource extraction and production, biorefineries, and the end-of-life (EOL) stages of a biowaste to bioproducts and bioenergy life cycle. Generally, four system boundaries are defined for LCA (a) cradle to grave (CTG) that includes biomass cultivation, harvesting, transportation, pretreatment, thermochemical conversion, consumption and disposal. (b) cradle to consumption (CTC) which is similar to cradle to grave system except for disposal stage. (c) cradle to bioenergy (CTB) product comprises all the steps from cultivation to production but excluding consumption and disposal (d) wheel to bioenergy (WTB) mainly focus from transportation of biomass to gate of the product. It does not involve cultivation, consumption and disposal [80]. Clift et al. [81] presented an approach for life cycle assessment (LCA)-based management of mixed biowaste in accordance with the European Directive on Integrated Pollution Prevention and Control. Laurent et al. [82], who conducted an extensive examination of LCA, based their findings on sound biowaste management frameworks [38]. There are numerous publications on the life cycle assessment of biowaste management frameworks at the local or territorial level, which primarily include municipal solid waste (MSW). Björklund and Finnveden [83] conducted a life-cycle assessment of biowaste burning in a critical natural evaluation system. The purpose of the Starr et al [84] inquiry is to develop an LCA concept for associates and to identify potential changes in biogas update technology, which has a limited market presence thus far. Maria et al. [85] compared the LCA to three organic management practices for natural division of biowaste [3].

Numerous bioproducts are included in the *meta*-analysis of LCAs. It is shown a GHG reduction associated with a chemical matching routine. Transparency in information, design methodologies, and co-bioproduct care LCA is as critical in bioproducts as it is in biofuels, especially as this field of study expands [86]. The systematic examination of LCA tool papers published on Science Direct in recent years revealed that primary burdens are caused by MSW treatment (i.e. mechanical organic treatment, landfill, waste-to-energy) and by the export/transport of natural division of MSW outside the locale (due to the need for neighbourhood treatment plants), in nearly all effect categories examined. For the biowaste management route, the SimaPro programme version 8.0.5.13, Ecoinvent v3.1 (2015), sensitivity analysis in conjunction with life cycle inventory and situation examination, affectability analysis to determine the impact of potential advancements, and recognisable proof of criticality and enhancement potential are used [87]. Colón et al. [38] demonstrated that the LCA can be used to ensure the natural impacts associated with a bioproduct, from seed to grave, from the generation of the basic materials. The objective and scope definition, inventory examination, impact evaluation, and interpretation are critical phases in the LCA review. SimaProv.7.1.8 is used to evaluate the natural consequences of all biowaste management solutions (Fig. 2).

Jensen et al. [88] outlined the collection of data on all aspects of natural biowaste treatment, including information on the composition of biowaste and data from treatment facilities and associated vitality frameworks. On this basis, the natural biowaste management frameworks in the border region are proven using the EASETECH waste management life cycle assessment model. The LCA examinations are conducted using the GABI 7.2.1.12 computer program's cumulative energy demand (CED) tools [89]. Zhang et al. [90] make use of modelling tools such as Aspen Plus V9, Simapro 8.1, and Ecoinvent 3.2 for financial analysis. Examining LCA tools just in terms of their use of low-cost feedstocks with high change responses can not ensure a naturally friendly final product [90]. The Easetech software and International Reference Life Cycle Data System (ILCD) technologies are used to assess the natural performance of planned improvement routes for the metropolitan solid waste management framework in a major urban zone [91]. Environmental impact scenarios are generated using the Impact 2002 + method (V2.12). The inventories are processed using the Ecoinvent v3 database and the SimaPro 8.2.3 application. Microsoft Office 2010 is used to prepare all the data [92]. The natural maintainability of a framework for manufacturing ethanol from biowaste is assessed using life cycle assessment techniques. Papadaskalopoulou et al. [93] used life cycle impact assessment and worldwide reference life cycle data 2013 to determine the natural sustainability of a biorefinery and the effect of enhanced protein dose on natural performance (Table 2). There are always certain constraints to consider. They do not detract from the depth of understanding gained through the entire LCA method in the case of LCAs. These limitations include the following: Studies focus on normal operations rather than on areas where incidents occur, which must be understood through separate risk assessments; The quality of available data determines the validity of the entire LCA; The reliability of the environmental scores is dependent on the skill of the LCA practitioners employed; and Investment decisions are deferred.

6. Modern circular economy for bioenergy and bioproducts sustainability

The modern CE definitions are used as a baseline for research, comparing them to previously published definitions and presenting a convergent result, so that researchers and practitioners can use them as a reference to facilitate future studies that provide a complementary vision to the exhaustive studies conducted thus far, rather than starting from scratch [94]. Typically, a single firm controls a small portion of the

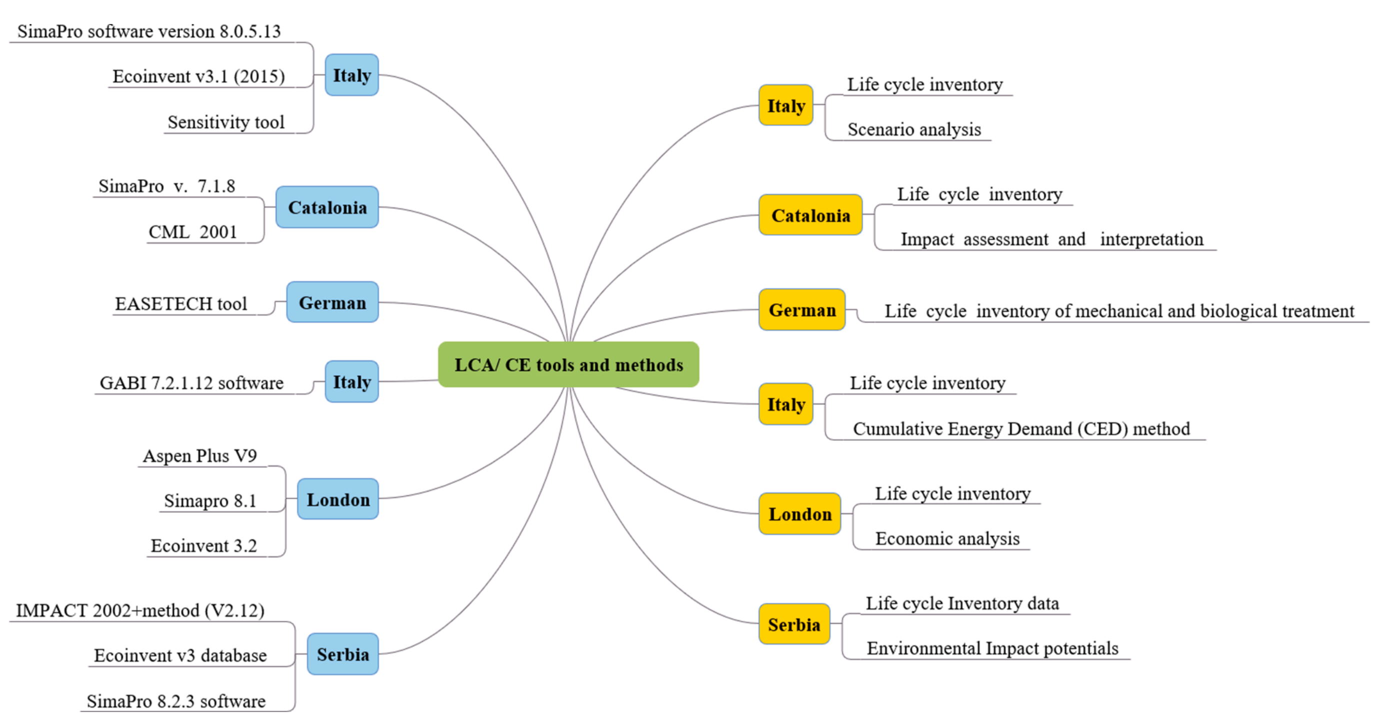

Fig. 2. Life Cycle Assessment tools and its methods for bio-waste utilization.

Table 2
Life cycle assessment tools for biowaste utilization approaches and its advantages.

Country	Feedstock type	LCA/ CE tools and methods	Other approaches	Approach advantages	Reference
Italy	Municipal solid waste	• SimaPro software version 8.0.5.13; • Ecoinvent v3.1 (2015); • Sensitivity tools	• Life cycle inventory; • Scenario analysis	• Compared different waste management routes; • Sensitivity analysis to test the influence of potential improvements; • Identification of criticalities and improvement potential	[87]
Catalonia	Municipal solid waste	• The inventory investigation, impact assessment and its interpretation; • Software SimaPro v. 7.1.8; • CML 2001 used; • The impact categories considered: abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion and photochemical oxidation.	• Life cycle inventory with quality; • Origin of the data	• The environmental presentation of the dissimilar biowaste handling technologies are comprised as a decision measure in biowaste management forecasting.	[38]
Danish–German border(Germany)	Organic waste	• Used EASETECH model	• Life cycle inventory mechanical; • Biological treatment	• Waste convert all streams into important resources. • Successful exploitation of agrowaste residual biomass; • Low price bioethanol manufacture; • Cost-effective and environmental-friendly approach	[88]
Italy	Municipal solid waste	• GABI 7.2.1.12 software; • Cumulative Energy Demand (CED) method investigates the energy use throughout the life cycle of the analysed system; • Evaluate the environmental impacts	• Life cycle inventory (LCI); • Input and emission flow analysed	• Compare the environmental impacts of four different scenarios analysed for technological and economic aspects; • Compare possible alternative scenarios and create an evaluation grid	[89]
London	Biomass waste	• PLC production process; • Modelling tools; • Aspen Plus V9, Simapro 8.1; • Ecoinvent 3.2; • Economic analysis	• Life cycle inventory (LCI); • Both mass balance and energy balance calculated	• Energy efficient separation techniques for the design of eco-friendly chemical processes use of sustainable feedstocks with high conversion reactions; • Energy source for the sustainable synthesis of biochemicals	[90]
Campo Grande, Brazil	Municipal Solid Waste (MSW)	• Easetech software; • International Reference Life Cycle Data System (ILCD) method	• LCI process; • Scenario-based treatment options were modelled	• Addressed the environmental performance of prospective development pathways; • Comprehensive planning and analysis of environmental and socio-economic effects; • Potential range for significantly higher impact reduction and even positive externalities	[91]
Serbia	Chicken meat	• Environmental Impact potentials were calculated using IMPACT2002 + method (V2.12) to CML IA baseline (V3.03); • Ecoinvent v3 database; • SimaPro 8.2.3 software	• Life cycle Inventory data collected from companies and households	• Identify and quantify the environmental impacts; • Some environmental impact potentials are calculated like global warming potential, ozone layer depletion and cumulative energy demand	[92]
Greece	Biowaste	• LCIA and ILCD 2013 method; • Anaerobic digestion and the landfilling methods	• NA	• Environmental sustainability of a biorefinery; • All the impact categories examined; • Increased enzyme dosageto the environmental performance	[93]

value creation process in modern bioproducts and bioenergy production and consumption networks. Reuse, remanufacturing, and recycling feedback loops typically demand collaboration, information sharing, and collaborative decision-making among multiple actors in the same supply chain [95]. Beyond traditional selection factors such as price, quality, and lead time, new selection criteria incorporate green practices, programmes, and attitudes. The government seeks industries that are environmentally conscious and capable of producing technically restorative and regenerative materials. The new criteria for selecting a sustainable modern circular economy may include environmental certifications, pollution control indicators, the extent to which waste items are substituted for virgin materials, and environmentally friendly operations (quality checks, disassembling, etc.).

Paes et al. [96] found that the strengths, weaknesses, opportunities, and threats (SWOT) analysis of natural biowaste management is conducted using circular economy (CE) criteria to differentiate the state of the art in SWOT analysis of natural biowaste management. The advanced circular economy strives to reduce the consumption of virgin crude materials and the formation of biowaste, to advance toward the circularity of the crude materials used, and to extend their useful life by completing the financial and biological cycles of resource flows. Rada and Cioca [97] stated that further effort must be taken to ensure that the appropriate data for MSW optimization is produced without doubt. Achinas et al. [98] discovered that the biogas economy is dependent on characteristics such as the ease of utilising and logistics of biowaste, the productivity of the preparation process, and the end-product features. Developing bioproduct refineries using natural fractions of MSW as feedstock is an exciting potential to restructure the biowaste hierarchy in a future circular economy by connecting the biowaste and generating regions [29]. Tomi and Schneider [99] comprehensive investigation revealed that the guide to a resourceful Europe envisions the "transformation of peers in energy, agriculture, trade, fisheries, regulatory frameworks, and producer and consumer behaviour." CE is distinguished as the leading concept through which change in all zones should be determined. Closing the loop between the end of an item's life and its generation enables the circulation of properties, materials, and substances and preserves the item's vitality, material, and financial value within the economy for as long as possible (Fig. 3 and Table 3) [99]. The

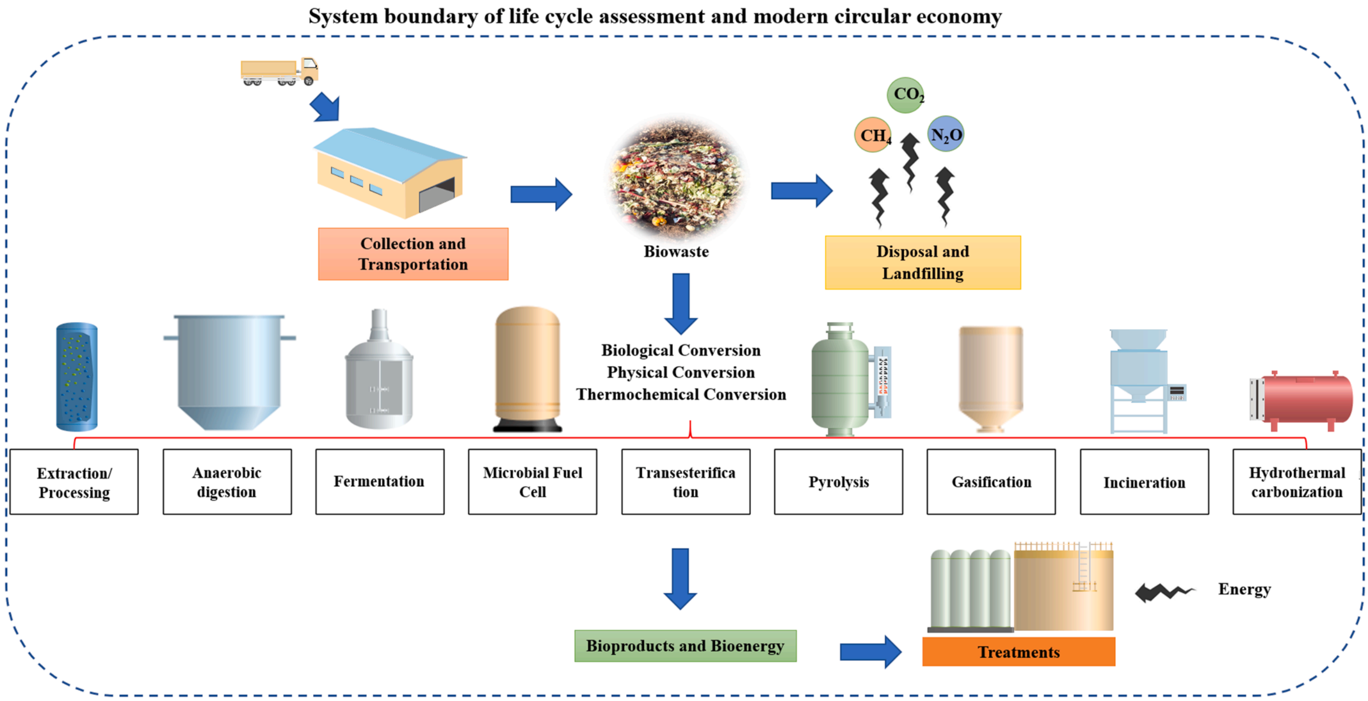

Fig. 3. Modern circular economy approaches and its key model for bioenergy and bio-products sustainability.

Zeller et al [100] investigation discovered that the urban context can limit the widespread valorisation of biowaste streams, and thus, instead of circularity islands, the circular economy (CE) is supplied with reusable things, recyclable resources, and supplements made from natural biowaste. Balaman et al. [101] stated that the organisation of biowaste to bioenergy supply chains creates a circular relationship between greening and financial development in order to address existing environmental issues and resource scarcity by increasing the asset utilisation effectiveness for internal energy generation and renewable energy utilisation. The biowaste hierarchy index (WHI) is used to determine the pecking order of biowaste in a circular economy context involving metropolitan solid waste [102]. Distinguishing how accounting techniques relegate upstream carbon to these 'wastes' in the examples of wood pellets and coal ash reveals how industrial interests, rather than established life cycle plans, shape choices. If the legislative issues surrounding outflow allocation continue to evolve in this direction, it may become increasingly difficult to discern where progress toward a low-carbon, ecologically sustainable, and circular economy is genuine and where it is a relic of one-sided and conflicting accounting practices [103].

6.1. A sustainable circular economy in the modern era

The scarcity of resources will worsen in the future, as will the ability to recover and manage these resources in a way that is feasible for the global economy [29]. Indeed, the circular economy is a sustainable option since it highlights the need for raw materials and products to circulate in the market for a longer period of time before being disposed of as waste. This minimises the amount of raw materials used in manufacturing and allows for the reuse of items that have reached the end of their useful life [104]. The complete investigation demonstrates that there are numerous interpretations of the study principles, all of which are inextricably linked. The participating enterprises commonly saw themselves as forerunners of the circular bioeconomy, emphasising the fundamental component of sustainability and reliance on "reasonable utilisation of biowaste and biomass" as well as its breadth [105]. The activities necessary to achieve this goal remain obscure, and the growth achieved has been limited: circular economy may be a topic of discussion among specialists involved in feasible progress at this level [106]. The EU bioeconomy strategy aims to improve the bioeconomy's sustainable financial growth [106]. Appropriately, there is a growing focus devoted to defining arrangements and modifying and rebuilding trade models in accordance with supportability principles. Productivity, life expectancy, social relevance, localization and involvement, ethical sourcing, and work improvement are all critical standards in sustainable trade models [105]. Additionally, model-based scenarios indicate that approximately \$697 billion of the Indian economy is at risk under a business-as-usual (BaU) scenario, but that risk could be reduced to \$382 billion under a technology-enhanced and circular economy scenario involving resource-efficient practices and closed value chains. Effective governance, based on strong policy frameworks, can serve as a catalyst for the development of a sustainable economy consistent with CE principles [107]. Numerous studies advocate reusing trash for biorefineries, for example, as a sustainable business model that contributes to the agricultural and food sectors' development, reduces greenhouse gas emissions, and satisfies the circular economy's aims. For instance, numerous European towns have separated residential organic waste due to its high energy content and potential for recovery through the manufacture of biogas [108].

By transitioning from a linear economy based on the take, make, and dispose concept to a circular bioeconomy based on the philosophy of recycle, reuse, remanufacture, and maintenance, waste biorefinery contributes to the construction of a sustainable circular bioeconomy [109–110]. Recently, renewable feedstocks have been determined by abundant and renewable biomass sources such as wood, biowaste tea, bamboo, and so on, or have been derived from food waste [111]. Bioproducts and bioenergy derived from biomass are critical substitutes for vitality and have received considerable attention in global deliberation [112]. Bioproducts of higher grade that are suitable for biorefineries must have the potential for physical market improvement and be capable of effectively competing against fossil fuels or expanding into new markets [23]. In some circumstances, the supplied volatile fatty acids have high market value and thus can be sold or used as substrates in other bioprocess applications such as microbial electrosynthesis systems and bio-electrochemical systems to add value. This technique of combining diverse wastes and bioproducts promotes maintainability

Table 3
Modern circular economy approaches and its key model for bioenergy and bioproducts sustainability.

Year	Region	Bio material	Approach	Key model of modern circular economy	Advantages	Reference
2019	Brazil	Organic solid waste	• Literature review and content analysis; • Strengths, weaknesses, opportunities, and threats (SWOT analysis) analysis for organic waste management	• The possibility to turn waste streams into valuable resources; • Contributing to environmental improvement and greenhouse gas emission reduction and costs reduction; • Stimulation of cooperative projects and production of bio-based chemicals, energy, job creation and new investment opportunities as the result of the development of a new business model; • Developed a new value chain based on organic waste	• Concentrated on emerging value chains and modifying existing business models, legislation and taxation	[94]
2019	Belgium	Urban waste	• The waste flow analysis revealed the amount of collected waste; • The proportion contributed by individual sectors; • Analysed the material composition of waste flows and the location of treatment.	• Urban context can restrict the local valorisation of waste flows; • Analysed the role of cities in a circular economy as mainly contributing; • Closing of material cycles at national or even global level	• Developed such tables for the city region for use them to analyse the urban waste metabolism in terms of waste flows; • Waste production intensity and waste treatment performance evaluated	[100]
2019	Portugal	Biowaste	• Promote prevention of waste and the application of a waste management circular economy; • Preparing for reuse, recycling, other recovery and disposal	• Proposed a waste hierarchy index (WHI) to measure the waste hierarchy within a circular economy context, applied to municipal solid waste	• Recycling and preparing for reuse, as defined by Eurostat, are considered as positive contributors to the circular economy; • Considered incineration and landfill as negative contributors	[102]
2019	United Kingdom	Biomass	• Biofuels derived from forests has catalysed a debate largely centred upon whether woody-biofuels drive deforestation	• Progress towards a low-carbon, environmentally sustainable and circular economy is real, from where it is an artefact of biased and inconsistent accounting practices	• Contested the nature of allocating environmental impacts for products and industries in highly connected systems; • Considered wastes have become increasingly valuable resources	[103]
2018	Denmark	Biowaste	• Mixed-biowaste biorefinery concepts; • Sustainable alternative the biorefinery; • Exploiting the biowaste for producing high value bioproducts	• Developing biorefineries applying organic fraction of MSW as feedstock presents a promising opportunity for moving up; • The waste hierarch by coupling the waste and production sector in a future circular bioeconomy	• Used organic fraction of municipal solid waste (OFMSW) as feedstock; • Producing enzymes, bioplastics, biopesticides and other high value product	[29]
2018	Croatia	Biowaste	• Tracking of each energy vector and calculating coverage of energy needs inside the analysed systems; • Energy from waste to drive whole waste management and recovery chain	• Alleviated via development of a low-carbon, sustainable, competitive and resource-efficient economy; • Threat of climate change are the key challenges that define the further development of energy systems	• Energy recovery of waste could help to “close the loop” in the whole waste recovery mindset	[99]
2018	Turkey	Biowaste	• New CE analysis is conducted to reveal the impacts of main economic and technological parameters on the supply chain performance indicators	• Critically important for meeting the circular economy (CE) goals; • Ensuring environmental sustainability in the planning and operation of energy systems	• Novel optimization methodology to aid sustainable design and planning of bioenergy supply chains; • Comprised multiple technologies as well as multiple product and feedstock types	[101]
2017	Italy	Municipal solid waste	• Few proposals in order to avoid mistakes and to deepen the reliability of the data generated during the analysis performed to classify the residual municipal solid waste in fractions	• The present role of landfill is minimized according to the circular economy principles; • CE Makes compulsory construction of treatment plants with precise capacities; • Suitable for treating exactly what is not source separated; • Direct landfilling is no longer viable for the authorization point of view	• A new model of characterization is thus proposed; • Suitable for planning waste management in the frame of the circular economy principles	[97]
2017	Netherland and Greece	Biogas	• Irrational use of fossil fuels and the impact of greenhouse gases on the environment are driving; • Research into renewable energy production from organic resources and waste	• Anaerobic digestion (AD) is an efficient alternative technology that combines biofuel production with sustainable waste management; • Enhance the production and quality of biogas; • Various technological trends exist in the biogas industry	• Provide an overview of biogas production from lignocellulosic waste, • Providing information toward crucial issues in the biogas economy	[98]

and contributes to a closed-loop approach centred on the unique confluence of microbiology and electrochemistry [113].

Biogas is a critical component of the modern circular bioeconomy [114]. Waste to energy (WtE) can be converted via traditional methods such as composting, bioethanol production, and waste incineration, or via advanced technical methods such as biomethanation, waste biorefinery, and biohydrogen production. It explored the modern methods for successfully implementing a circular economy (CE) and its implications for supply chains, corporate strategy, and industrial symbiosis. The preceding findings demonstrate that contemporary CE is a true business accelerator because it enables businesses to improve their environmental impact and social contribution while also discovering new and unusual business opportunities through collaboration with top management and shareholders, supply chain members, industrial partners, and consumers [115]. Organic leftovers (including dedicated biomass crops) and municipal sewage sludge can also be used as biorefinery substrates. However, organic waste is most frequently handled using anaerobic digestion, a rapidly increasing technology that combines trash treatment and biogas production. Due to the fact that waste-to-biogas facilities are dependent on organic matter circulation, they should be viewed as critical components capable of closing product/material loops in a modern bioeconomy. Similarly, approaches for biorefineries involving anaerobic fermentation and digestate usage require additional research and execution [114].

6.2. Implication and challenges

Circular bioeconomy strategies face numerous constraints and challenges, including a lack of upgrade, rigid framework boundaries, and precise information accessibility, changes in product ease of use, variations in measurable strategies, product type selectivity, neighbourhood conditions, and the environment. The circular bioeconomy of various types of biowaste biorefineries was a difficult assignment that required consideration of a variety of parameters, including biowaste quantities and characterization, energy inputs and carbon emissions from selected biorefinery innovations, biorefinery products determinations, applications, and purity, as well as nearby conditions and practices. Circular bioeconomies based on environmental considerations, socioeconomic assessment, financial input–output life cycle assessment (FIOLCA), life cycle costing (LCC), and life cycle sustainability evaluation (LCSE) can all be brought into compliance through the circular bioeconomy of biowaste biorefineries in developing countries [116]. The bioeconomy process is being spurred by the societal concerns that Europe and the globe are facing, such as population growth, uncertainty about food security, negative implications of human activities on climate change, and circular economy maintainability issues [117].

The debate between cornucopias (neoclassical financial specialists) and neo Malthusians has recently resurfaced, fueled by worry about climate change and the emergence of the water-energy-food-environment nexus concept [106]. Indeed, by recognising the critical role of connected linkages between (embodied) water, food, vitality, and land-uses in stabilising the functioning of social-biological frameworks (including climatic conditions), it became clear that external constraints on financial action development do exist [118]. Take note that the source nexus notion is inextricably linked to the bioeconomy and circular economy. A circular (bio) economy implies the capacity to be sustained over time by reusing the combination of nutrients and water required for a renewable supply of biomass for energy and food security in an easy manner [106]. On the other hand, there are still a few areas where the most urgent efforts must be made to make it more realistic. The two primary objectives are as follows: increased development of sustainable production methods, particularly precision farming; and (ii) financial valorization of biomass and reduction of biowaste [117]. When evaluating a biowaste biorefinery, the GHG-related impacts should not be overlooked, as they play a significant role in the development of the biorefinery and its financial worth [116].

7. Need and future directions for modern circular economy

In Europe (and other industrialised countries), sustainable biowaste management focuses on reducing the amount of biomass that is landfilled. Numerous European countries discard substantial amounts of biowaste alongside uncategorized MSW. As a result, the largest proportion of greenhouse-gas emissions are attributed to biowaste management [119]. The supply chain coordinates operations for biomass transformation, and usage is one of the most significant sectors affecting biomass-related creative development and commercialization activities [120]. In middle-and low-income countries, plans for solid waste biorefineries continue to be characterised by low collection fees and poor trash clearing. Uncontrolled transfer could result in the release of methane-a solid greenhouse gas-into the environment. Along with garbage, methane from landfills accounts for 90% of all global biowaste area outflows, or approximately 18% of all global anthropogenic methane outflows [62]. Biowaste must be considered as a source of material energy or material recovery that can assist rural communities in achieving sustainable rural development. Domestic composting is more rational and economically viable if biowaste is separated at the source and basic criteria are monitored properly [2].

Optimization of AD processes is critical for biowaste treatment plants to obtain energy. The major components of advanced synergetic intelligence that are broadly related are the optimal mixed percentage for progress, particularly in methane creation and digestate value. Optimizing vitality recovery via anaerobic co-digestion enhances natural performance while lowering the carbon footprint. This strategy can close the loop by building a link between waste generation and frameworks for future CE consumption in the inner cities [21]. Given the diversity of feedstocks, particularly open influences, method development, and LCA operational options, clarity in describing the biofuel LCA strategy and implementing it is critical for enabling cross-validation of revisions [120]. The application analysis of biowaste biorefineries resulted in the development of two feasible frameworks for the CE system, which include funding speciality markets, growing the bioeconomy, and reducing transportation costs associated with giving away biomass feedstocks. These designs of biomass biorefineries may provide a solution by insuring niche markets and optimising the conveyance of biowaste materials for sustainable yield [32]:

- To reaffirm the commercialization function by facilitating the synthesis of small molecules into higher-quality bioproducts.
- To alter straight economic prototype models in the direction of a circular bioeconomic system.
- To develop the production variables associated with the bioresource assembly position in order to ease the passageway and maintain stream order through the adjustable influence of bioresources.

Through increased production speed and customised biochemical structures, genetic bioengineering technologies may help increase the yield of biomass mixtures [112]. This will significantly improve the economics and viability of biowaste by converting it into higher-quality bioproducts and bioenergy. The regenerative bioindustry develops sophisticated bioproducts such as anticancer drugs, emulsifiers, surfactants, thickeners, colours, fragrances, and collagen. Biomass, algal biomass, or microbials may be used to create these biocosmetics [23]. Sustainability assessments are most beneficial when they support forward-thinking producers and innovators in making steady progress on natural, social, and financial parameters. When the traditional three-pillar model is expanded, superb administration is compromised, even with centrality, and must be implemented in sustainability appraisal systems. As such, methods must constantly evolve to accommodate the increasing diversity of biomass-derived products in today's bioeconomy [121].

8. Conclusions

The biowaste biorefinery concept has gained significant attention in recent years as a viable alternative bioproducts and bioenergy refinery that utilises biowastes to create high-value bioproducts. The review demonstrates that biowaste has played a critical role in achieving sustainable development through anaerobic digestion/co-digestion, composting/co-composting, and thermochemical and hydrothermal technologies based on a low-carbon concept with life cycle assessment integration and a modern circular economy. Notably, modern circular economy analyses should disclose the data sources, significant computations, parameters, and standards (together with the approach to co-product management), enabling comparison and replication of the results. This contemporary CE paradigm will be bolstered by LCA's potential to increase the sustainability of commercial bioproducts and biofuels, hence facilitating the creation of profitable bioproducts and biofuels. Biorefineries under development are utilising biowaste as a feedstock and offer a good potential for rising up the biowaste hierarchy over coupling waste in the production sector in a future modern circular bioeconomy.

Author contributions

Dr. Archana Jain: She has put some contribution to writing original draft of this article, data correction and formal analysis. Dr. Surendra Sarsaiya: He has put some contribution to writing original draft of this article, data correction and formal analysis. Dr. Mukesh Kumar Awasthi: He has conceptualization, design and Supervision of review and also writing - original draft this article. In addition, funding acquisition and project administration. Dr. Ranjan Singh: He has put some contribution to data correction and formal analysis. Dr. Rishabh Rajput: He has put some contribution to data correction and formal analysis. Dr. Umesh C. Mishra: He has put some contribution to data correction and formal analysis. Dr. Jishuang Chen: He has put some contribution to data correction and formal analysis. Dr. Jingshan Shi: He has put some contribution to data correction and formal analysis

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.

Acknowledgments

The AJ and SS are grateful for the financial support under Distinguished High-Level Talents Research Grant from a Guizhou Science and Technology Corporation Platform Talents Fund (Grant No.: [2017] 5733-001 & CK-1130-002), and Zunyi Medical University, China for their research facilities. RS would like to thank the Department of Higher Education, Government of Uttar Pradesh, Lucknow, Uttar Pradesh, India, for the financial support under the Scheme of "Research and Development in State Universities of Uttar Pradesh" (47/2021/606/77-4-2021-4/56/2020). We are also thanks to our all-laboratory colleagues for their help.

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