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Organic waste recycling for carbon smart circular bioeconomy and sustainable development: A review

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Abstract

The development of sustainable and low carbon impact processes for a suitable management of waste and by-products coming from different factors of the industrial value chain like agricultural, forestry and food processing industries. Implementing this will helps to avoid the negative environmental impact and global warming. The application of the circular bioeconomy (CB) and the circular economic models have been shown to be a great opportunity for facing the waste and by-products issues by bringing sustainable processing systems which allow to the value chains be more responsible and resilient. In addition, biorefinery approach coupled to CB context could offer different solution and insights to conquer the current challenges related to decrease the fossil fuel dependency as well as increase efficiency of resource recovery and processing cost of the industrial residues. It is worth to remark the important role that the biotechnological processes such as fermentative, digestive and enzymatic conversions play for an effective waste management and carbon neutrality.

Keywords: Circular bioeconomy; Sustainability; Low carbon; Environmental impact; Global warming; Carbon neutrality.

1. Introduction

Most of the energy, various chemicals and materials used today come from fossil fuels. New strategies are being developed to reduce dependence on fossil fuels and to produce alternative bio-based energy/fuels sources, chemicals and materials (Takkellapati et al., 2018; Duan et al., 2020; Liu et al., 2021a). On the other hand, some protocols similar to strategies are being also prepared in order to reduce greenhouse gas emissions resulting from excessive use of fossil fuels and to reduce global climate change-related effects. For example, some countries have committed to reducing their greenhouse gas (GHG) emissions based on the Kyoto Protocol on climate change (1997) and the United Nations Framework Convention on Climate Change (UNFCCC) (Kumar and Kumar, 2018). GHGs, carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbon (PFCs), and sulphur hexafluoride (SF_6) are emitted by consuming fossil-based fuels. Among them, low carbon economy strategies are being developed especially for the reduction of CO_2. It is thought that global warming can be limited by 1.5 °C with a low carbon economy (Knobloch et al., 2019; Awasthi et al., 2020a). For this purpose, the low carbon economy should be sustainable to mitigate the effects of climate change.

Low carbon circular bioeconomy is an integrated concept of circular economy and bioeconomy (Carus and Dammer, 2018; Awasthi et al., 2020b). A circular bioeconomy enables efficient use of substrates (wastes and by-products) for the sustainable production of value-added products such as biofuels, biomaterials, biochemicals, food and feed. For this purpose, it is important to (1) use the substrate efficiently, (2) achieve low GHGs release, (3) reduce dependence on fossil fuels, (4) use various industrial wastes, and (5) obtain biodegradable product (Awasthi et al., 2020c; Leong et al., 2021a; Pagliano et al., 2017). In addition, sustainable process (recycling, reuse, and remanufacturing) of value-added products can be defined as a low carbon economy for a green environment (Qin et al., 2021a; Leong et al., 2021a).

In addition to sustainable bioprocesses, algae also make a significant contribution to the low carbon economy in obtaining valuable products through the reuse of nutrients and CO_2 (Leong et al., 2021b). Algae, which could grow in the treatment of wastewater, produce low-carbon raw materials by using the nutrients in the wastewater and the CO_2 from the industrial exhaust.

Macro algae can be used for the treatment of wastewaters, as well as microalgae can be also cultured in open ponds and close systems (Aliyu et al., 2021). Considering the content of the produced algal biomass, it can be used as a food and feed source, or biofuel (biodiesel) (Mathimani and Pugazhendhi, 2019). In addition, some algae produce carbohydrate-rich biomass which can also be used for the production of bioethanol, biohydrogen, or valuable chemicals by simultaneous saccharification and fermentation (SSF) and separate hydrolysis and fermentation (SHF) of these biomasses (Leong et al., 2021b). Thus, algae also contribute to the low carbon bioeconomy by playing an active role in both the production of valuable products and the reduction of the CO_2 amount (Figure 1). However, microalgae is not yet industrial-oriented for the circular bio-production processes due to its high production cost (Awasthi et al., 2021a; Chung et al., 2017). Instead, cultures of microorganisms (bacteria, yeast and/or fungi) with fast fermentation ability and high product yield are needed in the conversion of wastewater and biomass into valuable products (Figure 2).

This review was based on possible opportunities and challenges for a low-carbon circular bioeconomy. Other existing and possible systems for the development of a sustainable low-carbon circular bioeconomy were also discussed in detail. The challenges and opportunities of lignocellulosic wastes, which are used in low carbon economy and are formed in excessive amounts, were emphasized. It was also discussed how the valuable products obtained with these substrates can be integrated into the industry.

2. Theoretical and conceptual framework

There may be various reasons such as global climate change, worldwide energy crisis and international political conflicts in the background and motivation of the low carbon economy (Awasthi et al., 2019, 2021b; Kokkinos et al., 2020). Recently, modern industrial facilities have been working towards a resource-conserving and low-carbon circular bioeconomy. In a circular bioeconomy, renewable bio-based resources are used as raw materials, while material and energy flows are cascaded and recycled in a closed-loop system to achieve sustainable production (Mohan et al., 2019). This system can be developed with the concept of biorefinery so that bioenergy (biofuels, energy and heat) and/or some value-added products (chemicals, polymers, food and feed) can be obtained. By following this concept, countries can thus provide their own bio-based energy sources and contribute to the reduction of greenhouse gas emissions (Table 1).

Concomitantly the production of own energy, it will also contribute to waste management and produce recyclable biomaterials (Cheng et al., 2012; Duan et al., 2021; Qin et al., 2021b).

A circular economy strategy is based on the eco-efficiency processes. While integrating agricultural, food and industrial wastes and by-products into the process, the reuse of the obtained products will make a significant contribution to the circular economy (Figure 1 and 2) (Awasthi et al., 2019; Carus and Dammer, 2018). The development of high-value products can improve resource recovery, cost effectiveness and process efficiency. Maintaining the circular economy effectively depends on determining the substrates according to the process type. In which sectors the product obtained at the end of the process will be used and the biosafety of the products are also important factors. Re-incorporating the products obtained with organic compounds released during the process into the process after reuse will contribute significantly to the low carbon economy (Carus and Dammer, 2018; Xu et al., 2020). For the purpose of the circular economy to be effective and active, the adoption of renewable energy technologies and their use must be encouraged. It is necessary to analyse the interaction of social and technological elements throughout the process and their effects on economic growth (Awasthi et al., 2022a; Kokkinos et al., 2020). To analyse the transition to a sustainable low-carbon economy, it's better to integrate ecological economic thinking with insights from socio-technical transitions, innovation systems, industrial dynamics and evolutionary economics (Foxon, 2011; Liu et al., 2021b). Therefore, researchers have proposed a framework for analysing the co-evolution of ecosystems, technologies, institutions, business strategies, and user practices (Figure 3) in a multi-level macro-meso-micro perspective (Foxon, 2011; Norgaard, 2006; Qin et al., 2021c).

3. Lignocellulosic biomass: challenges and opportunities for the bioeconomy

About 3% of the lignocellulosic biomass, which is estimated to be produced at 181.5 billion tons per year and efficiently incorporated into the circular bioeconomy (Dahmen et al., 2019; Rajesh Banu et al., 2021). A significant portion of lignocellulosic biomass forms wastes and residuals of agricultural activities. Agricultural crops such as maize, wheat, rice and sugarcane are responsible for producing the majority of lignocellulosic biomass, and other agricultural wastes make up only a small portion of the world's total agricultural waste production (Ravindran et al., 2021; Saini et al., 2015). Lignocellulosic materials consist of cellulose, lignin, hemicellulose, and extractives (pectic compounds, protein, tannin and etc.). Cellulose is a high crystallinity stable polymer with 1-4 bonds of β-glucose. Hemicellulose is a combination of polysaccharides with low polymerization degree and free from crystallinity. Lignin is a hydrophobic polycrystalline polymer composed of phenyl propane (Banu et al., 2021). Although, these materials are attractive substrate for circular bioeconomy, their complex structure (cellulose, hemicelluloses and lignin) complicates biotransformation processes (Table 2 and 4). For the recovery of lignocellulosic materials to the biorefinery, the lignin barrier needs to be removed, and the fractions need to be evaluated separately in bioeconomy (Capolupo and Faraco, 2016). Thus, value-added products (bioenergy, chemicals, and biomaterials (Figure 4) can be obtained with technologies such as thermo-chemical, biorefinery, biochemical and microbial fermentation of lignocellulosic materials (Qin et al., 2021a; Sarsaiya et al., 2019).

The lignocellulosic material can be hydrolysed by physical, chemical, enzymatic or biological, or a combination of them, and thus fermentable sugars can be obtained (Ahmad et al., 2018). Although, the use of enzymes in hydrolysis processes gives a high rate of efficiency, it is not preferred by enterprises because it increases the cost of the process (Ebaid et al., 2019; Qu et al., 2021). The dilute acid application is also a successful method, acid treatments may cause the release of some inhibitory substances which show inhibitory properties (Mussatto and Roberto, 2004). Recently, industrial production companies have started to produce their own enzymes by the cultivation of microorganisms (*Clostridium thermocellum*, *Cellulomonas*, *Trichoderma*, *Humicola grisea*, *Streptomyces lividans*, *Cellulomonas fimi*, *Penicillium* and *Aspergillus*) producing cellulolytic enzymes (cellulases) (Saini et al., 2015). Thus, the availability of cost-effective biologically based enzymes encourages technological advances (Ramli et al., 2022). The use of fungal laccases additionally to cellulases in biorefinery has begun to increase due to its broad substrate specificity, applicability in industrial processes such as pulp delignification and removal of phenolics (Moreno et al., 2020; Wang et al., 2019). Therefore, the expansion of enzyme cocktails enables the hydrolysis process of cellulosic materials and thus can improve the process and contribute to the bioeconomy.

Although, enzyme applications are successful for microbial processes, such applications cannot separate the lignocellulosic material into its fractions and make the product yield low. Alternatively, ionic liquids and deep eutectic solvents can be used to obtain cellulose (Avicel, microcrystalline cellulose, α-cellulose, and pre-hydrolysis sulphate pulp) and lignin from lignocellulosic material (Pena-Pereira and Namieśnik, 2014; van Osch et al., 2017). However, these methods do not guarantee high lignin extractability (van Osch et al., 2017). Organosolv application can separate the lignocellulosic material into three fractions as cellulose, hemicellulose and lignin in high purities (Awasthi et al., 2022b; Ferreira and Taherzadeh, 2020). The obtained cellulose and hemicellulose fractions can be mixed and evaluated in microbial fermentation for the production of metabolites such as ethanol, biomass, bacterial polymer, lactic acid, hydrogen and methane (Liu et al., 2021c; Sar et al., 2022). Lignin, on the other hand, can be used in productions such as biofuel, bio-oil, heat/electricity, biochar, biopolymer, carbon fibres and polyurethane foams (Figure 4). While a wide range of products can be produced with the organosolv application, the use of ethanol as a solvent may limit the production facilities. However, it may be advantageous to recover the used solvent and recycle it into the process, and to apply this method especially for ethanol production facilities (Bulkan et al., 2021; Sar et al., 2022).

4. A new framework approach for the advancement of technology readiness level (TRL)

4.1. Overview of mature technologies: bioenergy and biofuel productions

The biofuels generation from various bioresources employing numerous biological processes and developing technologies are rising (Liu et al., 2021d; Duarah et al., 2022). Agricultural crop residues and biomass waste use to produce biofuels has the potential to solve several environmental problems, like waste disposal and reduce environmental burden (Sun et al., 2021; Lee et al., 2020). More study has recently been conducted in generation of biofuels from microbially generated biomass material and various plants due to its eco-friendly nature to the environment (Zabermawi et al., 2022). Furthermore, photosynthesis allows these algae and plants to acquire biomass (Deviram et al., 2015). As a result, further research is being conducted in sophisticated technologies for production of biofuel as an energy source (Hossain et al., 2019). Biofuels are categorized as first; second; third; and fourth generation biofuels depending on the biomass-based resources utilized. The biofuels from first generation, includes bioethanol and biodiesel, these were made from food crop edible resources like potato, oilseed, sugarcane, barley, maize, soybean, wheat, and sunflower (Singh et al., 2022; Wainaina et al., 2020a). In this regard, the first biofuel chemical energy was ethanol that created from raw maize and sugarcane by fermentation employing fungal mycelia as an enzyme (Yuan et al., 2022; Devi et al., 2018). Wang et al. (2007) demonstrates the same finding that utilizing starch-digesting microorganisms like *Saccharomyces cerevisiae* and *Rhizopus* sp. can result in ethanol fermentation using raw flour of maize (Table 3). Thus, in the first generation, bioethanol massive amount was generated on a wide level from starch using first enzymatic hydrolysis techniques (Sheldon, 2018; Wainaina et al., 2020b).

The term "second-generation" refers to the production of biofuel from readily available organic waste material (such as straw, wood, switch grass, and oilseed-bearing) and lignocellulosic material (Singh et al., 2022; Wang et al., 2021). Under rising global energy demand vs., the strain of food security, lignocellulosic biomass is likely to play a significant role in transition to low carbon economy. High concentration of O_2 trapped in plant/crop carbohydrate polymers distinguishes chemical composition and energy contained in biomass from coal. Biomass is a glucose complex polymer that is made of 60-80% celluloses and hemicelluloses, 35% lignin, and 3-11% organic extract and inorganic mineral (Brown et al., 2019). Biomass contains natural chemical extractives including lipids, phenols, alcohols, acids, terpenes, waxes, resin, and another organic component. These carbohydrate polymer components, chemical extractives, and moisture content found in biomass may be converted to variety of thermal energy products, including producing biochar, bio-oil, and gas (Ayiania et al., 2019). Algae are used as feedstock in third-generation biofuels, generating a significant amount of lipids to produce biodiesel as well as other biofuels (Thanigaivel et al., 2022). The ability of algae to supply biomass for biofuel generation is generally acknowledged. Algae are aquatic photosynthetic microorganisms that develop quickly in coastal seawater, saline water, urban wastewater, or on terrain that is unsuitable for cultivation or farming (Chew et al., 2021). Most lipids are accumulated by micro-algal species (e. g. TAG). *Chlorella* and *Botryococcus* have significant lipid content (50-80%), that is sufficient for generation of biodiesel (Costa and de Morais, 2011). When fermented, cyanobacteria (*Spirulina platensis*, *Cyanothece* sp., and *Chamydomonas* sp.) and macro-algae collect primarily carbohydrate and produce bioethanol (Costa and de Morais, 2011). Furthermore, algae lack lignin with hemicellulose low level, leading in enhanced hydrolysis effectiveness, better fermentation yield, and hence lower cost (Pandiyan et al., 2019). Other than biodiesel and bioethanol, algal biomass may be utilized to make a variety of sustainable biofuels. Another common product that may be utilized in fuel cells is bio-hydrogen, whereas bio-methane generated as part of integrated processes can be utilized for heating or energy generation, transportation (Costa and de Morais, 2011).

The production of fourth-generation biofuels is based on genetically modified organisms and changed metabolic routes, microalgae post-genome technologies, and greater CO_2 fixation capacity (Kour et al., 2019; Shokravi et al., 2021; Rai et al., 2022; Das et al., 2022). Transgenic production of enzyme that changes the polysaccharides in the cell wall prior to complete maturity can improve biomass quality (Singh et al., 2021). Many glycosyl hydrolases (GH) are expressed in crop plants to help construct and remodel cell walls as well as promote growth (Barnes and Anderson, 2018). Native gene GH9Bs (OsGH9B3 and OsGH9B1) were discovered to improve quality of biomass in rice crops without impacting growth and development (Huang et al., 2019). Transgenic lines, on the other hand, showed 11-23% reduction in the crystalline index (CrI) and 23% drop in the degree of polymerization (DP) of cellulose. Following pretreatment of biomass, both transgenic lines, GH9B3 and GH9B1, releases more sugars (63 %) as compared to controlled line. In another study, over expression of the OsAT10 gene in rice increased cell wall glucose by 8-19% as then the wild-type rice. The use of this gene in transgenic rice and switch grass lines resulted in a 40% increase in total sugar output following enzymatic saccharification (Bartley et al., 2013; Brandon and Scheller, 2020). Over expression of the xyloglucanase gene (AaXEG2) of *Aspergillus aculeatus* in *Populus alba* resulted in increased growth and cellulose deposition, as well as up to 81% more glucose released following enzymatic hydrolysis (Park et al., 2004; Sun et al., 2022). Fonseca et al. (2020) employed a genetically engineered *T. reesei* RUT-C30 strain to produce cellulase enzyme efficiently. They were able to produce a cellulase titer of 80.6 g L^1 (0.24 g/L/h). The generated enzyme's saccharification effectiveness was determined to be quite good. It has the potential to be commercialized to manufacture a variety of gaseous and liquid biofuels. Genetic engineering is also used in the manufacturing of biodiesel (Rawat et al., 2022).

4.2. Overview of developed systems: platform or intermediate products

Carboxylic acids are widely accepted as platforms or important intermediate products. In recent years, the production of carboxylic acid by anaerobic fermentation has gradually become a research hotspot in the field of organic waste valorization. Carboxylic acids production by anaerobic fermentation is a process of inhibiting the methanogenic stage by a certain method, and avoiding the further consumption of short-chain carboxylic acid. Thus, how to effectively and selectively inhibit the methanogenic process is critical for efficient carboxylic acids production. The metabolic pathways of methane are generally divided into two categories: (1) acetoclastic methanogensis, which directly utilizes acetic acid as a substrate, and (2) hydrogenotrophic methanogenesis, which utilizes H_2 and CO_2 as substrates (Demirel and Scherer 2008). Among them, acetoclastic methanogensis usually accounts for 60-70% of the total CH_4 production, and this process is also one of the most sensitive processes to operating conditions (Pan et al., 2021). While in hydrogenotrophic methanogenesis, the availability of hydrogen is generally considered to be the only limiting factor. Therefore, compared with the acetate-trophic methanogenesis process, the hydrogenotrophic methanogens have stronger adaptability to toxicity and operating conditions (Merlin et al., 2014; Zhou et al., 2022a). Hence, the acetoclastic methanogensis process is the main target when suppressing the methanogenic stage. Blocking the methanogenic metabolic pathway and inhibiting the growth of methanogens are the common methods used for suppression of methanogenesis. Specific measures include below:

4.2.1. Add chemical inhibitors

Chemical inhibitors can be divided into specific inhibitors and non-specific inhibitors. Specific inhibitors include structural analogs of coenzyme M ($HSCH_2CH_2SO_3$ and COM) and hydroxymethylglutaryl-CoA reductase (Hydroxymethylglutaryl-SCoA, and HMG-CoA) inhibitors. The production of methane is composed of many enzymatic reactions. Among them, coenzyme M is an important enzyme required in the methyl transfer reaction of the methane synthesis pathway, and it is generally believed that it exists only in the process of methanogenesis. After the structural analog of coenzyme M is added, it can compete with coenzyme A, preventing the methyl group carried by coenzyme M from being reduced to methane, inhibiting the methyl transfer reaction, and then prevent the generation of methane. Inhibitors in this class include 2-bromoethanesulfonate (BES), 2-chloroethanesulfonate and etc. BES is generally the most widely used one, which can specifically inhibit methanogens at a lower concentration (10 mM) (Webster et al., 2016). HMG-CoA inhibitors hinder the production of mevalonate by inhibiting the reduction of HMG-CoA, thereby affecting the membrane lipid structure of methanogenic archaea. Such inhibitors mainly include drugs such as mevastatin and lovastatin. Nonspecific inhibitors can not only inhibit the activity of methanogens, but also have adverse effects on other microbes such as acid-producing bacteria (Liu et al., 2011). There are many inhibitors of this type, such as medium and long chain fatty acids, and halogenated aliphatic hydrocarbons. In addition, higher concentrations of inorganic salts in the fermentation broth also reduce the activity of methanogens and acidogens, but methanogens are generally more affected (Feng et al., 2020; Sarkar et al., 2020; Zhou et al., 2021, 2022b).

4.2.2. Heat treatment of the inoculum

Microbes that do not form spores, such as methanogens, are killed by high temperature; while some bacteria that form spores, such as acid-producing bacteria *Clostridiaceae* and *Thermoanaerobacteriacea* are not affected. Zhou et al. inoculated the heat-treated anaerobic sludge in the anaerobic fermentation acid production reactor, and no methane was detected in the headspace gas, and indicating that methane producing pathway was successfully inhibited (Zhou et al., 2017).

4.2.3. pH Control

Methanogens are strict with the environmental pH and their favorable pH range is 6.8-7.8 (Chen et al., 2015). At pH values below 6.0, methane production was not detected (Ortiz-Chura et al., 2021). In other studies, it was found that although the activity of methanogens was reduced at slightly acidic pH, a small amount of methane production could still be detected (Xiao et al., 2016; Zhou et al., 2022). This may be the contribution of the hydrogenotrophic methanogenesis process.

4.2.4. Reduced Hydraulic Retention Time (HRT)

The reported doubling time of acetate-trophic methanogens was 2.6 d, while the maximum doubling time of hydrogen-trophic methanogens was only 6 h (Merlin et al., 2014). Due to the slow growth of methanogens and the long doubling time, reducing the hydraulic retention time can inhibit the methanogenesis process to a certain extent. In addition, to using only one measure mentioned above, researchers also employ a combination of strategies to suppress the methanogenesis process. For example, to prevent the methanogenesis process from competing with the acetate reduction process for the co-substrate acetic acid, Steinbusch et al. used a combination of heat treatment (that is, boiling the medium for 15 min) and pH adjustment (Steinbusch et al., 2009). The results showed that the formation of methane was successfully suppressed, while the reduction process of acetic acid to ethanol was enhanced. To sum up, the targeted inhibition of methane process can be achieved by adding small amounts of specific inhibitors, while the method to reduce the activity of methanogens by controlling the operating conditions is relatively complicated, and the unstable microenvironment is not conducive to anaerobic systems. Therefore, adding specific inhibitors is considered to be the most efficient and feasible method, but the cost is relatively high. In order to reduce the cost of inhibiting chemicals, some researchers also use some by-products of chemical processes, such as tar, to replace them, but the inhibitory effect and mechanism remain to be studied. In addition, most of the anaerobic acid-producing fermentation broths are slightly acidic, which has a certain inhibitory effect on the acetic acid-type methanogenesis stage. However, the effect of different operating conditions on the hydrogenotrophic methanogenesis process remains unclear.

Organic waste is mainly composed of carbohydrates, proteins and lipids. Among them, carbohydrate is usually the most dominant fraction, so most of the literatures focus on carbohydrates. During mixed culture fermentation, the product is a mixture of various compounds. Among them, short-chain carboxylic acids are the main products in the liquid phase, including formic acid, acetic acid, propionic acid, butyric acid, valeric acid, and lactic acid and other organic carboxylic acids with 1-5 carbon atoms (Ramos-Suarez et al., 2021). With the exception of lactic acid, these short-chain carboxylic acids are volatile and are therefore also referred as volatile fatty acids (VFAs) in most studies. In addition, small amounts of alcohols and gases (H_2 and CO_2) are also generated in the reactor. In the process of acid production by anaerobic fermentation, and there are usually many different metabolic pathways (Table 4), and the dominance of each metabolic pathway is directly related to the structure of the microbial community in the reactor, while the operating conditions in the process (including pH, temperature, trace elements, and headspace gas, and etc.) will affect the growth, metabolism and interaction of the microbial community in the anaerobic fermentation reactor. According to the distribution of products, the metabolic pathways of carboxylic acids production are generally divided into the following five (Zhou et al., 2018), as shown in Figure 4:

a. Acetate-ethanol type fermentation

Acetic acid is a key product in the process of anaerobic fermentation of organic waste (Moscoviz et al., 2018). Acetic acid can be generated not only through the second stage of anaerobic digestion, but also in the third stage of the anaerobic process, the acetogenic stage, that is, through the oxidation of substances such as propionic acid, butyric acid, lactic acid or ethanol (Equation 1.3 ~ Equation 1.6) (Pan et al., 2021). In addition to using organic substances as substrates, inorganic carbon can also be used as substrates to participate in the formation of acetic acid. As a typical homoacetogenic metabolic pathway, and homoacetogenic bacteria can utilize carbon dioxide and hydrogen to produce acetic acid (Equation 1.7) (Wohlfarth 1994). In acetate type fermentation, acetic acid is the main product, and a small amount of ethanol may be produced, so it can also be called acetic-ethanol fermentation. Under reducing conditions, such as at higher hydrogen partial pressures, and acetic acid is converted to ethanol. However, due to the relatively high toxicity of ethanol to microorganisms, and it usually accounts for a low proportion in the products of anaerobic fermentation. In general, when the temperature is 60-70°C, the growth and metabolism of some thermophilic acetic acid bacteria are favorable (Cheryan 1995; Zhang et al., 2014). For example, Zhang et al. performed mixed culture fermentation at 70 °C, and the proportion of acetic acid was up to 90% (Zhang et al., 2014).

b. Propionic acid-type fermentation

Propionic acid can be produced through two ways: (1) Using glucose as a substrate, it is oxidized to pyruvate, and then converted into various intermediate compounds such as malic acid, fumaric acid, and succinic acid, and finally converted to propionic acid; and (2) Using lactic acid as a substrate to generate propionic acid, acetic acid and CO_2 in equimolar proportions (Equation 1.9). The researchers found that when lactic acid or glucose was used as a single substrate, the molar ratio of propionic acid/acetic acid was only 1.34 and 1.85, while when lactic acid and glucose were added simultaneously, the molar ratio of propionic acid/acetic acid could reach 7.63 (Martinez-Campos and De La Torre, 2002). *Propionibacterium acidipropionici* is a typical propionic acid-producing bacteria and has been widely used (Martinez-Campos and De La Torre, 2002; Suwannakham and Yang, 2005). In addition, the researchers found that the environment with high inorganic salt content is beneficial to enhance the dominance of the propionic acid-type fermentation metabolic pathway. He et al. found that when the inorganic salt concentration was increased from 0 to 70 g/L, the proportion of propionic acid increased from 6 to 51% (He et al., 2019). Furthermore, appropriate trace element concentrations can act as promoters of enzymes, thereby modulating product thresholds and altering the dynamics of microbial populations (Guo et al., 2019). Dahiya et al. found that the concentrations of trace elements Co^{2+}

and Zn^{2+} were 0.10 mM and 0.16 mM, which was beneficial to propionic acid fermentation (Dahiya et al., 2020).

c. *Butyric acid-type fermentation*

The main metabolites of butyrate-type fermentation (BTF) are butyrate and acetate. At the same time, it is usually accompanied by the production of a large amount of H_2. Acetyl-CoA (Acetyl-CoA) is a key intermediate metabolite during butyrate-type fermentation. The production of butyrate is dependent on the further conversion of acetyl-CoA generated during glucose metabolism into butyryl-CoA (Butyl-CoA), and then converted into butyryl phosphate and butyric acid with catalysis of phosphotransbutyrylase (PTB) and butyrate kinase (BK), respectively. At the same time, acetyl coenzyme A (Acetyl-CoA) is also converted into acetyl phosphate with the help of phosphotransacetylase (PTA), and then acetate kinase (AK) mediates the production of acetate. The processes from butyryl-CoA to butyryl phosphate and acetyl-CoA to acetyl phosphate are the rate-limiting steps in the production of butyrate and acetate, respectively (Feng et al., 2009). Most of the existing studies on the fermentation of butyric acid from organic wastes are usually observed under weakly acidic conditions around pH 5.0 (Jiang et al., 2013; Horiuchi et al., 2002; Feng et al., 2018). There are also a few literature reports that pH 6.0-6.5 is beneficial to the production of butyric acid (Yu et al., 2021). This difference may be related to substrate composition and inoculum type. In the butyric acid fermentation process, acetic acid is used as a by-product, which reduces the production of butyric acid and increases the cost of downstream separation and purification. How to reduce or eliminate the production of acetic acid is a research hotspot of butyric acid fermentation. Researchers have done this by knocking out acetogenic genes such as PTA (encoding phosphotransacetylase) and AK (encoding acetate kinase) genes responsible for acetate formation (Liu et al., 2006). Compared with the production process of acetic acid, the production of butyric acid requires an additional consumption of 2 mol of $NADH_2$, which means that increasing the reducing equivalent can promote the production of butyric acid. In addition, Fu et al. achieved 100% butyrate selectivity when co-fermented with mannitol/glucose in appropriate ratios (1:2 or 2:3) by inoculating *Clostridium tyrobutyricum* ATCC 25755 (Fu et al., 2020). This is partly due to the use of pure bacterial fermentation, and partly due to the fact that mannitol metabolism can provide additional NADH, and thereby promoting the further conversion of acetate to butyrate.

d. Lactic acid-type fermentation

Lactic acid fermentation refers to a fermentation process in which organic matter is converted into lactic acid as the main product. In addition to lactic acid, small amounts of acetic acid, ethanol or carbon dioxide may be produced. This mainly depends on the type of lactic acid fermentation. According to the different fermentation products, lactic acid fermentation can be divided into two types: homo-lactic fermentation (Equation 1.12) and heterolactic fermentation (Equation 1.13 and Equation 1.14). During homo-lactic fermentation, 1 mol of glucose can be converted into 2 mol of lactic acid, and the conversion rate of lactic acid is 100%. In heterolactic fermentation, in addition to the production of lactic acid, acetic acid, ethanol or CO_2 are also produced. Since lactic acid bacteria are more tolerant to pH than other acid-producing bacteria, when the pH is low, the lactic acid-type metabolic pathway is usually dominant. According to literature reports, when the pH value is extremely low (pH 3.5), the proportion of *Lactobacillus* can reach 97.55%. The abundance of *Lactobacillus* gradually decreased with the increase of pH. The relative abundance of *Lactobacillus* dropped to 65.54% at pH 4.5, while its presence was almost undetectable when pH reached around 6.0 (Feng et al., 2018; Ghosh and Das, 2022).

e. Mixed-acids fermentation

Mixed acid fermentation is the most common type of acidogenic fermentation. In mixed acid fermentation (MAF), almost every type of fermentation mentioned above is present in the reactor simultaneously. Thus, the organic matter was converted into a mixed solution consisting of compounds such as acetic acid, propionic acid, butyric acid, valeric acid, ethanol, and each organic carboxylic acid was dominated by a different acid-producing bacteria. It has been reported that at pH 6.0, the mixed acid metabolism pathway is dominant (Feng et al., 2018; de Jong and Jungmeier et al., 2015). At this time, in the microbial community, the proportions of *Prevotella* and *Megasphaera* were 57.47% and 27.54%. In addition, there is a small fraction of other genera such as *Acidaminococcus* exist. *Prevotella* is associated with the production of acetate and succinate, while *Megasphaera* converts glucose into propionate, butyrate, and valerate, among others. In summary, the dominance of the acidogenic metabolic pathway has important implications for the composition of the products in the fermentation broth. However, how to improve the dominance of specific fermentation types is still a research topic that has received much attention in recent years.

7. Overview of developing systems: future biorefinery systems

A healthy environment, economy and society are the main pillars for a well-succeed sustainable development, which in turns is defined as the world population ability to meet the present needs without compromising the future needs (Chiappetta Jabbour et al., 2020; Teigiserova et al., 2021). The worldwide bioeconomy is strongly considered a key approach to achieve sustainable progress by decreasing dependence on non-renewable resources through the application of biotechnology, bioresources and bioecology areas (Vance et al., 2022). Biorefinery concept is a fundamental part with substantial increasing attention within the bioeconomy, which is a flowing based-process to obtain several functional products from one or more raw materials (Imbert, 2017; Devi et al., 2022), for example, these systems can give rise various valuable and-products such as protein rich fractions directed for human consumption (foods and feed), biofuels (bioethanol and biogas), biochemicals (fertilizers, sorbitol, anthocyanins) and biomaterials (hydroxybutirate, adhesives films, and composites) (Dahiya et al., 2018; Solarte-Toro et al., 2021). Additionally, the biorefinery concept can be totally linked with consolidated biotechnological process like anaerobic digestion (AD), which can produce fertilizer and bioenergy in the same process (García-Galindo et al., 2019). The biorefinery concept is considered as one of the research milestones in the last decades as the best and suitable option to transform different biomasses into multi value-added products (Katakojwala and Mohan, 2021).

Moreover, the biorefinery systems are constructed according to the biomass feedstocks that entry to the process to obtain these valuable products, which are generally classified as first generation, second generation and third generation biorefineries (Table 2) (Budzianowski and Postawa, 2016; Duan et al., 2022). The first generation uses crops (edible vegetables, cane, rice, and wheat), second generation are categorized as yellow and green biorefineries, which utilize dry and wet lignocellulosic materials, respectively (straw, wood waste, non-food crops, waste cooking oil, leaves and grass) and the third generation also known as blue biorefinery that utilize marine-based materials such as algae; and brown or grey biorefineries, which their principal aim is to employ waste coming from municipal or agricultural sludge and solid residues (Bhatia et al., 2020; Manikandan et al., 2022). Overall, these all feedstocks have resulted to be promising resources to bring more sustainable product among fuels and chemicals through different consolidated and novel technologies such as dark fermentation (DF), photo-fermentation (PF), AD and a microbial fuel cell (MFC), enzymatic-assisted extraction (ESE), solid-state fermentation (SSF) as well as liquefaction, pyrolysis, gasification, supercritical conversion, crystallization and combustion (Gómez-García et al., 2012; Ren et al., 2015; Foletto et al., 2017; Turhal et al., 2018). Therefore, the biorefinery concept is playing a vital role for a sustainable world based on a bioeconomy low in carbon foot print, fulfilling the increasing needs for sustainable energy and goods (products) production that industries and human society is facing to move from a linear economy to a circular economy (Rabelo et al., 2011; Liguori and Faraco, 2016; Ocheieng et al., 2022). Bioeconomy encourages the utilization of renewable materials which promote to generate a wide array of biobased end-products through the conjunction of multiple areas, including research, management, business and engineering experts. In this regard, the first generation biorefineries are facing economic, social and environmental issues because these are developed based on food crops. Their high implementation can lead to increase foods cost and resource (land and water) depletion, and being not sustainable at all. Therefore, second and third generation biorefinery are under intensive revision and investigation because they can overcome suitability the social, economic and environmental issues without implicating on foods cost and avoiding environment depletion because they use non-edible and biodegradable feedstocks such as non-food crops, forestry residues and wood waste as well as microalgae, which have some interesting advantages related to being cultured at low-cost, eco-friendly and renewable. Although, the first generation biorefineries produce marketable viable end-products, the second and third generation biorefineries are not yet economically viable due to the enormous management challenges, scalability and manufacture cost issues.

Based on these facts, several researches have prompted the combination of the first, second and third generation biorefineries as future systems as multi-functional platforms with high benefits, and helping a step forward towards a circular bioeconomy (Moncada et al., 2014; Mizik and Gyramati et al., 2021). To achieve such integrations is very important to meet each of the sectors involved and develop more feasible technologies to take total advantage of the biomasses by knowing their entire physicochemical and biochemical composition with the objective to optimize and find the perfect fit between each different biorefinery in order to achieve high accuracy on the production processes as well as on the desired end-products (Daza Serna et al., 2016). The analysis of feedstocks, availability and market needs are concept that could help to discover the possible relationships between each biorefinery in which all of them can be combined in one process. Hence, it should continuously be taking into account that different products can be obtained from diverse processing systems by the conjunction of different raw materials and the desired end-products can be categorized into five main useful clusters: biofuels, bioenergy, biomolecules and natural chemicals, biomaterials, and functional food products (Ravindran and Jaiswal, 2016; Carmona-Cabello et al., 2020; Poul et al., 2020). For example, a process integrating first-second-third biorefineries using grains or juice (first), lignocellulosic materials (second), and algae (third) can obtain diverse fractions such as amino acids, vitamins, pigments, and antioxidants after the production of energy and chemicals (Moncada et al., 2014; Gómez-García et al., 2021).

8. Sustainable production and consumption

The demand to move from the traditional linear production to a more sustainable production and consumption has arisen and gained interest not only between researchers of biotechnology, environment and food science and technology areas, but also by industrial and governmental sectors, working for the same objective, decrease the environmental and social issues by promoting a suitable and correct management of natural resources (Campos et al., 2020; Camilleri, 2021). Sustainable production and consumption approach is an up-and-coming thinking for meeting sustainable development goals in the business environment (Roy and Singh, 2017). It generally embodies a consolidation of production and consumption outlooks for disclosing a more methodical methodology to achieve a sustainable development issue in the business environment. Additionally, this model has become considered a key research trend for diverse areas like sustainability management, innovation, entrepreneurship and new product development (Vlachokostas et al., 2021). Moreover, comply with the targets of sustainable development goals is a current challenge for the integration of a sustainable production and consumption systems that interest the production and consumption of products, services and resources in a suitable way that all of them should be environmentally friendly, economically feasible, and beneficial to society (Martin-Rios et al., 2021). This specifically demands active contribution of all the involved actors within the industrial value chain e.g., from government, communities, enterprises, households, and business. Furthermore, circular bioeconomy concept intends to improve operational efficiencies and to reduce waste in production processes during the product life cycle. Several theoretical fundaments have given good outcomes, reporting that efficient monitoring, traceability and control procedures can be implemented in all stages of the supply chain, from production-distribution until final consumption in order to minimize the cost of dealing with externalities including pollution and greenhouse gas (GHG) emissions (Ding et al., 2021). It has been suggested that in order to address a social fairness, environmental harmony and economic proficiency, it is essential to undertake the life-cycle approach (Table 3). Economic and environmental aspects being highly important in this matter, they can be assessed with different advanced methodologies for example value chain analysis and life cycle assessment. Life cycle assessment (LCA) is derived from the life cycle thinking (LCT), which is applied to measure the influences of a product, process or system over its lifetime (Liu et al., 2021; Katakojwala and Mohan, 2021).

As it is expected, biorefinery (eco-efficient and cost-effective) systems will be assumed to be introduced as new supply chains and used for the entire life cycle, they should be well designed and assessed by LCA approaches from the biomass input to the end-products (Table 4), this due to the highly composition variability of the feed stocks, their availability and great amounts (Vlachokostas et al., 2021). As mentioned in section 7, biorefineries can exploit large variety of raw materials, from lignocellulosic feedstocks to algae. Lignocellulosic materials includes a extensive variety of biomasses such as wood, grass, and agricultural and food residues, which are predominantly composed by cellulose (30-50%) dry weight DW), hemicellulose (20-40% DW), lignin (5-25% DW) and pectin (15-30% DW) as well as bioactive compounds such as enzymes, phenolic antioxidants and simple sugars (among others). Moreover, microalgal biomass can contain, free fatty acids (1.53%), carbohydrates (24.92%) triglycerides (28.47%), protein (5-47% DW) and amino acids (40.05%) (Peralta-Ruiz et al., 2013; Poveda-Giraldo et al., 2021). However, despite this nutritional and bioactive richness still present in these biomass residues, differences such as species, plant age, plant part, and growing conditions (soil, altitude, temperature and shading), leading to a significant variations in their compositions, affecting the end-products standardization and quality (Bakker, 2015; Blahuskova et al., 2019; Yang et al., 2021).

Lignocellulosic food waste can be an environmental and economic problem if not managed properly but it can meet various social demands of a country if it is employed as raw materials to obtain valuable end-products (Carmona-Cabello et al., 2020). The global food system is a major actor of land usage, resource exhaustion and environmental pollution by significant GHG emissions (Martin-Rios et al., 2021). The LCA approach is progressively employed for the valuation of the interactions of different food products on the environment in terms of GHG emissions (carbon footprint), water consumption and land use, chemical use, energy use and biodiversity loss to mitigation risk and bad habits throughout the supply chain steps (Esparza et al., 2020). For example, the environmental parameters assessed during pulses production were principally energy demand, climate effect, eutrophication potential, pesticide use and land utilization. For its consumption, the impact categories were energy demand, climate influence, land utilization and biodiversity impact from land use. The environmental performance of the cultivated pulse crops varied significantly, concerning 1.6-3.3 MJ for energy demand, 0.18-0.44 kg CO_2 for GHG emissions and 3.1-5.9 m^2 for land utilization per kilogram of dry pulse. Diesel was the major energy spend in the fields, followed by oil energy for grain drying. As specific conclusion, a determining factor for energy use and GHG emissions related with pulses for consumption was long transportation and whether the product was moved in dried basis or packed (Tidåker et al., 2021).

Currently, the LCA within circular bioeconomy has been recognized not only food crops but also food waste management as a vital approach to treat them as feedstocks for environmental impact mitigation since these waste biomasses are treated by non-sustainable process, including disposed in landfills, which involves high transportation costs and large landfill areas limiting the accessible land; incineration, which converts it into gases, ashes and heat, producing important volume of thermal energy, but liberating great concentrations of toxic gasses and fumes; composting method transforms organic waste into organic matter by microbes. This process reutilizes nutrient, but is prone to pathogenic microorganisms develop and produce significant GHG emissions (Gómez-García et al., 2021). Thus, these current processes for their treatment will not be further accepted. Hence, new processes must be implemented based on biorefinery and green chemistry approaches, helping with the reduction of environmental pollution and contribution for a sustainable development.

9. Conclusions

The current review highlighted the big opportunities that organic waste matter can offer as sustainable bioresources to produce different products under low carbon economy context. These processes must be able to take full advantage of the total nutritional and biological value of waste materials and be employed as new feedstock to develop multiple value-added products like bioenergy, biochemicals, foods and biomaterials, while bring benefits not only for industries, but also for society and environment, allowing a global economic growth. In this regard, biorefinery approach coupled to circular bioeconomy context could offer different solution and insights to conquer the current challenges related to decrease the fossil fuel dependency and increase efficiency of resource recovery as well as processing cost of the industrial residues.

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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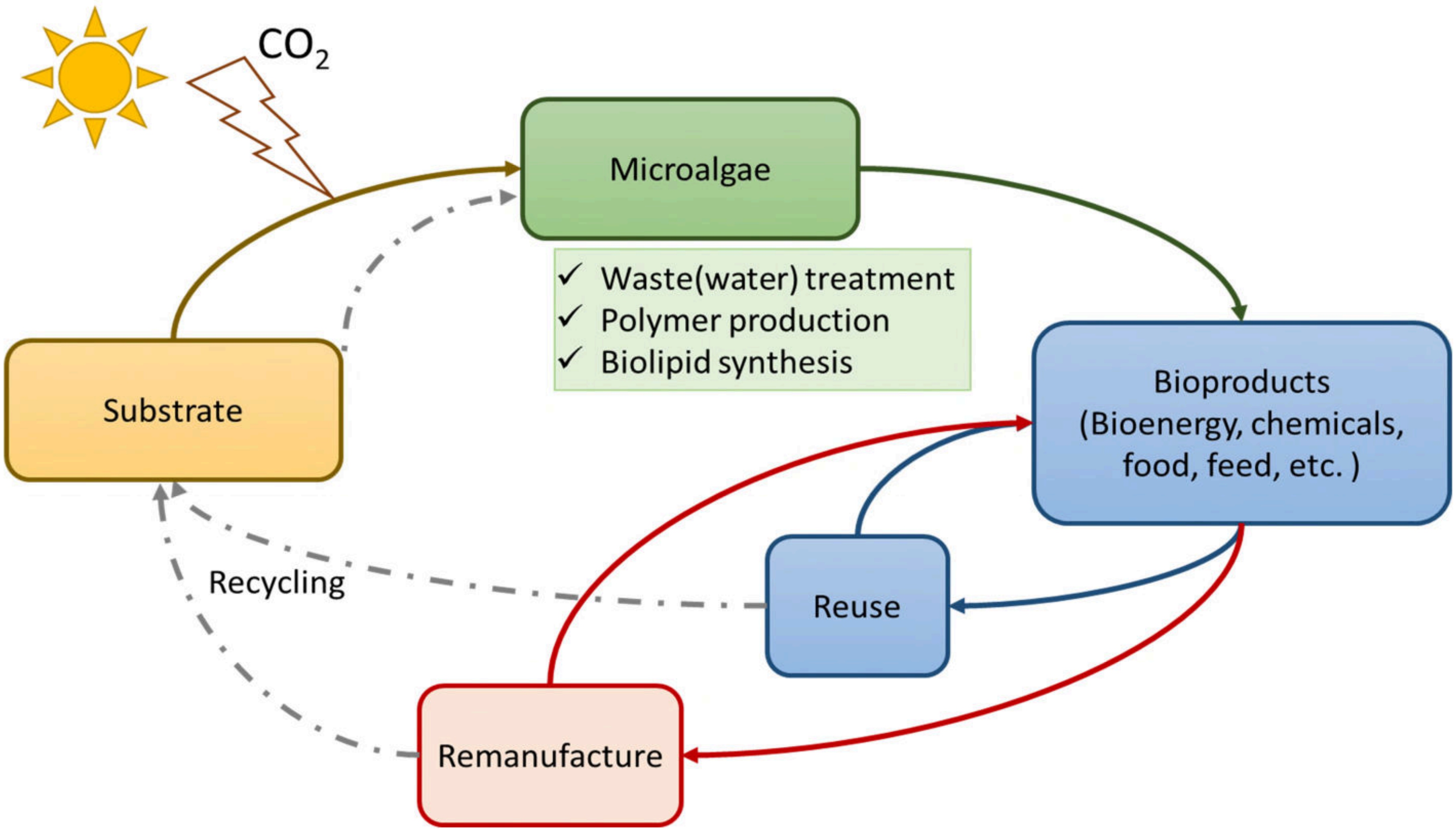


Figure 1. General schematic representation of algae-based low-carbon circular bioeconomy.

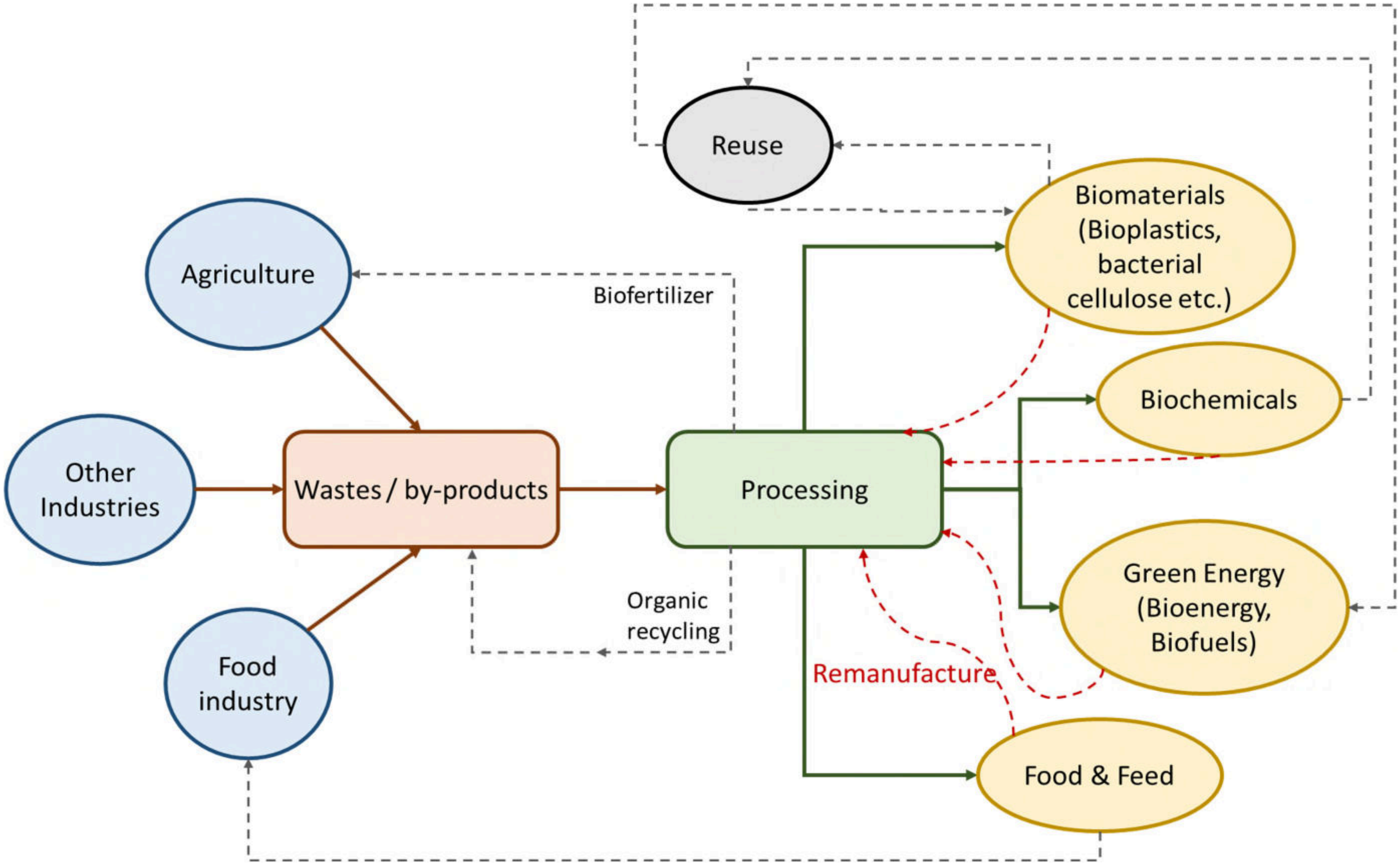


Figure 2. General schematic representation of microbial process-based low-carbon circular bioeconomy.

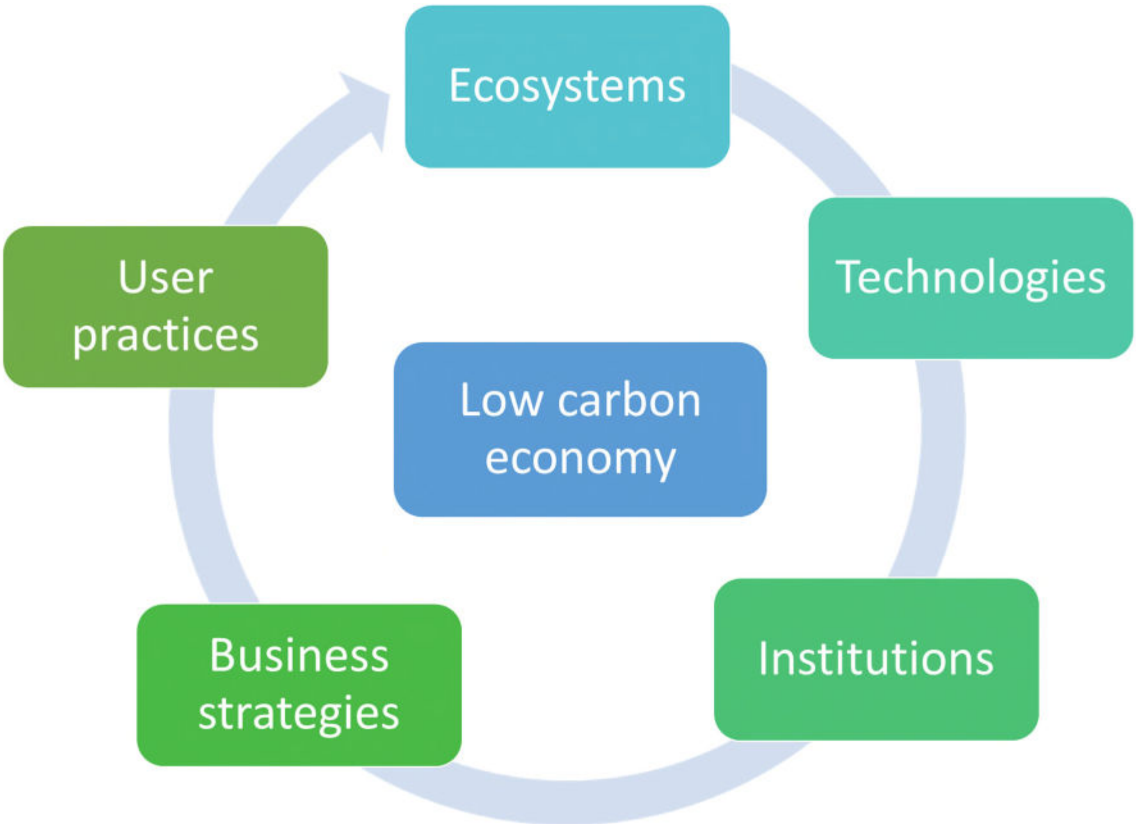


Figure 3. A framework for analysing the co-evolution of ecosystems, technologies, institutions, business strategies, and user practices.

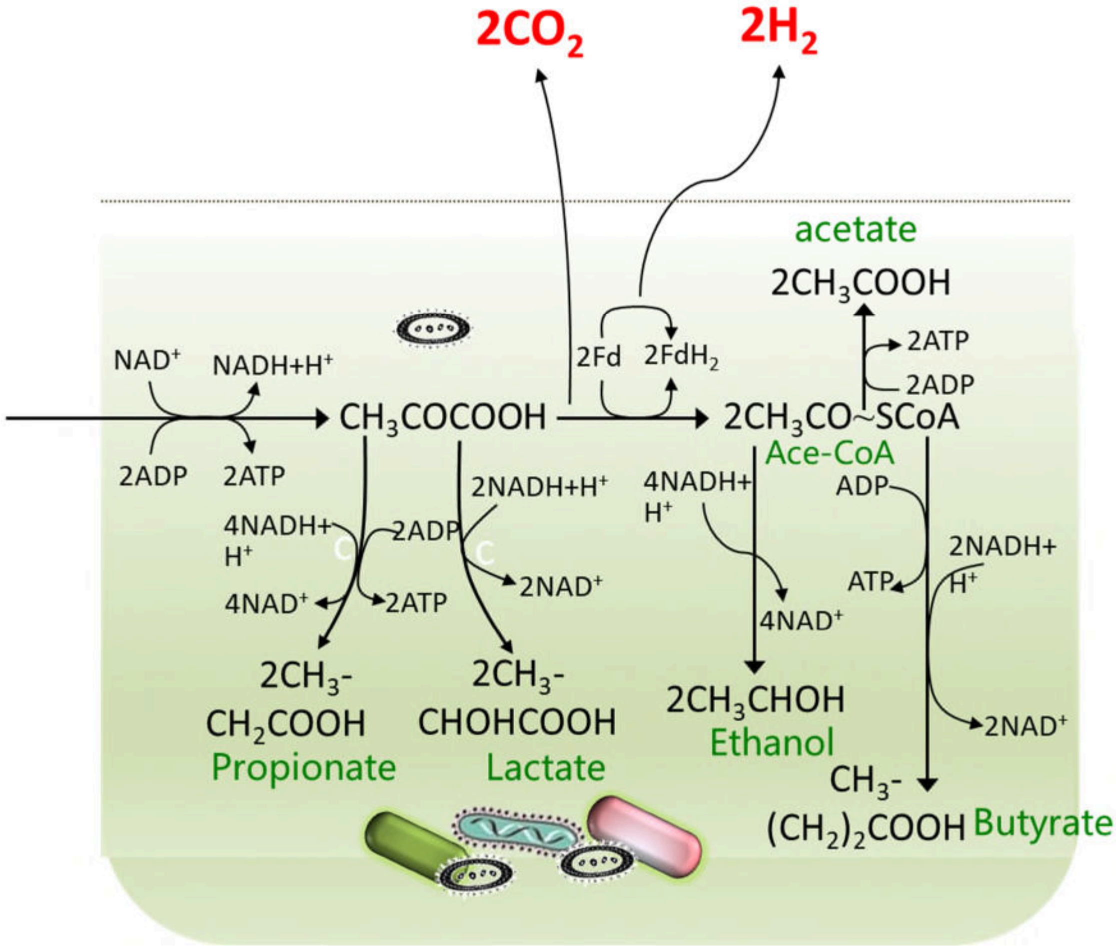


Figure 4. Metabolic pathway of acidogenic fermentation.

Table 1. The main metabolic pathway in acidogenic fermentation and Gibbs free energies.

Metabolic pathway	Eqs. No	$\triangle G^0$ (kJ/mol)	$\triangle G^0$(37℃) (kJ/mol)
AET			
$C_6H_{12}O_6 + 2\ H_2O \rightarrow 2\ CH_3COO^- + 2\ H^+ + 4\ H_2 + 2\ CO_2$	（1.1）	-133.44	-141.92
$C_6H_{12}O_6 \rightarrow 3\ CH_3COO^- + 3\ H^+$	（1.2）	-188.40	-188.21
$CH_3CH_2COO^- + 2\ H_2O \rightarrow CH_3COO^- + H^+ + 4\ H_2 + CO_2$	（1.3）	71.66	66.39
$CH_3CH_2CH_2COO^- + 2\ H_2O \rightarrow 2\ CH_3COO^- + H^+ + 2\ H_2$	（1.4）	88.16	86.27
$CH_3CHOHCOO^- + H_2O \rightarrow CH_3COO^- + CO_2 + 2\ H_2$	（1.5）	-9.52	-13.67
$CH_3CH_2OH + H_2O \rightarrow CH_3COO^- + H^+ + 2\ H_2$	（1.6）	-49.58	48.02
$4\ H_2 + 2\ CO_2 \rightarrow CH_3COO^- + H^+ + 2\ H_2O$	（1.7）	-54.96	-46.29
PFT			
$C_6H_{12}O_6 + 2H_2 \rightarrow 2\ CH_3CH_2COO^- + 2\ H^+ + 2H_2O$	（1.8）	-276.76	-274.69
$2CH_3CHOHCOO^- \rightarrow CH_3COO^- + CH_3CH_2COO^- + 2CO_2 + H_2$	（1.9）	-485.10	-488.10
BTF			
$C_6H_{12}O_6 \rightarrow CH_3CH_2CH_2COO^- + H^+ + 2\ H_2 + 2\ CO_2$	（1.10）	-221.60	-228.19
$4C_6H_{12}O_6 + 2H_2O \rightarrow 3CH_3CH_2CH_2COO^- + 2CH_3COO^- + 8CO_2 + 10\ H_2 + 5\ H^+$	（1.11）	-798.24	-826.50
LTF			
$C_6H_{12}O_6 \rightarrow 2\ CH_3CHOHCOO^- + 2\ H^+$	（1.12）	-114.40	-114.59
$C_6H_{12}O_6 \rightarrow CH_3CHOHCOO^- + H^+ + CH_3CH_2OH + CO_2$	（1.13）	173.50	-176.27
$2\ C_6H_{12}O_6 \rightarrow 2\ CH_3CHOHCOO^- + H^+ + 3\ CH_3COO^- + 2\ H_2$	（1.14）	-302.80	-302.79
MTF			
$3\ C_6H_{12}O_6 \rightarrow 2CH_3COO^- + 2\ H^+ + 4\ CH_3CH_2COOH + 2H_2O + 2CO_2$	（1.15）	-686.96	-691.30
Others			
$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$	（1.16）	-130.66	-125.74

Table 2. Biorefinery systems generalities and value-added products abstention.

Biorefineries classification				
Generation	**Colour ID**	**Feedstock characteristics**	**Biomass**	**New products**
First	Gold	Crops	Sugarcane/Cereals	Sugar, Fuel Ethanol, Electricity, and Steam
Second	Yellow	Dry lignocellulosic materials	Straw/Stover/Wood	Ethanol, Cellulose, Hemicellulose,
	Green	Wet lignocellulosic materials	Leaves/Grass	Lignin, and Second metabolites
Third	Blue	Marine-based materials	Algae	Oil, Biodiesel, and Vitamins,
	Brown/Gray	Municipal waste	Agricultural sludge/ solid waste	Water, and Fertilizer

Table 3. Life cycle approaches for a sustainable production and consumption applied on biorefinery systems according to Vance et al. (2022).

Type	Objective
Life Cycle Management (LCM)	Use sustainability knowledge for responsible decision-making
Life Cycle Thinking (LCT)	Impacts contributed by each sector involved in the production and utilization of that product.
Life Cycle Assessment (LCT)	Used to assess the impacts of a product, process or system over its lifetime
Environmental LCA (e-LCA)	Considers only environmental impacts
Social LCA (s-LCA)	Assess social impacts
Life Cycle Costing (LCC)	Assess economic impacts

Table 4. Available literatures for sustainable production of value-added products.

Substrate	Product	Primary Technology	References
Lignocellulose biomass / Lignocellulosic waste biomass (LCB/LCWB)	Biogas, Methane, Bioethanol, biodiesel, Renewable diesel, and Jet fuel Biobutano	Pretreatment methods (physical, chemical, biological)	(Ahmad et al., 2018; Aliyu et al., 2021; Capolupo et al., 2016; Chew et al., 2021; Pandiyan et al., 2019; Rai et al., 2018; Ren et al., 2015; Saini et al., 2015; van Osch et al., 2017)
Lignocellulose	Syngas, Fuels, Chemicals, Ethanol, Butanol, and Hydrogen	Biorefinery	(Dahmen et al., 2019; de Jong et al., 2015; Liguori et al., 2016; Rajesh Banu et al., 2021; Sarsaiya et al., 2019; Takkellapati et al., 2018)
Starch-based material, Molasses, sucrose, Lignocellulosic material, Whey-based culture media	PHAs, Biogas, and Biohydrogen	Fermentation	(Pagliano et al., 2017)
lignocellulosic Agricultural wastes	Laccases	solid-state fermentation (SSF)	(Wang et al., 2019)
Microalgae	Biofuels, Bioenergy, syngas, and Biochar	Anaerobic co-digestion, Anaerobic digestion, Thermochemical, Biorefinery	(Aliyu et al., 2021; Bhatia et al., 2020; Mathimani et al., 2019; Moncada et al., 2014; Ochieng et al., 2022; Rawat et al., 2022; Thanigaivel et al., 2022)
Microalgale	Biodiesel	Molecular strategies	(Chung et al., 2017)
Oily wastes	Biodiesel, Syngas, Bio-oil, and Biogas	Biorefining	(Awasthi et al., 2020b; Singh et

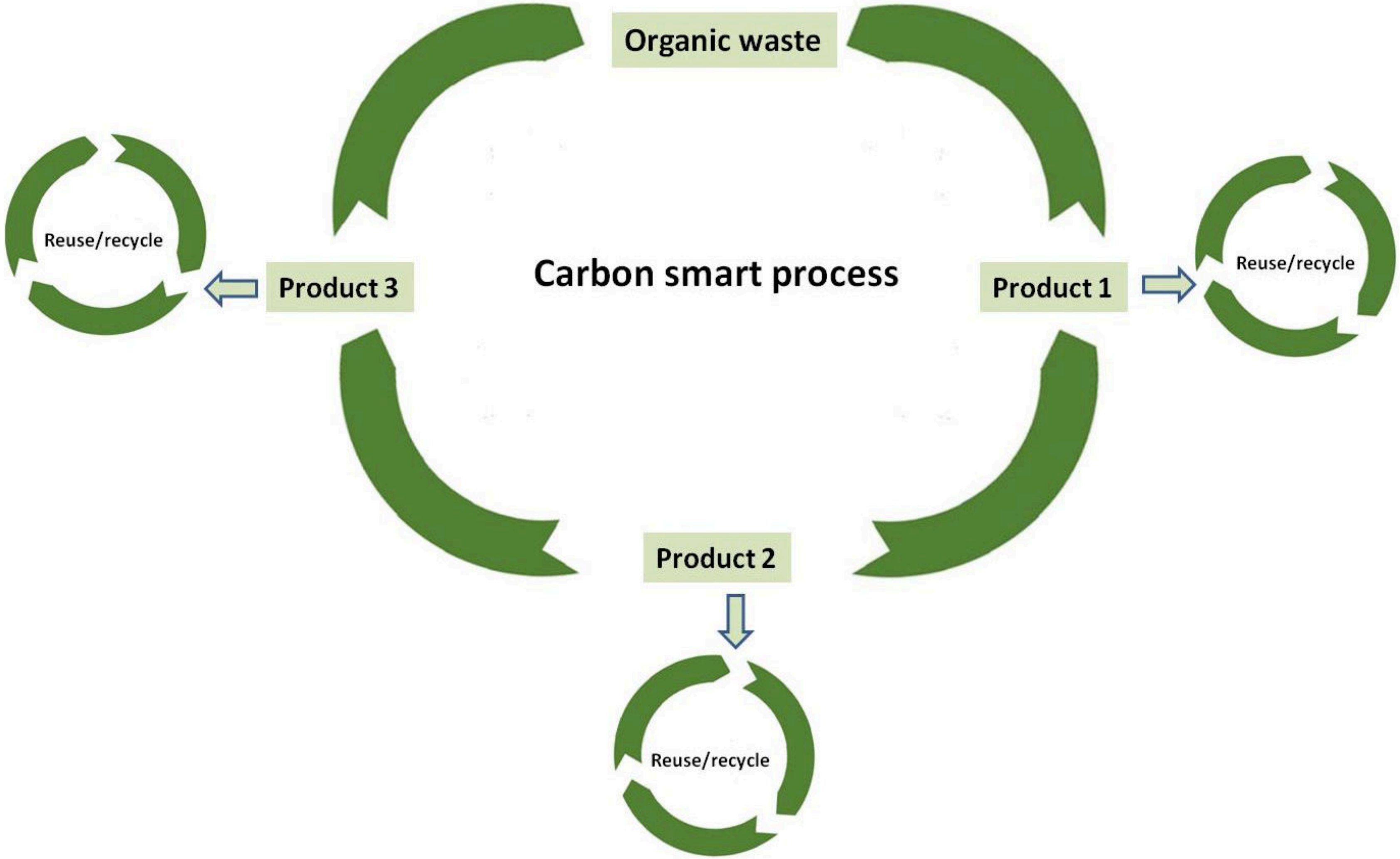
			al., 2021)
Apple processing-derived waste	Biofuels, Biochemicals, Biopolymers, Pectin, Phenolic, and Biogas	Biorefining, Extraction, Hydrothermal Carbonization	(Awasthi et al., 2021a)
Bio-waste	Charcoal,Syngas,CH_4, bioalcohol, and Biogas	Thermal and biological treatment	(Awasthi et al., 2021b)
Livestock	CH_4, CO_2, water vapor, fertlizer, CO, and H_2	Anaerobic digestion, Composting, Thermochemical technologies	(Awasthi et al., 2021b) (Awasthi et al., 2019; Xu et al., 2020)
Food waste	CH_4, N_2O, NH_3	Composting	(Awasthi et al., 2020c)
Food waste	Biohydrogen, CH_4, Bio-butanol, Biodiesel, and Bio-ethanol	Biorefinery	(Dahiya et al., 2018; Ravindran et al., 2016)
Food waste	CH_4, CO_2, H_2, N_2, NH_3, Syngas, Pyrolysis oil, and Bio-oil	Anaerobic digestion, Composting , Vermicompostin g, Thermal treatments	(Chen et al., 2015; Esparza et al., 2020)
Food waste	Acetic acid, Lactic acid, Propionic acid, Butyric acid, Valeric acid, Ethanol, Propanol, Caproic acid, Heptanoic acid, CO_2, CH_4, and H_2	Two-phase anaerobic digestion (TPAD)	(Feng et al., 2020)
Food waste	Acetic acid, Lactic acid, Propionic acid, Butyric acid, Valeric acid, Ethanol, H_2, and CO_2	anaerobic digestion	(Feng et al., 2020) (Feng et al., 2018; Wainaina et al., 2020a; Yu et al., 2021; Zhou et al., 2018)
Municipal solid waste	Biochar	Pyrolysis	(Ayiania et al., 2019)
Biomass residues and waste	Biohydrogen	Bacterial	(Bakker, 2015)

		fermentation	
Oat husk	Ethanol	Organosolv pretreatment	(Camilleri, 2021; Sar et al., 2022)
Biomass	Biofuels, and Biochemicals	Biorefinery	(Cherubini, 2010)
Corn, Lignin C_5/C_6sugars	Bioethanol, Animal feed, and Fischer-Tropsch diesel	Biorefinery	(Cherubini et al., 2009; Poveda-Giraldo et al., 2021; Sheldon, 2018)
Microalgae	CH_4, Biodiesel, Ethanol and	Biotechnology	(Costa et al., 2011; Deviram et al., 2020)
Synthetic wastewater	VFAs	Co^{2+}/Zn^{2+} synergistically	(Dahiya et al., 2020)
Wheat and paddy straw, Spent mushroom substrate	Bioethanol, Lignocellulolytic Enzymes, Biogas, and Biohydrogen	Composting	(Devi et al., 2022)
Organic solid waste derived from agriculture, industry and urban	Bio-oil, Biachar, Syngas, Biofuels, CH_4, H_2, and Lactic acid	Pyrolysis, Gasification, Acid hydrolysis, Anaerobic digestion, Composting, Microbial, Enzymatic	(Daza Serna et al., 2016; Duan et al., 2020; Lee et al., 2020; Ravindran et al., 2021; Wainaina et al., 2020b; 2019)
Apple orchard waste	Biomethane, Bioethanol, Biofuels, Biofertilizers, Biochar, and Biochemicals	Microbial fermentation, anaerobic digestion,inclneration,gasification,prolysis	(Duan et al., 2021; Qin et al., 2021)
Waste activated sludge rice	Acetic, Propionic, Iso-butyric, N-butyric, Iso-valeric, N-valeric acids, Ethanol, CH_4, and CO_2	Anaerobic co-digestion	(Feng et al., 2009)
Wood materials, Agricultural waste, Other herbaceous biomasses，Other	Enzymes, Ganoderic acid, Xylose, Furfural, Levoglucosenone, Methane, Bioethanol, Rhamnolipids, Bioethanol, Succinic acid,	Selective fractionation with organosolv	(Ferreira et al., 2020)

lignocellulosic substrates	Fat-rich yeast, Fat-rich microalgae, Carboxymethylcellulose, Bio-oil, and Biochar	pretreatment	
Mannitol, Glucose	Butyric acid, Acetic acid, and Lactic acid	Anaerobic co-digestion	(Fu et al., 2020)
Grape waste	Polyphenolic compounds	Enzyme technology	(Gómez-García et al., 2012)
Protease- and glycosidase-less mutant	Ethanol	Fermentation	(Gómez-García et al., 2012)
Nano-additive applications, microalgae	Biofuel	Cultivation and harvesting, Biofuel extraction	(Hayashida et al., 1982)
Blueberry crop residues	Biochar, Bio-oil, Bio-energy, Bio-products, Biofuel, Biogas, and Syngas	Hydrolysis, Anaerobic digestion, Gasification, Pyrolysis, Hydrothermal liquefaction	(Liu et al., 2021c)
Apple pomace	PHAs (polyhydroxyalkanoates)	Hydrolysis,acidogenesis, Transesterification, Anaerobic conversion	(Liu et al., 2021d)
Glucose	Butyric acid, Acetic acid, CO_2, and H_2	Fermentation	(Liu et al., 2006; Zhou et al., 2017)
Glucose, Lactate	Propionate	Co-metabolism	(Martinez-Campos et al., 2002; Qin et al., 2021c)
Microalgae biomass	Microalgae oil	Exergy analysis	(Peralta-Ruiz et al., 2013)
Corn stover	Acetic acid, Lactic acid, Butyric acid, Propionic acid, Valeric acids, Ethanol, CH_4, and CO_2	Aerobic hydrolysis, Anaerobic	(Qu et al., 2021)

		digestion	
Sugarcane bagasse	Lignin, ethanol, and CH_4	Pretreatment, Anaerobic digestion	(Rabelo et al., 2011)
Citrus peel wastes	Essential oil	Mechanical cold press, Thermal extraction with water or steam media, Thermal microwave-assisted extraction, Ultrasound	(Teigiserova et al., 2021)
Melon and watermelon mixture	H_2 and CO_2	Dark fermentation	(Turhal et al., 2018)
Sewage sludge	Biogas, Biodiesel, Bioethanol, and Biobutanol	Biotechnology	(Zabermawi et al., 2022)

Graphical abstract



Organic waste recycling for carbon smart circular bioeconomy and sustainable development: a review

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