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Sustainable food waste management towards circular bioeconomy: Policy review, limitations and opportunities

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Abstract

Research attention is increasingly drawn on constructing a circular bioeconomy and enhancing the value of material flows. Circular bioeconomy aims to achieve sustainable consumption and production with reduction of greenhouse gas emission. This study identifies research gaps on how circular bioeconomy can be achieved through sustainable food waste management by comparing the similarities and differences in concepts of bioeconomy and circular economy, reviewing the benefits and limitations of the existing policies, and evaluating the global situations of food waste and its management on household and commercial basis to promote circular bioeconomy. Future development on food waste management is expected to capitalise on the multi-functionality of products, boundary and allocation in a circular system, and trade-off between food waste and resources. With future technological advances, food waste management in circular bioeconomy policy can facilitate the accomplishment of sustainable development goals.

Keywords: Circular bioeconomy; Food recycling/valorisation; Sustainable waste management; Life cycle assessment; Bio-based chemicals/products.

1. Introduction

Sustainable consumption and production, an emerging concept for achieving sustainable development, arouses more attention for the purpose of efficient and sustainable utilisation of resources, energy, and infrastructure to assure quality life for human beings. It aims to devise overall development plans with reduced costs on economy, environment, and society, enhance economic competitiveness, and diminish poverty. Global consumption of natural resources has been increasing, which had reached 92.1 billion tons in 2017 and a 254% increase from 27 billion in 1970, with the growing rate of annual extraction since 2000 (United Nation, 2019). The bioeconomy is defined as the generation of renewable biological resources and the transformation of these resources into value-added merchandise including food, animal feed, bio-based products, and bioenergy (European Commission, 2012). However, the demand of land is increasing due to the evolving bioeconomy, while some land has to be retained to meet specific needs such as afforestation to sequester carbon. In this regard, sustainable and synergistic use of resources should be encouraged with the development of the bioeconomy rather than adding to resource pressure. The delivery of a circular bioeconomy (CBE) was emphasised in the revision of the European Union's Bioeconomy Strategy, which aimed to achieve United Nation's Sustainable Development Goals (SDGs) and commitments on sustainable consumption and reduction on greenhouse gas emission (Institute for European Environmental Policy, 2018). It is crucial to review the latest studies to understand what policies and measures are required to enhance the success likelihood and acceptance of circular bioeconomy on food waste management.

This study intends to elucidate how circular bioeconomy can be achieved through sustainable food waste management, review the existing food waste management literature, and suggest possible research directions and limitations. This study identifies research gaps on how circular bioeconomy can be achieved through sustainable food waste management. Section 1 provides a brief description on the concepts of bioeconomy and circular economy. Similarities and differences of the two concepts are identified. The existing national bioeconomy and circular economy policies are introduced and discussed concerning their synergies and conflicts. Situations of global food waste and loss are then reviewed to elucidate the need of sustainable food waste management system. Section 2 gives comprehensive literature review on household and commercial food waste management. Section 3 elucidates the linkage of food waste management and circular bioeconomy by explaining the importance of food waste in circular bioeconomy policy, concern for food waste management, and possible research tools. Section 4 proposes the research opportunities on food waste management and circular bioeconomy.

1.1 What is Circular Bioeconomy?

"Circular economy" and "bioeconomy" are concepts at the frontier of latest change. "Circular economy" is defined as conservation of product value, materials and resources in the economy for a long period with the reduced waste generation, according to Circular Economy Action Plan (European Commission, 2015). Raw materials including fossil carbons, minerals, metals, biomass will be produced to products, traded, utilised and then enter the waste hierarchy by sharing, reusing, redistributing and recycling (Carus and Dammer, 2018) (as illustrated in Figure 1). Two sectorial priorities were directly linked to bioeconomy according to the aforementioned Action Plan, which were food waste and efficient biomass conversion (European Commission, 2015). In particular, food waste is a major aspect in the circular economy and should be considered at various levels throughout the value chain. Food products that are excreted and digested end up in organic waste recycling, energy recovery, or landfill disposal. Biodegradable products can undergo organic waste recycling as an end-of life alternative with carbon capture to sequester CO_2 (Carus and Dammer, 2018). The CBE is defined as the overlap of the concepts of circular economy and bioeconomy, which aims at improving resource- and eco-efficiency, lowering greenhouse gases (GHGs) footprint, reducing demand in fossil carbon, and valorising waste streams.

Similarities and differences between “circular economy” and “bioeconomy” are identified. The two terms are similar as they share some of the same targets. Circular economy aims to enhance the efficiency of resource utilisation and recovery of waste materials to decrease the emission of additional fossil carbon during manufacturing and extraction processes. The concept of bioeconomy shares similar targets but focuses on different approaches that replace fossil carbon by renewable biomass from agriculture, forestry, and marine environment. Elements of bioeconomy go beyond the objectives of circular economy, which include areas in product or service functionality. Bioeconomy can be greatly profited from increased circularity by integrating the huge volumes of organic processes and waste from agriculture, forestry, fishery, food and animal feed, and organic processing waste in the circular economy. Bioeconomy and other industrial sectors require novel knowledge-based procedures including biotechnology, algae for food, new applications, and new connections, which can contribute to each other in different areas. Biomass waste generated from agriculture, forestry, fishery, aquaculture, food and animal feed, and organic processes can be utilised for various applications such as aquaculture feed and chemical production. Moreover, biodegradable products can re-enter into the organic and nutrient cycles. The recyclability of other materials can be enhanced by adding innovative additives from oleo-chemicals, which can be derived from vegetable and animal oils and fats from petrochemical feedstocks through physico-chemical transformation. It is also economically viable and competitive to collect and recycle bioplastics if the critical volume of new, bio-based polymers can be achieved. Furthermore, different industrial sectors such as food industries and chemical industry should be connected (Carus and Dammer, 2018). To better explore the opportunities of adopting circular bioeconomy in sustainable food waste management, understanding current situations of food waste around the world is a necessary foundation.

1.2 Global food waste and loss

To date, an estimated 1.3 billion tonnes of global food waste is disposed of in landfills annually (Hao et al., 2015). Around the globe, over 30% of food is lost or wasted, which is equivalent to 1.32 billion tonnes of food generated for individual consumption (Gustavsson et al., 2011), costing the global economy over USD 900 billion. Food waste in landfill goes through a series of bioconversions into biogas, which is an inflammable mixture of methane and carbon dioxide and trace amount of hydrogen. Biogas can be captured in modern engineered landfill sites and utilised for district heating or electricity generation. However, generation and combustion of biogas leads to increased GHG emissions since methane is a much more potent GHG than carbon dioxide (USEPA, 2017). In 2007, over 3 Giga tonnes of carbon dioxide were released by food wastage that includes agricultural production, post-harvest handling and storage, processing, distribution, and consumption (FAO, 2013). Global annual generation of food loss and waste amounts to 4.4 Giga tonnes equivalent of carbon dioxide, which is about 8% of total anthropogenic GHG emissions and only slightly less than that of global road transportation (Sims et al., 2014).

Food waste generation has been found to be somewhat related to income in some industrialized countries (Lyndhurst, 2007; Secondi et al., 2015). Globally, food loss and waste constitute approximately over 20% of supplied food for individual consumption

(Kummu et al., 2012). “Food loss” is defined as losses in the course of preparation and post-harvest processing, while “food waste” refers to wastage during distribution and consumption stages (Gustavsson et al., 2011; Kummu et al., 2012; van der Werf and Gilliland, 2017). It is observed that food loss in developing countries was much higher at the immediate post-harvest stages than other stages. Post-consumer food waste was the highest overall loss in affluent economies (Parfitt et al., 2010), which are influenced by factors such as aesthetics and arbitrary sell-by dates. In countries with higher gross domestic product (GDP) per capita nominal such as Switzerland (USD$82,839) and Singapore (USD$64,582) (World Bank, 2019), food distribution and consumption accounted for the highest wastage in household food waste. In the United Kingdom, the estimated amount of annual household food waste amounted to 25% by weight. In particular, bread was the greatest contributor to food waste, of which 32% of all bread procured was disposed. In contrast, countries with lower GDP per capita nominal, such as the Central African Republic (USD$510) (World Bank, 2019), had the highest food loss in the agricultural and post-harvest stages (Parfitt et al., 2010; Kummu et al., 2012). With the huge amount of food loss, a substantial amount of variations occurred in different stages of the supply chain at which losses take place. Characteristics of some specific countries such as culture, climate, category of harvest each jurisdiction generates, market access and legislation could affect wastage composition (Parfitt et al., 2010).

Food waste can be categorised into avoidable food waste (edible) and unavoidable food waste (non-edible). The generation of avoidable food waste can be reduced by performing precautionary measures at each stage from cradle to grave. The reduction of unavoidable food waste can only be achieved with proper waste management and recycling strategies (Dahiya et al., 2018). Food waste mainly consists of organic fractions, carbohydrates, proteins, lipids and inorganic components. Simpler organic compounds such as glucose, amino acids, and fatty acids can be produced (Lin et al., 2013). Food waste can be converted into bio-commodity chemicals and bio-energy by applying various chemical and biological processes (Kiran et al., 2014; Dahiya et al., 2015; Xiong et al., 2019). Plenty of scientific research studies on food waste valorization are emerging, which prove the technological feasibility of converting food waste into a diverse range of value-added chemicals and bio-fuels. For example, hydroxymethylfurfural (HMF), which is one of the top building blocks and important precursors for the manufacturing of various derivatives, can be synthesized via catalytic thermal conversion from starchy, cellulosic and sugary food waste (Yu et al., 2017a; Yu et al., 2017b; Yu et al., 2019). Production of other chemicals with high commercial values such as glucose (Yu et al., 2016) and levulinic acid (Chen et al., 2017) are also proved viable through valorization of source-separated food waste. Reaction kinetics and operating conditions would act as significant research prospects for technological advances (Yu et al., 2017c).

In addition, researchers are highly interested in producing biogas with food waste as a substrate in anaerobic digestion (Sen et al., 2016). Recent research studies on food waste valorisation generate products such as liquid biofuels, commodity chemicals, biohydrogen, and bioelectricity (Lee et al., 2014; Pasupuleti et al., 2014; Karmee, 2016; Sarkar and Venkata Mohan, 2017). Electroactive bacteria can also be generated by food waste with an abundant source of electrons, which can generate bioelectricity from waste treatment (ElMekawy et al., 2014). In order to enhance production of biogas and biochemicals from the hydrolysis of food waste, different pretreatment approaches including physical, chemical, physio-chemical and enzymatic approaches can be adopted (Kondusamy and Kalamdhad, 2014), and integrated into the food waste collection and recycling systems. In order to actualise the benefits in implementing circular bioeconomy, the synergies and conflicts of the existing national policies should be evaluated and discussed.

1.3 Synergies and conflicts of existing national bioeconomy and circular economy policies

Several countries were selected as representative examples to discuss the synergies and conflicts of their existing bioeconomy and circular economy policies. The European Union implements the Renewable Energy Directive (European Commission, 2017a), Bioeconomy Strategy (European Commission, 2012), and the EU Action Plan for the Circular Economy (European Commission, 2015b). Both the action plans for circular economy and bioeconomy are consistent in encouraging the cascading use of biomass, which consider material utilisation of biomass over energy. However, a systematic restriction on the direct use of biomass for energy purposes was not performed in the Renewable Energy Directives (Philp and Winickoff, 2018). In Denmark, the National Bioeconomy Panel and Waste Prevention Strategy (The Danish Government, 2015) have been implemented. Denmark sets an ambitious target to recycle half of the household waste by 2022, as a frontier in circular economy and industrial symbiosis since 1972 (Philp and Winickoff, 2018). Novel utilisation of waste such as sludge and municipal solid waste for energy recovery may be hindered by the current legislation. Finland intends to strongly encourage the joint deployment of the National Bioeconomy Strategy and the Strategic Program (European Commission, 2017b) for circular economy by improving cascading use of wooden materials for resources and energy uses. China has an ambitious target to address the challenges of waste management and resource optimisation through the implementation of Plan for Development of Bioindustry and the Circular Economy Promotion Law (World Economic Forum, 2014).

Another concern is the decarbonisation of the economy, where fossil material and energy sources are replaced by biomass resources. Brazil has implemented the Innovation Law in 2005 and has a long history in bioeconomy with its pioneering Proalcool program. Regional and private initiatives aiming at resource optimisation and reverse logistics have been put forward, such as the 2010 Solid Waste National Policy. However, there is no federal policy to define a strategy for the circular economy. In Spain, the Spanish Strategy on Bioeconomy considers bioeconomy as a tool for the Circular Economy, especially for the use of biological wastes and residues. Meanwhile, Circular Economy Strategy includes a proposed measure of bioeconomy yearly action plan (Philp and Winickoff, 2018). However, researchers hold reservation and uncertainties whether these policies can deliver their objectives. Apart from understanding the global situation of food waste and the potential technological advancement of food waste conversion, the existing literature on household and commercial food waste management are further reviewed and discussed to identify the opportunities in fostering circular bioeconomy.

2. Behavioural studies of household and commercial food waste management

Household food waste in the European Union accounts for over 50% of the food wasted along the value chain (Stenmarck et al., 2016). Researchers from a range of disciplines addressed their concerns on food waste and adopted both quantitative and qualitative methods. Since there is a discrepancy on what individuals claim they would do and what they actually did, a more accurate method such as food waste diaries should be adopted to evaluate individual's food waste practices rather than self-reporting surveys. Quested et al. (2013) reported that over 40% of individuals under-reported the amount of food waste (Table 1).

In Europe, some research studies were conducted to quantitatively investigate the amounts of household food wasted in different countries such as Switzerland, Norway, and Finland (Beretta et al., 2013; Katajajuuri et al, 2013; Hebrok and Boks, 2017). Previous studies acknowledged that the largest amount of food wasted were fresh fruits and vegetables, bread and other bakery goods, and leftovers (Stenmarck et al., 2016; Kliaugaitė and Kruopienė, 2018). Also, there was higher possibility to dispose of food with shorter shelf lives such as dairy products and meat (Sonesson et al., 2005), which accounted for over 65% of total food waste in Norway households (Hanssen and Schakenda, 2014; Stensgård and Hanssen, 2016). The volume, availability, accessibility, affordability, and caloric density of food resulted in an increase in over-consumption and wastage in the developed countries, such as the United States (Rozin, 2005; Blair and Sobal, 2006). Food waste generation is influenced by collective forces including cultural, personal, and geographic that affect behaviour in particular practices (Pearson et al., 2013; Thyberg and Tonjes, 2016). It may also differ from individual to individual, and from society to society. Different perceptions in attitudes on food and food waste have been investigated both within and across countries (Stuart, 2009). Perceptions on the disposal behaviour could be influenced by culture and personal choice, which could vary over time as well. Increased food wastage could also be correlated to particular socio-demographic characteristics (Table 1).

The wastage patterns varying with demographics change can be better understood by comprehending demographic patterns such as aging, population, and income level within or across nations. Age was proven to influence food waste generation, while elderly wasted less than young people (Cox and Downing, 2007; Quested and Johnson, 2009; Porpino et al., 2015). Food waste generation reduced significantly as age increased in Australia. In particular, about 40% respondents aged 18 to 24 year olds wasted more than USD$20 compared to 7% of people aged 70 or above on fresh food over two weeks (Hamilton et al., 2005). In the United Kingdom, individuals aged average over 60 wasted substantially less food than the other age group of the population as they felt that it was incorrect to waste food, which may due to the reason that these elderly experienced economic austerity and food rationing in the World War II (Quested et al., 2013). Food waste generation could also be greatly affected by family composition and household size. Previous studies discovered that households without children wasted less than those with children (Hamilton et al., 2005; Parizeau et al., 2015; Mallinson et al., 2016). Smaller households, especially those where individuals live alone, waste more per capita than larger households (Williams et al., 2012; WasteMinz, 2015; Elimelech et al., 2018). Food wastage also depends on income levels (Pearson et al., 2013). Low-income families were found to generate less food waste than high-income families (Cox and Downing, 2007; WasteMinz, 2014), and food waste generation was positively correlated to household income (Baker et al., 2009). Apart from identifying the impact of demographic factors on food waste generation, researchers further argued that investigations should be theory-driven to discover the determinants of potentially modifiable behaviour.

Theories can provide a framework to identify causal relationships for drawing up and implementing constructive and replicable policies (Michie and Abraham, 2004; Steg and Vlek, 2009). Theory of planned behaviour (TPB) is currently one of the most popular and well-established social-psychological models to understand and predict human behaviour. It is extended from the earlier theory of reasoned action (TRA) as suggested by Ajzen and Fishbein (1980). TRA hypothesizes two factors that influence intentions, i.e., attitude and subjective norm. “Attitude” is defined as an individual’s favourable or unfavourable evaluation leading to a behaviour, while “subjective norm” refers to the perception of social pressure leading to a behaviour. TPB extends the original TRA with the third factor that is perceived behavioural control, which measures an individual's perception of the ease or difficulty in having a certain behaviour (Ajzen, 1991). In general, the more favourable the attitude and subjective norm with respect to engaging in the behaviour, and the greater the perceived behavioural control, the more likely an individual would come up with an intention, which may turn into a behaviour. It helps to conceptualize the relationship between attitudes and behaviour even when behaviour is self-reported, according to the TPB principle. The TPB accounted for more than 11% of the variability in behaviour, whether the behaviour is objective or observed (Armitage and Conner, 2001; Ghani et al., 2013; Yu et al., 2018). It was also proved that additional role of concepts can be easily and flexibly adopted upon the scope of the original model (Collins and Mullan, 2011; McDermott et al., 2015; Mak et al, 2018) (Table 1).

In the context of household food waste, the role of food-related practices and the core cognitive constructs specified by the TPB are explored. In particular, researchers investigated the impacts of attitude, subjective norm, and perceived behavioural control on individual's intention to reduce household food waste. Results revealed that only attitude as a significant factor to predict intention not to waste food, which comprised two constructs, i.e., moral attitude and lack of concern. Evidence showed that neither subjective norm nor perceived behavioural control drove intention. In addition, cross-sectional food waste behaviour was not significantly related to intention of food waste reduction (Stefan et al., 2013; Russell et al., 2017). The key predictors of food waste behaviour in households were mainly associated with attitude, followed by moral norms and perceived behavioural control (Ghani et al., 2013; Visschers et al., 2016; Russell et al., 2017), while an indirect impact was caused by reuse/recycling habits (Stancu et al., 2016). Researchers also applied TPB model to identify the culture, participation dimensions, and reputational concerns that played important roles in influencing recycling behaviour and shaping pro-environmental behaviours (Crociata et al., 2015). Previous literature explored the relationship between culture and waste recycling with data collected from the Italian Multipurpose Survey on Household Daily Life Aspects over 19,000 Italian households for a sum of about 48,000 individuals (Alpízar and Gsottbauer, 2015). Economic incentives, legislation, and public education are commonly implemented in pilot recycling projects to motivate citizens. However, it is challenging to specify and quantify the actual effectiveness of these factors through direct observation, while previous studies suggested a volatile relationship between these factors and individual behaviour (Valle et al., 2004; Hu et al., 2019) (Table 1).

Industrialisation, urbanisation, and globalisation lead to modernisation in food supply chains and affect commercial food waste generation. Industrialisation refers to a transformation from food production and preparation in households to commercial operations and factories. In developed countries, there was an increased occurrence of dining at restaurants and consumption of takeout food (Sobal, 1999). Food preparation and consumption was increasingly performed in restaurants, factories, or supermarkets, which demonstrated a shift in the types and quantities of food waste produced in different sectors (Thyberg and Tonjes, 2016). Population transit from rural to urban areas led to an expansion of food supply systems to supply urban population, which resulted in diet diversification and a disconnection from food sources that eventually increased food waste (Parfitt et al., 2010; Pellegrini et al., 2019). Globalisation refers to a transition from local to global food sources and a change in dietary patterns towards the global trend (Thyberg and Tonjes, 2016). Consequently, a higher consumption of less locally produced plant foods and more imported and processed foods was observed (Pingali and Khwaja, 2004) (Table 1).

At the retail and institutional levels, amounts of available food and visual standards of food cause food wastage. Buzby and Hyman (2012) provided some reasons such as damaged packaging, damaged or inadequately prepared items, and overstocking or over-preparation of food. In particular, rigorous quality standards concerning weight, shape, and appearance in supermarkets cause retailers to waste foods (Gustavsson et al., 2011; Alexander et al., 2017). Overstocking is another concern as retailers prefer stocking up item, while restaurants prefer having a wide range of available menu alternatives (Stuart, 2009). Also, food wastage can result from imprecise prediction of food needs in restaurants and hotels (Mena et al., 2011; Busetti, 2019). The quantity of food wastage varied in different commodities. Buzby et al. (2015) revealed that the percentage of unsold fresh food ranged from 2.2% to 62.9% in U.S. supermarkets, while that of fruits ranged from 4.1% to 43.1%. This may be attributed to differences in packaging, high susceptibility to damage, and a lack of public awareness on food knowledge (Table 1).

Apart from investigating recycling behaviour in households, the theories such as TPB have also been applied in the commercial sectors to understand food waste recycling. An extended TPB was applied to investigate food waste recycling in the commercial sector in Hong Kong (Mak et al., 2018) (Figure 2). Researchers identified, prioritized, and quantified the relationships between key determinants that would affect the food waste recycling behaviour of hotel, food and beverages, and property management industries. Integrated qualitative content analysis and quantitative structural equation modelling were conducted to demonstrate that commercial food waste recycling behaviour was influenced by three predictors, which were administrative incentives and corporate support, logistics and management incentives, and economic incentives. Predictors explained over 60% of the variance of recycling intention, which demonstrated substantial strength of the model. Indicative positive correlations among moral attitudes, logistics, and management incentives were observed. In particular, hotel and food and beverages industries were of the greatest concern to administrative incentives and corporate support, whereas property management representatives paid greater attention to logistics and management incentives to facilitate recycling activities (Mak et al., 2018). A recent investigation also found that insufficient resources could lead to difficulties in handling food waste and changing recycling behaviour in restaurants (Sakaguchi et al., 2018) (Table 1). Apart from identifying the major determinants in both household and commercial food waste recycling behaviour, the significance of food waste in circular bioeconomy policy should then be addressed.

3. Food waste management and circular bioeconomy

3.1 Importance of food waste in circular bioeconomy policy

The Federal Ministry of Education and Research (2010) formulated The National Research Strategy BioEconomy 2030 (NFSB 2030). Five elements were established in the strategy, including global food security, sustainable agricultural production, healthy and safe foods, the industrial application of renewable resources, and the increasing use of biomass-based energy (Schütte, 2018).

The increasing requirement on energy and materials is encouraging a transition from fossil-based linear economy to sustainable circular bioeconomy. Diverse bio-based products can be produced from renewable feedstocks, which require multidisciplinary study in science, management, and engineering (Amulya et al., 2015; Xiong et al., 2019). To date, biomass waste is recognized as a promising feedstock in establishing a bioeconomy (Mohan et al., 2017), where generated food waste can be considered as a potential source. Three strategies including elimination, reduction, and reuse can be adopted to control the amount of avoidable food waste to certain extent. Biorefinery can fully utilise the amount of avoidable and unavoidable food waste by adopting different biological and thermochemical processes such as acidogenesis, fermentation, methanogenesis, photosynthesis, bio-electrogenesis (Lin et al., 2013; Dahiya et al., 2015; Yu and Tsang, 2017; Xiong et al., 2019). Such processes can obtain beneficial products by deploying strategic waste valorisation. Products such as biofuels, platform chemicals, bioelectricity, biomaterials, and biofertilizers provide added values with higher efficiency in waste treatment (Dahiya et al., 2018; Xiong et al., 2019). Integration of these conversion processes leads to organic-rich effluents, which provides an extra benefit in product recovery and overcomes the restrictions of individual stage.

The development of a sustainable waste-based bioeconomy can be achieved by employing biorefinery for the production of bio-based products (O'Callaghan, 2016; Mohan et al., 2016a; Mohan et al., 2016b; Chen et al., 2017). Biorefinery of food waste can substitute fossil-based refinery and the major determinants for the manufacture of bio-based products include climate, resource security, and ecosystem services (Amulya et al., 2015). Biorefinery of food waste can promote sustainable approaches with the least environmental consequences in the long run. The market is developing rapidly on circular bioeconomy and shaping towards integrated vision. For example, an Italian plant has been newly built in August 2019 to promote the most innovative biorefinery in Europe with annual processing capacity of up to 750,000 tonnes for treating substantial quantities of used vegetable oil, animal fat, algae and by-products to produce high-quality biofuels (CSIR-IITR, 2019).

3.2 Concerns of food waste management in achieving circular bioeconomy policy

Secondary feedstocks such as food waste are utilised for biomass valorisation and production of value-added chemical products (Lin et al., 2013; Pfaltzgraff et al., 2013; Xiong et al., 2019). These secondary feedstocks would not compete with food production, which was controversial and debatable in the aspect of bioeconomy (Scarlat et al., 2015). Nevertheless, the development of producing energy and biomaterials from food waste is still at an early stage, therefore, uncertainty should be reduced and investment should be encouraged by enhancing transparency (Kretschmer et al., 2013). Lower environmental impact of bioenergy and biomaterials can be secured by providing accurate information on the food waste availability. Also, it should be comparable between the use of bio-based products and fossil-based alternatives. Life cycle assessment (LCA), life cycle costing (LCC), and social life assessment (s-LCA) should be conducted to assess sustainability by taking into consideration of its economic and social aspects (Imbert, 2017; Lam et al., 2018a). The life cycle approaches emphasize the advantages of bio-based products to policy makers and the society, as the transformation to more sustainable circular models will not succeed without a robust public consensus.

Kretschmer et al. (2013) conducted a SWOT analysis on the most relevant challenges and benefits related to the development. Strengths of the development include the improvement of sustainability of agriculture and food production with a higher chance to convert waste streams into valuable products, increase in green jobs and economic activities, enhanced development of conversion technologies, production of bio-based chemicals and bio-energy, and identification of strong development potential of bio-based plastics. There are some opportunities that come along with the development of green sector. Jobs creation and economic growth of the sector would attract further investments. Decision making of industries can be stimulated as the Bioeconomy Communication, which is a bioeconomy strategy implemented by the European Commission (2018) as a high-level policy initiative. Although the development benefits the society and industries, there are some potential weaknesses and threats that concern the public. High costs, financial constraints, and current lack of demand-pull effect lead to a slowdown of commercial demonstration of technologies. The availability of sufficient biomass as feedstock is limited by logistic, technical, economic, and seasonal factors. Policies would be implemented to reduce wastage along food supply chains. The lack of sustainability guidelines for bio-based materials and biofuels would diminish the trust in the sector. Market penetration may be complicated as there is a void of technical standards for bio-based products. There is also insufficient public awareness in bio-based products. Lastly, profitability of bio-based products is greatly affected by the fluctuating oil price, rendering its development beyond the sector's control.

Overall, the implementation on a commercial scale of biorefining from food waste counts on the following five factors (Lin et al., 2011; Kretschmer et al., 2013). Firstly, the quality and volume of food waste are substantially variable, depending on an efficient food waste collection system to improve the homogeneity of food waste as feedstock. Secondly, sources of food waste entail a wide range from distributors to hospitals, which lead to low coordination. Thirdly, as food waste decomposes quickly, there are limitations on the infrastructure for timely transfer and temporary storage. Fourthly, the demand of bio-based products is highly dependent on policy implementation, which requires strong legislative support and substantial society's interest. When compared to conventional products, public awareness is a concern for increased demand of bio-based products as they are more costly (de Besi and McCormick, 2015). Lastly, there are limitations on the economic feasibility of scaled-up plants and technologies.

3.3 LCA, LCC, and s-LCA towards circular bioeconomy

LCA is an international standardized method to evaluate the environmental impacts of a product, process, or activity throughout its life cycle (ISO 14040, 2006; ISO 14044, 2006). LCC is a cost management approach that concerns the development of a product during its product life cycle, which is from the cradle to grave (Verein Deutscher Ingenieure, 2005). SLCA is the least developed method, which examines the social and sociological aspects of products as well as the actual and potential positive and negative impacts throughout the life cycle (Finkbeiner et al., 2010). LCA has been adopted to evaluate different management systems of solid waste and food waste (Laurent et al., 2014; Lam et al., 2018b). Research studies have emphasised the application of LCA to the traditional waste hierarchy, of which the purpose was to manage waste towards methods that integrate waste prevention (Nessi et al., 2013; Bernstad and Andersson, 2015). Research attention also focused on circular economy concepts of producing or conserving the value of material flows (Ruggieri et al., 2009; Mak et al., 2019). When considering food waste utilisation, the following areas should be addressed. Firstly, one should address the multi-functionality of products, e.g., nutrient recovery, carbon sequestration, and microbial biomass substrate that promote biodiversity (Martínez-Blanco et al., 2009; Ruggieri et al., 2009). Secondly, one should consider the system boundary and allocation by dividing the different life cycle stages in a circular system (Nicholson et al., 2009). Lastly, stakeholders' perspectives on the waste definition should be well addressed (Cheyne, 2002).

Salomone et al. (2016) conducted a LCA study on food waste by generating livestock feed and biodiesel. Traditional production of protein and lipids was compared with alternative origins of raw materials. Results demonstrated that the greatest benefit of the production of proteins and lipids was the reduction on land use, while energy consumption was demonstrated as the major burden. Many uncertainties would influence the projection of Global Warming Potential. The substitution of synthetic nitrogen fertilizers had substantial environmental benefits, even though the literature mainly focused on the high economic advantages and larvae production than the residue of the bioconversion process. In another study, Fiala et al. (2016) investigated the environmental performance of rice cultivation fertilised with sewage sludge from urban sources with LCA. Among various mitigation strategies, the most effective one was the replacement of sewage sludge by compost in urban areas and the introduction of extra aeration time for cultivation. It was suggested that country specific emission factors should be established, while standard emission factors should not be adopted for methane estimation to enhance the accuracy of assessment.

LCC has only been recently adopted to examine economic costs of food waste management. Nevertheless, it is a long-term research in quantifying the cost of products and services over the life span or life cycle perspective. Unlike LCA (ISO, 2006), LCC was regulated for particular categories, such as petroleum and natural gas (ISO, 2008). Three main approaches of LCC were proposed by Hunkeler et al. (2008), which are conventional (c-LCC), environmental (e-LCC), and societal Life Cycle Costing (s-LCC), respectively. The majority of the c-LCC studies have the perspective of a single stakeholder, either from the producer or consumer. c-LCC examines the decisions that require high initial capital over products or investments (Dhillon, 2010). A specific working group has established e-LCC that targets at the combination of cost examination in LCA (Heijungs et al., 2013). It aims to investigate costs along the life cycle of products, services, and technologies (Hunkeler et al., 2008). As specified by the International Organization for Standardization, e-LCC should contain the same product system, functional unit, and system boundaries as LCA (ISO 14040, 14044). e-LCC considers multiple stakeholders and externalities that might be possibly internalized

(Hunkeler et al., 2008; Swarr et al., 2011). s-LCC further extends the limits of the analysis by examining the direct and indirect costs incurred in the community at a broader perspective (Petti et al., 2016; De Menna et al., 2018).

There is still insufficient research on food waste LCC investigating how various geographical locations, food waste management systems, and methodological contexts influence the results. For instance, LCC approach was adopted to investigate the financial status of selected food waste management systems in Australia, which evaluated at the state level and did not consider externality costs (Schacher et al., 2007). Parameters in the sorting, collection, and pre-treatment procedures in food waste management systems are region-specific, which impose restrictions on the analysis of general financial status. A recent study conducted LCC case study analysis that considered local variables, compared different food waste management systems, and examined externality costs in the United States (Martinez-Sanchez et al., 2017). Nevertheless, the applicability of this study was restricted as a United States-specified model developed by Levis et al. (2014). Furthermore, this study only considered externality costs on air emission while anaerobic co-digestion of food waste and sewage sludge as alternative management systems were excluded. Burn et al. (2014) highlighted LCC of anaerobic co-digestion of food waste with sewage sludge both within the waste system and as a standalone treatment. A latest study therefore developed a LCC model to test on two case studies and compared seven food waste management systems in Australia, suggesting food waste anaerobic digestion or co-digestion could be implemented with marginal increase in overall cost (Edwards et al., 2018). Meanwhile, composting systems had lower costs per household than business-as-usual, although their environmental impacts were more significant than digestion systems.

To date, researchers also focus on the assessment of the s-LCA as a platform to quantify social impacts. Previous studies specifically handled the assessment of methodological and application issues as a novel research aspect (Parent et al., 2010; Reitinger et al., 2011). Thus far, there were only a few s-LCA studies on waste management systems, which mainly focused on recyclable material collection systems (Teerioja et al., 2012; Ferrao et al., 2013; Aparcana and Salhofer, 2013; Umair et al., 2015). For instance, a s-LCA of packaging waste management systems in Portugal was conducted on the number of job employments created as a social issue (Ferrao et al., 2013). Social consequences of formal and informal collection systems were compared comprehensively to suggest a formalized collection system (Aparcana and Salhofer, 2013). In Finland, the social life cycle costs of a stationary pneumatic waste collection system were compared with a vehicle-operated door-to-door collection system, which only considered the costs of maintenance and operation of the entire system (Teerioja et al., 2012). Other examples of s-LCA includes studies on wood-based products. In Germany, Siebert et al. (2018) suggested a context-specific s-LCA framework to investigate wood-based products in a bioeconomy region. Potential social implications of foreground activities related to a wood-based production system were articulated, where societal impacts outside the system boundary but not with the same level of detail were considered. The establishment of particular social indices and corresponding indicators was relevant to examine wood-based production activities.

4. Opportunities and prospects

A bio-based economy plays a critical role in tackling multiple critical global obstacles, including climate change, escalating population, limited natural resources, and growing demand for food and materials. For instance, by implementing a bio-based economy and sustainable production of chemicals, materials, and fuels from biomass, Europe has relieved the negative impacts on the environment and reduced the dependency on fossil resources (GEF, 2012). It is a critical issue to ensure sustainability for a bio-based economy. Globally, certification schemes with different scopes and purposes including fair-trade and organic agriculture were developed for different products in various sectors. A number of certification systems were adopted for the agricultural sector including IFOAM and FAIRTRADE, which aimed to guarantee environmentally friendly and sustainable agricultural production with respect to the sustainability criteria. Sustainable biomass production and GHG emissions should be considered in the sustainability criteria for bio-based products, bioenergy, and biofuels that are similar to avoid leakage (EC, 2012). The Roundtable on Sustainable Biomaterials (RSB) extended its scope to include biomaterials and bioenergy including liquid biofuels, biomass, and biogas for energy production and bio-based products and chemicals (RSB, 2014). Scientific breakthrough on more cost-effective technologies are urgently needed, which can further integrate with policy development. Future research should help to suggest suitable sustainability criteria for different products and evaluate bioeconomy strategies in different jurisdictions and regions. The evolution of circular bioeconomy and its reciprocal impacts should be analysed over time (Garud and Gehman, 2012), understanding the synergies and limits for achieving circular bioeconomy.

In devising future policy options, it is essential to consider the need for consequential modelling platform for LCA, LCC, and s-LCA. While some guidelines were available on attributional approaches, LCA was less systematised (Unger et al., 2016). It is even more critical in LCC when considering its conventional microeconomic nature that put emphasis on costs than on long-term economic benefits. Since both e-LCC and s-LCC are performed with LCA, consequential approaches should be more applicable to include various supply chain phases and cost bearers as well as potential external factors on other systems. Therefore, further studies should be conducted to establish a combined LCA-LCC analytical framework (e.g., Lam et al, 2018a), which should include guidelines on the expansion of food waste management system, criteria of economic outcomes and external factors, and a rational method to multifunctionality and product replacement. A high degree of variability and inconsistency in food waste studies often results from a lack of coherent approaches. Such incomparability obstructs the systematisation of case studies and cross-study result analysis. There are attributional or consequential scopes of food waste studies. It is suggested to recognise a series of evaluation typologies and focus on the variations between scenarios such as prevention, valorisation, and management. Cut-off levels should also be considered in a coherent analytical framework, which should be based on alternatives and cost modelling. Guidelines on the uniformity of cost typologies, assessment objectives, and evaluation criteria are also recommended.

5. Conclusions

Bioeconomy creates opportunities to expand bio-based industries, provides financial support for bio-based products/chemicals, and utilises resources in a more effective and environmentally friendly way. Research attention is increasingly drawn on constructing a circular bioeconomy and enhancing the value of material flows. The life cycle approaches such as LCA, LCC, and s-LCA offer information to raise the awareness of policymakers and the public for the transition towards sustainable circular bioeconomy. Future development on food waste management is expected to explore the multi-functionality of products, boundary and allocation in a circular system, and trade-off between food waste and resources.

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List of Figures

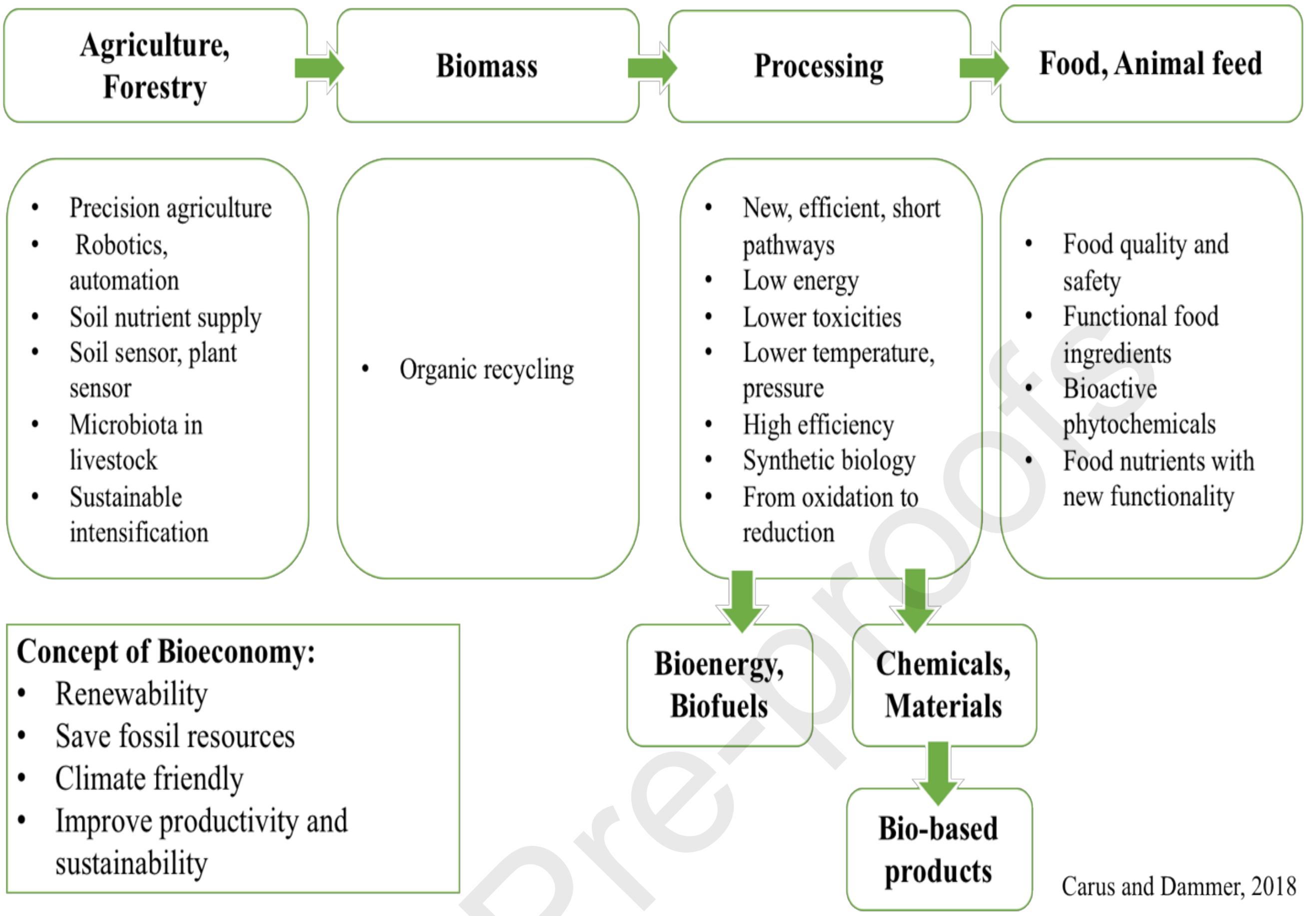


Figure 1. Concept of bioeconomy (Carus and Dammer, 2018).

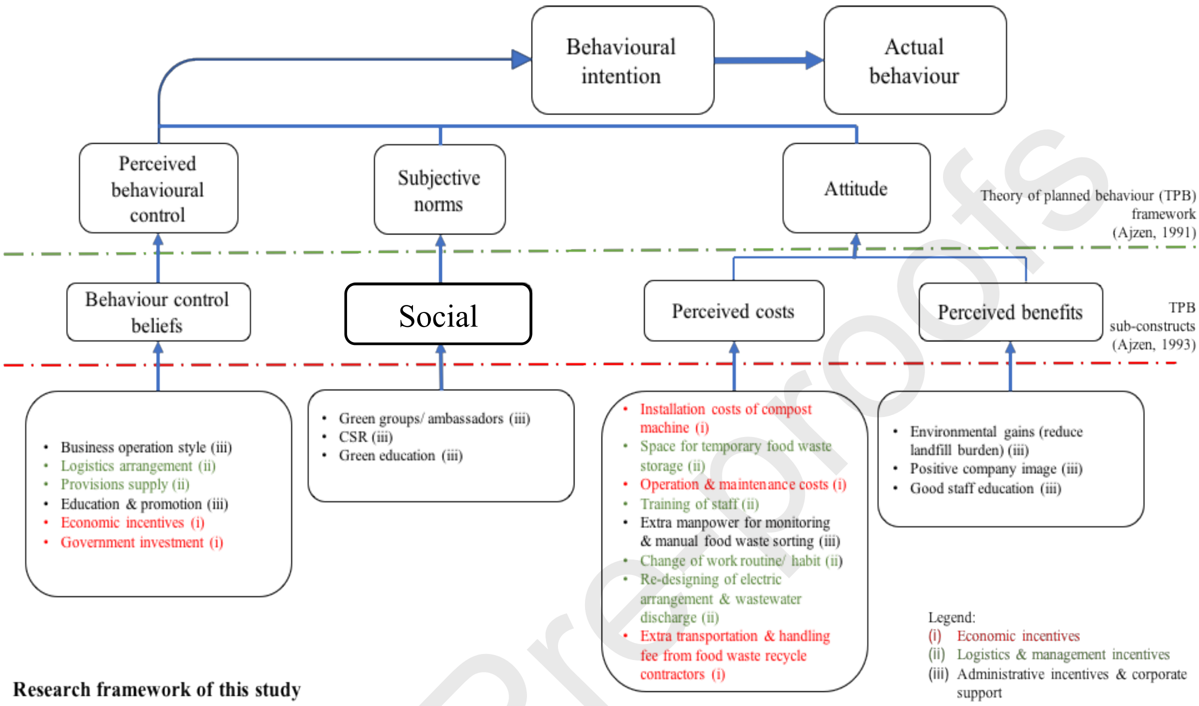


Figure 2. Extended theory of planned behavior for food waste recycling in commercial and industrial sector (Mak et al., 2018).

List of Table

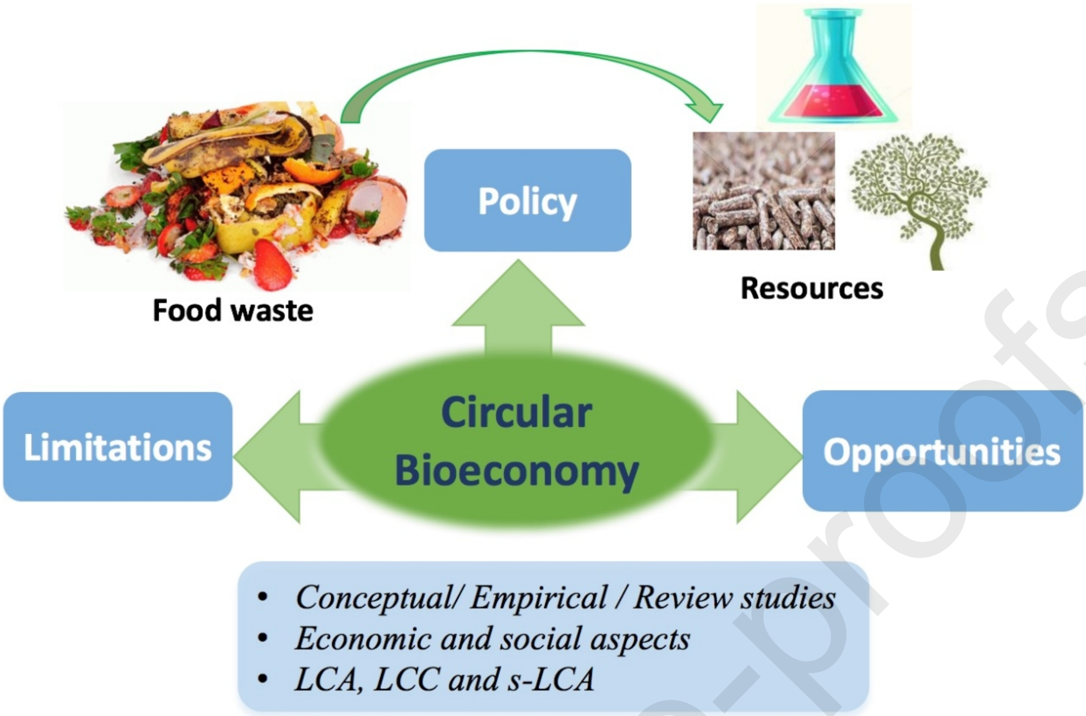
Table 1. Summary of food waste management studies

Year	Source	Geographical scope of analysis	Type of study (Conceptual/ Empirical / Review)	Type of food waste (Household/ Commercial & Industrial/ Not-specified)	Focus of Analysis 1 = Quantification & characterization of food waste and its impacts 2 =Causal relationship and drivers of food waste behaviour 3 = Managerial approaches to mitigation
2001	Armitage and Conner	-	Conceptual	Not-specified	2
2004	Michie and Abraham	-	Review	Not-specified	2
	Valle et al.	Portugal	Empirical	Household	2,3
	Pingali and Khwaja	India	Empirical	Not-specified	3
2005	Rozin	France	Conceptual	Household	2
	Hamilton et al.	Australia	Empirical	Not-specified	1,2,3
2006	Blair and Sobal	United States	Empirical	Household	1,2
2007	Cox and Downing	United Kingdom	Empirical	Household	1
2009	Stuart	Europe, United States	Empirical	Commercial & Industrial	1,3
	Quested and Johnson	United Kingdom	Empirical	Household	1

	Baker et al.	Australia	Empirical	Household	1,3
	Steg and Vlek	-	Conceptual	Household	2
2010	Parfitt et al.	United Kingdom	Conceptual	Household	1
2011	Collins and Mullan	Australia	Empirical	Household	2
	Gustavsson et al.	-	Conceptual	Not-specified	1,3
	Mena et al.	United Kingdom and Spain	Empirical	Commercial & Industrial	2
2012	Williams et al.	Sweden	Empirical	Household	2
	Buzby and Hyman	United States	Empirical	Commercial & Industrial	1
2013	Quested et al.	United Kingdom	Empirical	Household	1,3
	Beretta et al.	Switzerland	Empirical	Commercial & Industrial	1
	Katajajuuri et al	Finland	Empirical	Household and Commercial & Industrial	1
	Pearson et al.	Australia	Empirical	Household	2
	Ghani et al.	Malaysia	Empirical	Not-specified	2
	Stefan et al.	Romania	Empirical	Commercial & Industrial	2
2014	Hanssen and Schakenda	Norway	Empirical	Household	1
2015	Sonesson et al	Sweden	Empirical	Household	2

	Porpino et al.	Brazil	Empirical	Household	1
	Parizeau et al.	Canada	Empirical	Household	2
	Waste Minz	New Zealand	Empirical	Not-specified	1
	McDermott et al.	-	Review	Not-specified	2
	Crociata et al.	Italy	Empirical	Household	2
	Alpízar and Gsottbauer	Costa Rica	Empirical	Household	2,3
	Buzby et al.	United States	Empirical	Commercial & Industrial	1
2016	Stenmarck et al.	Europe	Empirical	Household and Commercial & Industrial	1
	Stensgård and Hanssen	Norway	Empirical	Household and Commercial & Industrial	1
	Thyberg and Tonjes		Review	Not-specified	2
	Mallinson et al.	United Kingdom	Empirical	Commercial & Industrial	2
	Visschers et al.	Switzerland	Empirical	Household	2
	Stancu et al.	Denmark	Empirical	Commercial & Industrial	2
2017	Hebrok and Boks		Review	Household	2,3
	Russell et al.	United Kingdom	Empirical	Commercial & Industrial	2
	Alexander et al.		Empirical	Not-specified	1,2
2018	Kliaugaitė and Kruopienė	Lithuania	Empirical	Commercial & Industrial	1
	Elimelech et al.	Israel	Empirical	Household	1

	Mak et al.	Hong Kong	Empirical	Commercial & Industrial	2
	Sakaguchi et al.	United States	Empirical	Commercial & Industrial	2
2018b	Yu et al.	China	Empirical	Household	2
2019	Hu et al.	China	Empirical	Commercial & Industrial	2
	Pellegrini et al.	Italy	Empirical	Household	2,3
	Busetti	Italy	Empirical	Not-specified	3


Food waste
Policy
Resources
Limitations
Circular
Bioeconomy
Opportunities
Conceptual/ Empirical / Review studies
Economic and social aspects
LCA, LCC and s-LCA

Highlights:

- Circular bioeconomy is elucidated through sustainable food waste management.
- Global situations and policies of food waste management are comprehensively reviewed.
- Research prospects of food waste management in bioeconomy are discussed.

Declaration of Interest Statement

All authors approve submission and declare no conflict of interest.