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The role of chemical engineering in the organic waste-based circular bioeconomy: what has been done and what still needs to be done. A perspective

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In recent years, various institutions around the world have emphasised the need to change the economic paradigm from linear to circular. In this framework, waste - particularly organic waste - has become a source of opportunities for converting a wide range of organic waste types into bioproducts or bioenergy. This strategy gives rise to the concept of a biorefinery: a multi-product facility combining technologies and processes to maximise the potential of organic waste, going beyond the traditional waste treatment plant. In this context, chemical engineering (CE) is the most suitable discipline for studying the bioeconomy based on organic waste. By its very nature, CE is multidisciplinary and flexible, and is based on mass and heat balances. Thus, it has powerful tools with which to address the technical challenges of organic transformation. Furthermore, Life Cycle assessment (LCA) and Techno-Economical Analysis (TEA) should be based on CE. In turn, LCA and TEA are the main tools that different stakeholders use to successfully implement an organic waste-circular bioeconomy. This perspective paper explores how CE has already helped and could help in the future with the development of a bioeconomy based on organic waste, using both classical and newly developed CE principles and techniques.

KEYWORDS
bioproducts, bioenergy, biorefinery, circular bioeconomy, organic waste, solid-state fermentation

1 Introduction

The growing population and increasing demand for materials and bioenergy are shifting the world from linear processes to a circular paradigm. This is known as the circular economy and is defined as 'a system in which materials are kept in circulation through processes such as maintenance, reuse, refurbishment, remanufacturing, recycling and composting', according to The Ellen MacArthur Foundation (2025). In fact, circular economy involves several aspects, from technology issues to social acceptance, as presented in Figure 1. This figure illustrates the four pillars of a successful circular economy in the context of waste management: i) waste reduction and prevention should be the first step in any waste hierarchy, ii) adequate and locally adapted regulations and policies are needed to avoid the voluntary nature of some adopted actions, iii) consumers must understand the benefits of bioproducts made from waste and recycling habits for their everyday lives and iv) technology and infrastructure must be well designed and proportionate to achieve

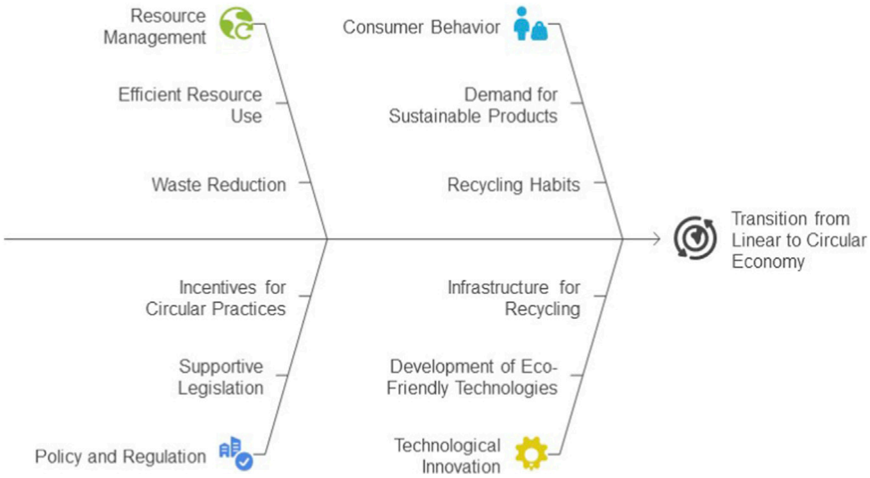

FIGURE 1
Some issues involved in the development of circular economy for organic waste.

environmental and economic objectives and support the previous points, especially consumer perception.

This paradigm shift involves significant changes at every stage of industrial production, particularly with regard to waste, which becomes a raw material for producing new products in an endless cycle (Islam et al., 2024). In this context, organic waste is of particular interest. In the developed world, there has been a shift in approach to organic waste, moving from landfill to composting and anaerobic digestion, which are clear examples of the circular economy. However, there is a trend to go beyond these technologies and explore the potential for transforming this waste into more valuable bioproducts (Molina-Peñate and Sánchez, 2025). One such example is solid-state fermentation, which has been used for centuries in food production. In the context of the circular economy, it can be defined as "the biological, aerobic, solid-state transformation (SSF) of biodegradable organic waste into bioproducts that can replace raw materials and energy sources" (Sánchez, 2024).

In this framework, chemical engineering (CE) has proven to be a multidisciplinary discipline for solving, designing and implementing solutions to all types of environmental problems, which are often complicated and open to interpretation. Typical items included in CE are important to highlight, such as the design of bioreactors, kinetics, simulation, control, modelling, and, in particular, heat and mass balances. The latter two should form the basis for applying the principles of the circular economy and one of its main tools: Life Cycle Assessment (LCA). Another important issue related to implementing new approaches to existing problems is Techno-Economic Assessment (TEA). In this case, CE-based mass and heat balances should provide the necessary data to assess the economic viability of new circular processes (Sánchez, 2019).

This perspective paper has the objective to explore the potential relevance of CE in developing a circular economy, specifically in the case of using organic waste as raw materials, which as an evident change of paradigm. Although the paper does not intend to be an extensive review of the topic, it will carefully assess the most implemented technologies in organic waste treatment and valorisation: composting, anaerobic digestion and SSF, as well as their multiple combinations in the form of biorefineries. The intention of this perspective paper is to highlight some existing research gaps and demonstrate how CE can improve the environmental and economic consistency of these facilities, which are currently in an embryonic stage of development. More generally, the paper is a preliminary attempt to demonstrate how CE can help in the development of this research topic.

2 What is expected from organic waste in the bioeconomy framework?

The first issue to consider when dealing with organic waste and its role in the circular bioeconomy is its definition. From a chemical perspective, the definition is quite clear: "waste containing carbon compounds derived from animal and plant materials" (GEMET, 2021). However, this definition is incomplete when dealing with organic waste in a bioeconomy framework, where strategies that have a low environmental impact are promoted, especially aerobic or anaerobic treatments. In this context, an essential yet often overlooked characteristic of organic waste is its biodegradability. According to the definition of organic waste, all organic waste is biodegradable. However, the lack of information about how long it takes for waste to biodegrade or transform into a bioproduct will hinder the implementation of key bioeconomy strategies such as biorefineries.

Today, there seems to be a consensus on using respiration indices to express the biodegradability of organic waste (Sánchez, 2023). As these techniques are a small-scale reproduction of the measurement of oxygen uptake, it is evident that they are a reliable way of quantifying the aerobic biodegradability of organic waste, in the same way that Biochemical Oxygen Demand (BOD) is used to define wastewater biodegradability (Lacalamita et al., 2024). Nevertheless, if anaerobic digestion is used, it is also important to use the appropriate method, such as Biochemical Methane Potential (BMP) tests, which are widely used (Liu et al., 2024).

The difference in biodegradability under aerobic or anaerobic conditions for most organic polymers, such as cellulose, lignin and fats, makes using different tests highly recommended (Silva et al., 2023).

However, it is important to note that, from a modern point of view, organic waste that takes a long time to biodegrade should also be considered in an overall bioeconomy strategy. This applies to lignocellulosic waste, which is also the most abundant type of organic waste by mass. Recently, non-biological treatments such as pyrolysis (Mukherjee et al., 2022) and a variety of pre-treatments combining physical, chemical and biological technologies have been used to increase the biodegradability of this waste (Olaitan Bamidele et al., 2025). Any advance in incorporating lignocellulosic waste into the bioeconomy is therefore of critical importance. Current research is paying attention to a paradigmatic example: the combination of pyrolysis and anaerobic digestion to improve energy production using biochar, a key material in today's organic waste research (Singh et al., 2022; García-Prats et al., 2024).

Due to its social impact, municipal organic waste is a special case (Molina-Peñate et al., 2022). Public administration should use this fraction to raise awareness of the importance of organic waste as a future source of bioproducts and bioenergy. In this context, the mandatory source separation of organic municipal solid waste, which is being implemented in most European Union countries, is a powerful tool for achieving these goals, which align well with the Sustainable Development Goals promoted by the United Nations (2015). The diversion of this fraction away from landfill is probably one of the main challenges in waste management overall, as a life cycle assessment has repeatedly confirmed (Ouedraogo et al., 2024; Oviedo-Ocaña, 2025).

3 Key technologies

This perspective paper does not aim to explore the scientific and technological insights of key organic waste-based circular bioeconomy technologies, as this information is available elsewhere. Instead, the intention is to highlight existing research gaps and demonstrate how CE principles can improve the environmental and economic consistency of these strategies.

3.1 Composting

More than 30 years ago, Haug (1993) presented the first engineering approach to composting. In his excellent book, he presented the typical tools of CE, particularly mass and heat balances, which could be used to extract reliable and reproducible results from composting experiments. The book's emphasis on the scale of the process as a cause and consequence of the data obtained was also historically significant at a time when composting simulation and modelling were still in their infancy. Composting research has evolved significantly since then. Mass and energy balances, kinetics and the design and modelling of bioreactors are typical CE strategies for overcoming composting challenges (Sánchez et al., 2025). The results are evident: composting plants have been implemented all over the world, and our understanding of composting-related topics such as gas transfer, compost sanitation and microbiology has improved considerably. However, further research is needed to address issues such as compost quality and the impact of composting engineering on the final product (Komilis, 2015), as well as the prediction of composting gaseous emissions (Wang et al., 2024), among other minor issues.

3.2 Anaerobic digestion

3.2.1 Biogas as source of bioenergy

In modern waste treatment plants and the design of future complex biorefineries, anaerobic digestion is clearly set to play a key role in providing renewable energy in the form of heat and electricity for the plants' operation. Any surplus energy could also be a valuable economic asset (Holm-Nielsen et al., 2009).

CE has been demonstrated to be a powerful tool in the production of biogas from the anaerobic digestion of a wide range of organic waste. The most paradigmatic case is probably the detailed model released by the International Water Association (IWA) in 2002, which has formed the basis of numerous amendments to improve a continuously updated model (Batstone et al., 2002; Mo et al., 2023). Another important area in which CE plays a significant role is biogas upgrading. This is currently being studied using several alternatives that consider the removal or conversion of carbon dioxide after biogas desulfurization. The first approach involved the use of selective membranes in specific reactors, an important area of CE research (Brunetti and Barbieri, 2021), although two other approaches are currently being studied and implemented on a pilot scale. On the one hand, biomethanation is proposed as a biological process involving syntrophic relationships between hydrogen producers (acetogens) and hydrogen scavengers (homoacetogens and hydrogenotrophic methanogens), typically using biotrickling reactors (Feickert Fenske et al., 2023) or hollow-fiber membrane bioreactors to overcome hydrogen transfer problems (Fachal-Suárez et al., 2024). On the other hand, the hydrogenation of carbon dioxide to methanol as an easily manageable energy source and a platform chemical using novel heterogeneous catalysis is also very promising (Alireza-Vali et al., 2025). Consequently, green methanol plants based on carbon dioxide from organic waste are becoming a reality (Hydrogen Insight, 2025). In all cases, biogas upgrading has been considered using CE principles involving various subdisciplines (reactor design, heterogeneous catalysts, transport phenomena, modelling, etc.).

The pending role of CE in systematically studying anaerobic digestion is probably found in the field of using additives, such as nanomaterials and biochar, to improve biogas and/or biomethane yields. Publications on this topic have increased exponentially over the last 10 years, but it is clear that successful implementation requires rigorous CE analysis of the mechanisms and dosages related to the use of these additives. Even more importantly, scaling up and experiments under continuous conditions are needed, as this is how anaerobic digestion operates in reality (Cerrillo et al., 2021).

3.2.2 Digestate

Anaerobic digestion is currently experiencing a boost all over the world due to the production of biomethane as a renewable energy source from organic waste, which has hindered the generation of increasing amounts of digestate. In fact, it is quite probable that most existing organic waste will become digestate in the next few decades. However, the future use of this material is unclear, as its use as an organic soil amendment presents challenges due to the presence of pollutants, regulatory issues and the difficulty of dealing with large quantities of digestate.

In this sense, two alternative strategies have received more attention in recent research. On the one hand, pyrolysis is a popular technology due to the production of biochar, a versatile material (Biochar, 2025). Some studies have proposed integrating anaerobic digestion and pyrolysis to achieve a higher level of sustainability (Singh et al., 2022). However, these studies lack reliable mass and energy balances, in which CE must play a predominant role. The idea is straightforward: use anaerobic digestion to obtain biomethane and then use the resulting digestate in pyrolysis to obtain biochar. This is a well-known strategy for increasing the methane yield in an integrated system designed for maximum energy production (Yang et al., 2025). In any case, results obtained at pilot scale are necessary for environmental and economic analysis, and to increase the technology readiness level for further implementation at commercial scale.

Conversely, SSF is an emerging technology that is shifting the paradigm from waste to raw materials (Sánchez, 2024). Examples of organic waste used in SSF can be found in Oiza et al. (2022), as well as in more recent publications focusing on specific waste sectors as the use of by-products in animal feed (Kalaiselvan et al., 2025). It is important to note that the types of organic waste used as substrates in SSF and the bioproducts obtained from them are constantly evolving, with new publications emerging daily. Nevertheless, the main substrates used are the source-selected organic fraction of municipal solid waste, municipal green waste, residues from agriculture and farm activities (manures), food industry by-products and wastewater sludge, together with their respective digested materials. The list of bioproducts is also growing, with enzymes, biofertilisers, biostimulants, biopesticides, biosurfactants, bioplastics, biofuels, antioxidants, antibiotics, pigments, flavours and aromas being among the most widely studied. However, very specific products can also be found in recent publications (Dong et al., 2025).

In the short term, two main issues should be addressed as a result of the current increase in anaerobic digestion for the production of renewable energy. Even more importantly, this energy is locally available and independent of climate conditions. Firstly, digestate production will dramatically increase and much of the raw waste currently in use will simply disappear as it is converted into digestate. This will necessitate finding alternatives to using digestate as the main waste product in a circular, waste-based bioeconomy. However, digestate is "the waste of waste" with particular characteristics, the most important of which is probably its moderate-to-low biodegradability. Therefore, using digestate in SSF to produce added-value bioproducts will be challenging, and co-SSF using complementary substrates will probably be necessary.

Nowadays, some papers present the use of digestate for producing biopesticides using *Bacillus thuringiensis* (Font-Pomarol et al., 2025) and *Trichoderma* spp. (Rodríguez et al., 2019; Bulgari et al., 2023). Good results have been achieved using digestate from various sources, such as wastewater sludge, biowaste and agricultural waste. However, one of the main issues related to the scaling up of SSF is the resulting problems with mass and heat transfer occurring during SSF, which hampers the implementation of this biotechnology. Currently, Mejías et al. (2025) have presented the largest reactor for this purpose, showing good results with *Bacillus thuringiensis* and biowaste digestate in a 290 L packed-bed reactor with carefully designed temperature control to prevent self-heating and deactivation of microorganisms.

In SSF, it is clear that CE must play a crucial role in order to implement the process on a commercial scale, particularly when it comes to digestate. Therefore, studying transfer phenomena to gain a reliable understanding of oxygen diffusion in solid matrices is essential. Reliable energy balances that are consistently coupled with biodegradation should also be used to anticipate self-heating problems. This knowledge should result in consistent and flexible models that can describe and simulate SSF performance. The efforts already made by some researchers are particularly important, although there is still a long way to go in this field (Casciatori et al., 2016; Jung Finkler et al., 2021).

4 Biorefineries and chemical engineering

As previously mentioned, CE is an extremely powerful approach to the organic waste bioeconomy of the future (Sánchez, 2019). It also provides an opportunity to avoid the "rules of thumb" that have been used to design critical composting technologies in biotechnology (Haug, 1993). In this sense, all of the sub-disciplines included in CE can contribute to the design, construction, commissioning and operation of current and highly complex future biorefinery facilities (Figures 2, 3).

Table 1 summarises some examples of typical items forming part of any undergraduate course in CE. Clearly, mass and heat balances are the most important contribution that CE can make to the organic waste bioeconomy. They are responsible for sizing the main operations (including bioreactors) of the biorefinery. However, they are quite complex in relatively simple plants, such as the one presented in Figure 2. Until recent decades, no comprehensive studies were available (Pognani et al., 2012). This is a significant disadvantage when comparing the use of energy and mass balances in traditional petroleum-based refineries. One of the main reasons for this is the scarcity of experimental data from existing installations. This is particularly important when designing complex biorefineries aimed at maximising energy and bioproduct output (see Figure 3). Figure 3 shows an example of an advanced biorefinery in which the biogas is separated into methane (which is fed into the natural gas grid) and carbon dioxide (which is converted into methanol using green hydrogen). Additionally, digestate is valorised through SSF into selected bioproducts. Other configurations, including pyrolysis coupled with anaerobic digestion, are also possible and are currently under study (Singh et al., 2022).

Nevertheless, it is important to note that mass and energy balances are necessary to address another critical issue of the proposed biorefinery: its environmental and economic sustainability, which is crucial when comparing the organic waste-based bioeconomy to existing solutions (D'Amato and Korhonen, 2021; Nguyen et al., 2025). Thus, robust and

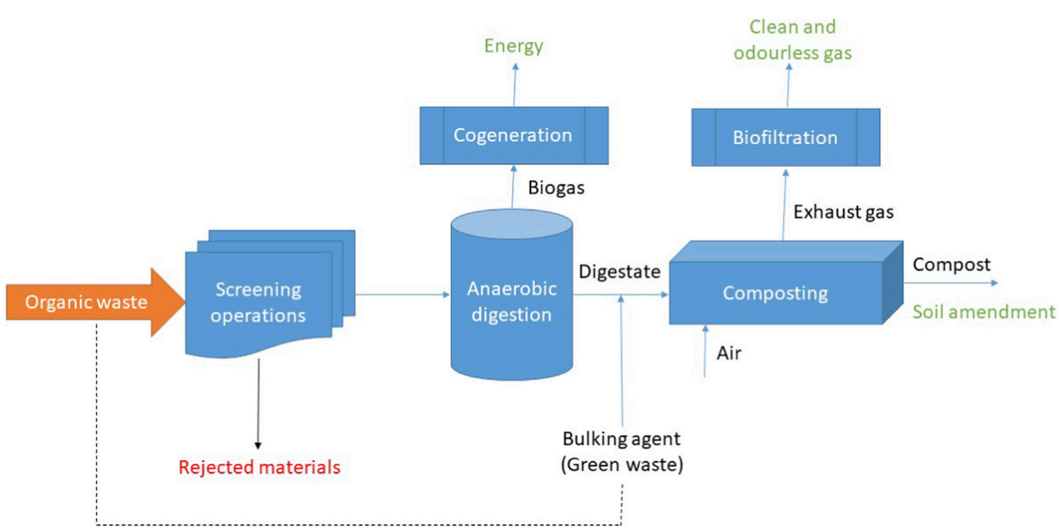

FIGURE 2
Current configuration of organic waste treatment plants.

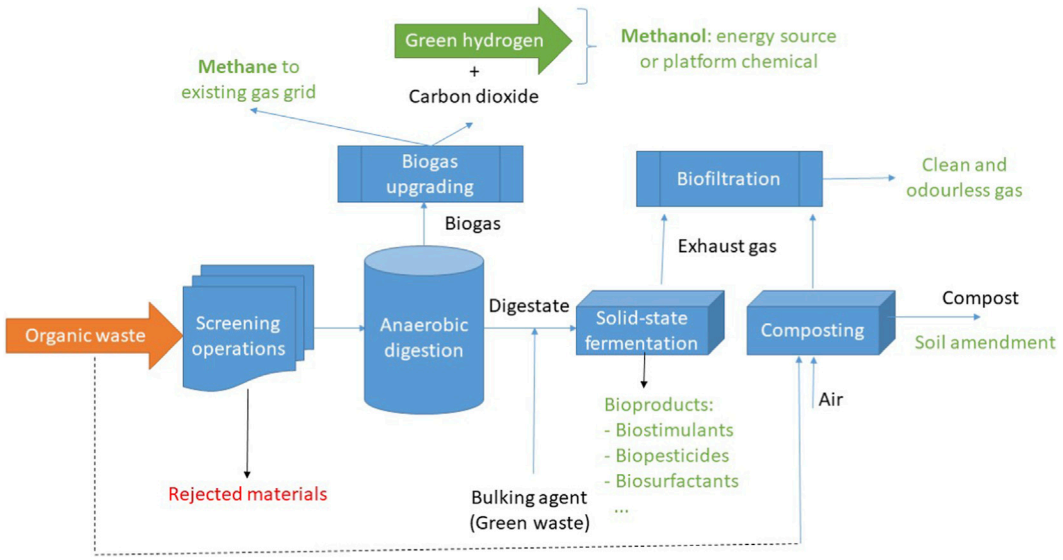

FIGURE 3
Scheme of a hypothetical biorefinery optimising bioenergy and biomaterials production.

consistent balances are of outstanding importance in building reliable Life Cycle Assessments and Techno-Economic Analyses (Molina-Peñate et al., 2024) of the proposed biorefinery, which will ultimately result in stakeholders' decisions on its implementation.

Another significant issue for biorefineries is the lack of reliable models for simulating their results. Current research is starting to propose models for composting (Sole-Mauri et al., 2007), anaerobic digestion (Mo et al., 2023) and solid-state fermentation (Casciatori et al., 2016), as well as other non-biological operations such as pyrolysis, which could complement biological-based technologies excellently. However, these operations are not yet implemented in the powerful simulators typically used in CE (Aspen HYSYS, among others). This is important because the raw organic waste entering a biorefinery is heterogeneous and dependent on the season; therefore, flexible, non-steady state simulators are necessary. In modelling and simulation, however, CE and other disciplines are undergoing a period of transition. Traditional modelling based on mass and heat balances (in steady or non-steady states) is being replaced by data-driven techniques; machine learning is currently the most widely used in the organic waste bioeconomy (Velidandi et al., 2023; Butean et al., 2025). The next few years will probably see exponential growth in the use of artificial intelligence in this field, and the bioeconomy cannot remain outside this phenomenon, as some recent studies suggest (Olawade et al., 2024).

Finally, it is important to note that CE disciplines should not be approached in isolation when attempting to overcome challenges

TABLE 1 Classical paradigms of chemical engineering and their potential applications in the design and optimisation of biorefineries.

Chemical engineering item	Application
Mass and energy balances	Size of operations and bioreactors
Mass and energy balances	Life cycle assessment
Kinetics	Bioreactors design
Chemical reactors	Bioreactors design
Transport phenomena	Scale-up
Modeling and simulation	Test the performance of different configurations of the biorefinery
Heat transfer	Optimization of energy balance
Cost analysis	Techno-economic analysis

associated with organic waste technologies. Scale-up is a paradigmatic case in this regard, as mass and heat balances must be accompanied by modelling and simulation tools to ensure reproducible results (Molina-Peñate and Sánchez, 2025). This approach should also be adopted beyond CE strategies. Clearly, other crucial disciplines such as microbiology and biotechnology cannot be used separately and must be strongly coupled with CE. This is an erroneous and dangerous trend in papers related to the bioeconomy based on organic waste, and it is time to move away from it.

5 Conclusion

At a time when there is an increasing demand for circular economy strategies to cope with the search for new materials and energy sources, organic waste could be an excellent way to meet this demand. However, the success of these new circular approaches depends on them being economically attractive and having a lower environmental impact than existing solutions, particularly with regard to carbon and water footprints. To achieve these objectives, CE and its particular fundamentals (mass and heat balances, reactor design, modelling and simulation, etc.,) has an already unexplored potential to be a consistent, reliable and reproducible multidisciplinary discipline that can assist in the design of complex facilities, such as biorefineries, which are considered fundamental to the organic waste-based circular bioeconomy. Combining CE with the circular economy could be one of the most important developments for the future of this paradigm shift. However, this perspective paper should be considered a preliminary attempt to demonstrate how CE can improve the treatment and valorisation of organic waste in the context of a circular bioeconomy, based on my experience.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Writing – original draft, Writing – review and editing.

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