Title	Organic waste biorefineries: Looking towards implementation
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Publication Date	2020-07-16
Publication Information	Alibardi, Luca, Astrup, Thomas F., Asunis, Fabiano, Clarke, William P., De Gioannis, Giorgia, Dessì, Paolo, Lens, Piet N. L., Lavagnolo, Maria Cristina, Lombardi, Lidia, Muntoni, Aldo, Pivato, Alberto, Polettini, Alessandra, Pomi, Raffaella, Rossi, Andreina, Spagni, Alessandro, Spiga, Daniela. (2020). Organic waste biorefineries: Looking towards implementation. Waste Management, 114, 274-286. doi:https://doi.org/10.1016/j.wasman.2020.07.010
Publisher	Elsevier
Link to publisher's version	https://doi.org/10.1016/j.wasman.2020.07.010
Item record	http://hdl.handle.net/10379/16459
DOI	http://dx.doi.org/10.1016/j.wasman.2020.07.010

Organic waste biorefineries: looking towards implementation*

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** This position paper presents the view of the authors, as members of the IWWG Task Group on Waste Biorefinery, about critical aspects of the concept of organic waste biorefinery, it discusses the role of this concept on modern waste management strategies and indicates possible ways to achieve implementation.*

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Abstract

The concept of biorefinery expands the possibilities to extract value from organic matter either in form of bespoke crops or organic waste. The viability of biorefinery schemes depends on the recovery of higher-value chemicals with potential for a wide distribution and an untapped marketability. The feasibility of biorefining organic waste is enhanced by the fact that the biorefinery will typically receive a waste management fee for accepting organic waste. The development and implementation of waste biorefinery concepts can open up a wide array of possibilities to shift waste management towards higher sustainability. However, barriers encompassing environmental, technical, economic, logistic, social and legislative aspects need to be overcome. For instance, waste biorefineries are likely to be complex systems due to the variability, heterogeneity and low purity of waste materials as opposed to dedicated biomasses. This article discusses the drivers that can make the biorefinery concept applicable to waste management and the possibilities for its development to full scale. Technological, strategic and market constraints affect the successful implementations of these systems. Fluctuations in waste characteristics, the level of contamination in the organic waste fraction, the proximity of the organic waste resource, the markets for the biorefinery products, the potential for integration with other industrial processes and disposal of final residues are all critical aspects requiring detailed analysis. Furthermore, interventions from policy makers are necessary to foster sustainable bio-based solutions for waste management.

Keywords: organic waste; biorefinery; pre-treatment; biological processes; thermal processes; implementation

1. Introduction

Organic waste treatment has traditionally been based on layouts involving a single bioprocess such as composting or anaerobic digestion, and in some cases a combination of the two (Ma and Liu, 2019; Cossu, 2009). Composting is a simple process that can be implemented for solid organic waste with relatively small capital investments. The composting process, however, involves an energy-intensive treatment due to the need for forced aeration; at the same time, the marketability of the final product may be limited due to very low market prices or lack of acceptance from final users (e.g. farmers) if compost quality is compromised by the presence of contaminants (e.g. high metals concentration) or undesired components (e.g. plastics) (Cattle *et al.*, 2020; Asquer *et al.*, 2019). Anaerobic digestion has been increasingly practised over the last two decades for the treatment of both solid and liquid municipal and industrial organic residues, with economic incentives coming from government policies being key drivers for process implementation. Such incentives stimulate the production of electric energy, thermal energy or biomethane from biogas as a renewable resource to be exploited beyond the plant boundaries (Kapoor *et al.* 2019; Kougias and Angelidaki, 2018; De Gioannis *et al*., 2017). The total installed electric capacity of anaerobic digesters in Europe has almost tripled during the last ten years (from 4158 in 2010 to 10532 MW in 2017; EBA, 2018), contributing to achieve renewable targets for energy production in many countries (e.g. the energy roadmap defined by the EU; European Commission, 2011).

In a world with finite resources, waste or residues, including organic waste, must be considered as sources of secondary raw materials. Currently, recovery of the organic waste "value" is obtained in the form of only a few products, e.g. biogas, compost, and nutrients in the liquid phase of the digestate. These have a relatively low economic value, often supported by incentives for the production of renewable energy granted by environmental and energy policies adopted in some countries (Clarke, 2018).

A shift to renewable resources (e.g. green hydrogen, biofuels, bioplastics) (Papież *et al.*, 2018, Carley and Browne, 2013; Lu *et al.*, 2013), driven by businesses and the general public looking to implement circular economy principles, (Sarc *et al.*, 2019; Walmsley *et al.*, 2019; Vrancken *et al.*, 2017) has changed the perception of organic waste. Organic waste materials are now seen as readily available and widely distributed and flexible renewable resource (Ma *et al.*, 2018; Girotto *et al.*, 2015; Diacono and Montemurro, 2010). This has moved the frontiers of organic waste management towards more ambitious and articulated targets that may be fulfilled by the implementation of the waste biorefinery concept.

A number of definitions exists for biorefinery (Schieb *et al.*, 2015) but in essence all refer to a series of processes converting biomass into chemicals, material and fuels (Schieb *et al.*, 2015; Dubois, 2012; Cherubini *et al.*, 2009). An organic waste biorefinery can therefore be an evolution of the biorefinery notion to include waste as an alternative to dedicated biomass or to introduce a management practice enhancing the recovery of value from organic waste. The concept has raised great interest in the last years as technologies to recover value from waste feedstocks have been improved ensuring its environmental and economic sustainability (Cristóbal *et al.*, 2018; Go *et al.*, 2019). The range of products from a biorefinery receiving organic waste may be limited by the variability of the waste stream, but organic waste can also be homogeneous waste such as agroindustrial by-products or surplus materials which can be as defined as dedicated crops (Caldeira *et al.*, 2020). In this paper, the terms organic waste or waste feedstock were used in the broadest sense to include any biogenic waste, effluent, by-product and production surplus (Fava *et al.*, 2015; Coma *et al.*, 2017).

The aim of this paper is to (i) provide an overview of the framework and context that organic waste biorefineries are viable, (ii) discuss critical aspects associated with future implementation, and (iii) develop recommendations for suitable configurations of organic waste biorefineries.

2. Scope and boundary conditions for organic waste biorefineries

The purpose of waste biorefineries is to exploit the potential of organic residues from different sources to generate a range of bioenergy, biofuel and biochemical products (Cherubini *et al.*, 2010). Waste biorefineries offer platforms for integrated utilisation of a wide range of resources in organic waste. The development and implementation of the waste biorefinery concept offer a range of economic, environmental, social and political benefits:

- stimulate the engagement of local communities to promote and apply sustainable waste management strategies;
- provide a profitable alternative solution for waste management in areas with growing urbanisation;
- support the implementation of circular economy principles;
- reduce the pressure on non-renewable resources;
- help diversify sources of strategic supply and decrease dependence on imported resources;
- promote distributed production systems and sustain regional and rural development;
- contribute to mitigate climate change impacts by providing useful products and off-setting the use of fossil carbon.

The general concept of a biorefinery has evolved driven by three pivotal aspects: (i) synergism with other industries; (ii) economic sustainability; (iii) environmental sustainability (Muntoni, 2019; Akhlaghi *et al.*, 2016).

2.1. Underlying principles of waste biorefineries

The cascading approach involves the flexible and sequential integration of different biological, chemical and/or thermal processes aimed at producing a mix of biofuels and biomolecules to maximise production yields and incomes (Olsson *et al.*, 2016). To this aim, both the direct and the inverse cascading approach may be implemented depending on whether bioenergy generation is downstream or upstream of biomaterials production (Poggi-Varaldo *et al.*, 2014). The integration of processes for both cascading approaches depends on technical feasibility, economic sustainability, market conditions, environmental issues as well as local needs and constraints, and leads to a specific array of biofuels and biomaterials (Maina *et al.*, 2017). Increasing the range of output products is expected to impact the achieved level of waste recovery preventing organic waste from being disposed to landfill or open dumps. The flows that are diverted from landfill would need to meet quality and technical standards specific to the biorefinery. Compared to a conventional biorefinery, a waste biorefinery would, therefore, involve an additional layer of complexity due to the variability, heterogeneity and low purity of waste materials as opposed to dedicated biomasses (Duan *et al.*, 2020; Ubando *et al.*, 2020; Sadhukhan and Martinez-Hernandez, 2017).

The alternative of using suitable organic waste as is without processing must always be considered, such as the application of non-putrescible crop residues on land or the use of clean food waste as animal feed (Caldeira *et al.*, 2020; Cristobal *et al.*, 2018; Matharu *et al.*, 2016).

2.2. Technical and economic sustainability

From the technical and economic viewpoint, the main challenges involved are: (i) mitigating the impacts that the fluctuations in waste composition and characteristics can have on the array of processes adopted in a biorefinery (Matharu *et al.*, 2016); (ii) arranging an integrated set of suitable waste materials as the feedstock to maximise the final product yield and quality (Roni *et al.*, 2019); (iii) determining the optimal size of the system which can range from high-performance, multi-feedstock installations to decentralised, more specialised systems with a reduced number of platforms (Galanopoulos *et al.*, 2020; Roni *et al.*, 2019); (iv) integrating the system with other industries to allow for improved circulation of materials and energy (Caldeira *et al.*, 2020); (v) accommodating for fluctuating market demands and price volatility of products (Duan *et al.*, 2020).

Organic waste feedstocks mainly consist of agricultural and forestry waste, food processing waste and effluents, sludges, yard and organic household waste. Such diversified materials contain valuable amounts of proteins, sugars, lipids, fibres, vitamins and bioactive agents (antioxidants and antimicrobial agents, enzymes) that are worth recovering. Through specific combinations of treatments followed by proper separation and purification procedures, pigments, pharmaceuticals, flavours, organic acids, biopolymers, biofuels and soil improvers can be extracted or produced (Fava *et al.*, 2015).

Organic wastes represent a plurality of substrates having different characteristics and whose availability changes significantly over time. In general, post-consumer organic waste is heterogeneous but less affected by seasonal availability, while waste at the food processing stage is more homogeneous but affected by seasonality (Cristóbal *et al.*, 2018). Differences in origin and characteristics as well as seasonality drive production strategies, design, operation, and logistic choices for a biorefinery.

The treatment train could be potentially designed to match and buffer variations. For example, biorefineries might be designed to switch between seasonal feedstocks or use mixed supplies rather than a single source. Seasonal flow can also be buffered using air-tight storage and preservation techniques such ensiling or bio-drying. The synthesis of these various approaches to manage seasonal waste would arguably require a combinatorial problem-solving approach (Pyrgakis and Kokossis, 2019).

Transportation of the waste feedstocks to the biorefinery is another main logistic issue. Whilst more attention is usually given to the choice of the value recovery processes, the feasibility analysis should include also the management of the supply-chain (Caldeira *et al.*, 2020). Matching generation points and biorefinery location is a key factor that affects the viability of a biorefinery. In this respect Cristóbal *et al.* (2018) considered two diametrically opposite scenarios while performing a techno-economic and profitability analysis of four food waste biorefineries for tomato, potato, orange, and olive processing waste. Fewer large biorefinery plants co-located with the food processing plants would be effective for processing wastes from harvested goods, but would not represent the optimum transport solution for harvesting wastes and rejects, while, a strategy based on numerous smaller plants would minimise the transport costs for these in-farm wastes. The analysis stressed that few large plants would be the most profitable scenario as this allows for concentrated production, takes advantage of economies of scale, and simplifies transport logistics (Cristóbal et al., 2018). An economic analysis on a biorefinery treating citrus waste for the recovery of limonene, ethanol and biogas was performed by Lohrasbi *et al.* (2010). The ethanol production cost proved to be sensitive to the feedstock transportation costs. Increasing the transport cost from approximately 9 to 27 €/ton resulted in ethanol cost rising from 0.8 to 1.3 €/L, a feature reported also by Satari and Karimi (2018). The economic feasibility of biorefineries for food processing waste is enhanced if the bio-refinery is co-located with the food processing plant, eliminating transport as a cost for the biorefinery (Caldeira *et al.*, 2020).

2.3. Environmental sustainability

Waste management schemes are characterised by environmental impacts associated with the activities and technologies within the system, *i.e.* the handling and processing of waste materials. The outputs recovered or produced from waste contribute to the environmental savings by offsetting the demand for other resources. For a waste biorefinery to be environmentally sustainable, the environmental "value" of these outputs has to be higher than the "effort" invested in providing the outputs. More specifically, it is necessary to assess whether the use of organic waste as a starting material is less resource-demanding than the manufacturing of the same products from virgin materials (Cristóbal *et al.*, 2018). The environmental performance of a biorefinery will depend on the regional settings and whether simpler alternatives such as composting or anaerobic digestion have equal or greater environmental benefit. As such, a wide range of aspects are important when assessing the environmental sustainability of a waste biorefinery, e.g. the (i) feedstock availability, composition, properties and variability which may lead to higher proportions of rejected feedstocks that require disposal, (ii) logistic issues such as transport distance and need for storage capacity, compared to that of simpler and more scalable composting or digestion plants, (iii) more elaborate process configurations, including the need for complex pre-treatments, (iv) framework conditions and integration into "surrounding" industrial and waste management sectors, (v) and management of co-products and side streams from the refinery chain. The combination of all these aspects has a strong context-specific connotation and defines the overall environmental gain achievable in comparison with the use of simpler waste management strategies. Collecting reliable information on the available waste feedstocks is pivotal, although data on the streams that can be intercepted are seldom available (Cristóbal *et al.*, 2018).

Life cycle assessment (LCA) offers a systematic framework for evaluating the environmental consequences of waste management technologies and systems (e.g. ISO, 2006) with respect to a range of selected impact categories, such as climate change, resource depletion, eutrophication, and toxicity effects. Relatively few consistent LCA studies have been carried out with a focus on organic waste biorefineries, although a wider range of studies have addressed individual components such as anaerobic digestion and composting (e.g. Boldrin *et al*., 2011; Eriksson *et al*., 2005), fuel production (e.g. Venkata Mohan *et al*., 2016) and incineration (e.g. Astrup *et al*., 2015). Most of the LCA studies in literature focusing on integrated biorefinery systems have evaluated combinations of traditional waste technologies, such as material recovery facilities, anaerobic digestion, pulping and incineration, with the recovery of specific biofuels or biochemicals (e.g. Tonini *et al*., 2013; Sadhukhan and Martinez-Hernandez, 2017; Nizami *et al*., 2017; Chen *et al*., 2017; Moretti *et al*., 2017). As such, generic conclusions regarding the specific sustainability of organic waste biorefineries may be difficult to draw from existing literature due to variations in conditions and assessment approaches. However, biorefineries based on organic waste from households offer larger climate benefits compared to biorefineries that process industrial food industry (Tonini *et al*., 2016).

Two different LCA perspectives may be applied when evaluating the environmental sustainability of organic waste biorefineries: (i) a “waste management perspective” focusing on comparing the waste biorefinery with other (traditional) waste management options such as composting or landfilling, or (ii) an “output perspective” focusing on comparing one or more waste biorefinery products with alternative (traditional) production options. The alternative management options are important in both of these perspectives: if the waste was otherwise landfilled, the environmental benefits of waste utilisation in a biorefinery may be significantly larger than if the alternative management was anaerobic digestion or energy recovery via incineration (Astrup *et al*., 2015). This also relates to indirect effects, such as land-use-changes when crop markets are affected, *e.g.* organic waste fractions previously upgraded to animal feed products and now used as feedstock in biorefineries with different target outputs. In this case, the environmental impacts associated with the animal feed products need to be accounted as well. As waste biorefineries are multi-output technologies per definition, the environmental consequences associated with all outputs should be considered.

While the feedstock composition and properties can be considered fundamental for the environmental performance of waste biorefineries (Bisinella *et al.*, 2017), also the configuration and performance of individual unit-processes are critical. Recently, Lodato *et al*. (2020) developed an LCA approach specifically targeted towards integrated technologies such as (waste) biorefineries, thereby demonstrating that process efficiencies and mass, energy, and substance flows within a biorefinery have profound importance for the overall environmental performance. This includes the composition of side streams, rejects and co-products from the biorefinery (e.g. digestate, fibre fractions or contaminants) and the environmental implications of their management and final disposal. An important aspect is the potential effects associated with carbon or metals sink options (Morello *et al.*, 2018), and the risk of spreading micro-pollutants or microplastics (Butkovskyi *et al.*, 2016).

2.4 Market potential

The use of organic waste as a feedstock for biorefineries can be the nexus between environmental protection, bio-economy and circular economy promoted by EU policies (European Commission, 2015). In particular, waste biorefineries could potentially exploit the untapped potential stored in approximately 130-151 million tonnes/year of biowaste estimated to be generated in the EU by 2020 (European Commission, 2011). The latest data published by Eurostat (Eurostat, 2020) indicate an actual total (municipal + industrial) production potential of about 230 million tonnes/year of organic waste for EU28 in 2016, composed of ca. 42% of animal and vegetable waste, 26% of the organic fraction of municipal solid waste, 20% of wood waste and 9% of non-hazardous sludge from sewage treatment plants or food processing plants.

The market targeted by waste biorefinery products has grown steadily notwithstanding the economic crisis of the last decade. The global production of organic chemicals accounts for a major share of the overall chemical industry and is estimated to amount, excluding fuels, to more than 300 Mtons/year. The associated market was worth over USD 6 billion in 2014, growing at an average rate of 8% per year from 2009 to 2014. It is expected to reach USD 16 billion by 2025, at a compound annual growth rate of about 7-8% from 2019 to 2025 (Fiormarket, 2019).

The primary outputs of the traditional organic chemical industry are a relatively limited number of building blocks used to produce a plethora of end products for various sectors (e.g. food and beverages, pharmaceuticals, personal care products and cosmetics, fertilisers, pesticides, agrochemicals, water treatment chemicals, automotive components, gasoline additives and polymers).

The current global bio-based chemical and polymer production is estimated to be around 90 million tonnes. The demand for bioproducts from renewable sources is estimated to reach, depending on the market conditions, 26–113 Mtons/year in 2050, up to 38 % of the total organic chemicals production. The associated market is projected to account for 7–8 billion USD, with a growth rate of 15% per year that could further benefit from the increasing demand for biopolymers (IEA Bioenergy - Task 42 Biorefinery, 2020). This indicates a market with a large potential that has not yet been tapped. Basic building blocks can indeed be obtained from organic waste, enabling the supply of raw materials from internal and diffused sources. This would de-risk the supply chain from external and potentially volatile suppliers, guarantee a secure supply at lower production and transport costs and achieve economic sustainability even for disadvantaged and isolated contexts such as, for instance, some of the main Mediterranean islands.

3. Implementation of waste biorefinery systems

3.1 From traditional biorefineries to waste biorefineries

The technological and economic perspectives of traditional biorefineries are not entirely applicable to waste biorefineries. Waste materials fluctuate in composition (Bisinella *et al.*, 2017; Alibardi and Cossu, 2014) and contain impurities or other undesired fractions (e.g., small plastics) that are not easily removable.

Pre-treatment of organic waste is considered a crucial step in a biorefinery scheme to cope with the complexity and heterogeneity of waste materials. The aim of pre-treatments is to remove unwanted constituents, change the physical properties of the solid matrix (e.g. its crystallinity) to speed up downstream processes (Tonini and Astrup, 2012) and make valuable components more available to subsequent treatments. Recovery of building blocks of interest for the chemical industry, which can be further transformed into compounds for downstream utilisation, often requires the isolation of homogeneous fractions and the disruption of the original chemical structure. This is particularly true for complex residual materials (e.g. lignocellulosic). Three major analysis points arise in this respect, including (i) the selectivity of the applicable pre-treatment techniques; (ii) the amount of rejected fraction generated; and (iii) the intensity (amount of chemicals and energy) of the pre-treatment stages. Appropriate tools to assess the overall environmental profile and economic sustainability of the whole process should therefore be adopted to evaluate and compare different valorisation options (Albizzati *et al.*, 2019; Astrup *et al.*, 2018).

3.2 Production strategies in waste biorefineries

The simplest layouts of a waste biorefinery are those aimed at recovering low-added-value products, i.e. biofuels or energy carriers, soil improvers and fertilisers. A higher complexity is required to generate pure streams of platform chemicals for the production of biomaterials, where more specific technical standards must be met. The feasibility of a complex biorefinery with high-value outputs is linked to the availability and type of feeding residues, the market conditions and demand for these products and the possibility for a waste biorefinery to be integrated within the existing industrial system (Shahzad *et al.*, 2017). Indeed, some organic waste streams contain appreciable quantities of substances whose value may be as high as 12,000 €/g, e.g. biophenols such as hydroxytyrosol and tyrosol (Tinikul *et al.*, 2018), or are suitable for conversion into profitable molecules and pivotal building blocks, e.g. lactic acid, acetic acid and ethanol (Moretto *et al.*, 2019; den Boer *et al.*, 2016). While biorefineries earn revenues from the sale of products, waste biorefineries can also earn income from gate fees. Gate fees strongly depend on the territorial context, the balance between demand and offer for waste treatment and local regulations. In an initial stage, gate fees can contribute to assuring a stable income for a waste management company to de-risk the uncertainties of a non-mature market for biofuels or bioproducts. In the long-term, the generation of high-value products might increase the profitability, allowing for reducing or even eliminating waste gate fees (Sadhukhan *et al.*, 2018).

It is generally acknowledged that, in order to generate high-value outputs and ensure environmental sustainability (what is commonly referred to as a second-generation biorefinery), the process should be arranged to comprise two or more platforms (Budzianowski and Postawa, 2016; Naik *et al.*, 2010). According to the definition introduced by Task 42 of the IEA (IEA Bioenergy, 2012), analogous to the petrochemical industry, platforms are intermediates linking feedstocks and final products. The combined production of multiple platforms would ensure an optimised recovery of individual precursors from the feedstock. For instance, in order to make the selling price of biofuels competitive with that of fossil fuels, it is necessary to combine biofuel production with bioproducts that have high value and a sufficiently large market. In turn, producing multiple platforms requires the integration of a range of different treatment processes, the nature of which is a function of the characteristics of both the feeding waste to be exploited and the final products. Furthermore, adequate fractionation of individual waste components may be necessary to generate an array of outputs of different characteristics. To this regard, the selectivity, accuracy and yield of separation play a key role in view of full implementation of multi-platform biorefineries.

3.3 Size-dependent waste biorefinery approaches

The minimum economically viable size of complex biorefinery installations, the criteria for acceptable waste feedstocks and the viable products that can be generated from waste biorefineries is still the subject of debate. Traditional biorefineries are generally indicated as requiring large plants with a minimum size in the range of about 500,000–700,000 tons/year to ensure economic sustainability (Kuchta, 2016). Using organic waste as a feedstock for biorefineries would presumably reduce the minimum size required, because of the expected income from waste treatment fees on top of the revenues from the obtained products.

The array of options available for biorefineries may range from large, high-performance installations to decentralised, simplified-layout systems (Budzianowski and Postawa, 2016). Larger installations benefit from the economies of scale and must produce bio-commodities that feed into large markets. As a result, larger installations are expected to include more complex process layouts, integrating several platforms and processes of different nature in order to diversify, functionalise and maximise materials and energy recovery. For the same reasons, large biorefineries are also envisaged to accept a range of feedstocks, both residual and non-residual biomass, to allow for larger treatment capacity. This flexibility will accommodate the seasonal variability of organic residues and bio-product markets, although a consolidated market pattern for bioproducts, in terms of both demand and price stability, is a highly relevant prerequisite. For large-scale centralised systems, however, the need for transportation of organic residues from different sources may be a concern from both the logistical and the economic point of view. The typically low energy density and solids content of organic residues, the need to reduce the storage period to a minimum to prevent biodegradation as well as the need to develop a highly structured supply chain represent significant constraints on the siting of a biorefinery.

Small scale biorefineries involve less complex treatment layouts with lower capital and operating costs, due to a reduced number of platforms and a smaller range of end products. Decentralised dedicated medium- to small-scale plants will use a reduced number of feedstocks, which are expected to be available at the local scale. At the same time, decentralised installations allow the generated biofuels and biomolecules being tailored to the existing context, promoting close integration with other local industries in view of the circulation of materials and energy. The technological complexity and the industrial know-how of waste biorefineries is less developed than highly specialised chemical processing installations. It therefore appears more reliable, at least from a short-term development perspective, to conceive a waste biorefinery as a system producing intermediates, precursors or building blocks, which are then further processed beyond the boundaries of the biorefinery.

A critical risk associated with waste-derived products is the potential spreading of impurities and contaminants, either associated with the original waste or produced during the processing as a result of side reactions and/or the addition of external chemicals. This aspect should be considered in relation to all waste management and recycling systems (Astrup *et al.*, 2018). The characteristics of final residues from complex biorefinery schemes will be different from those of traditional bioprocesses such as composting and anaerobic digestion, which needs to be considered when evaluating the feasibility of biorefinery configurations (Cattle *et al.*, 2020; Sharma *et al.*, 2019, Alvarenga *et al.*, 2015). To this regard, ecotoxicological parameters can be used to determine more realistically the risk posed to ecosystems by complex and highly variable matrices. For these bioproducts, the approach proposed by Hennebert (2018), who suggested an array of ecotoxicological tests with aquatic and soil organisms, provides a good starting point.

4. Waste biorefinery configurations

4.1 Multi-platform waste biorefineries

As shown in Section 3, a unique layout of the most suitable processes to be included in an organic waste biorefinery cannot be defined. The possible options on hand are related to the quantity and characteristics of the waste, the specific local conditions and constrains, market trends and legislative constraints. Nonetheless, in the authors' view, anaerobic digestion, being a well-established biological process currently adopted for complex and heterogeneous waste at large scales, is regarded as a suitable candidate to play a central role in biorefinery schemes in the near future. Stemming from this, a potential process layout for a multi-platform, multi-product biorefinery integrating anaerobic digestion with other chemical, biochemical and thermochemical treatment units is presented in Figure 1. The proposed layout includes an initial separation of the individual components of the waste feed (carbohydrates, starch, cellulose, lignin, proteins and lipids), followed by dedicated treatments of each component to maximise the yield of biofuels and biomolecules recovery (Asunis *et al.*, 2019; Girotto and Cossu, 2019; Alibardi and Cossu, 2016). The nature of the separation processes relies inherently on the composition and characteristics of the input waste, and may involve processes such as washing and extraction (Ao *et al.*, 2020; Matharu *et al.*, 2016), use of enzymes (Arbige *et al.*, 2019; Escamilla-Alvarado *et al.*, 2017) and solid-liquid or membrane separation processes (Abels *et al.*, 2013; Huang *et al.*, 2008). Waste fractionation by main chemical components enables parallel processing lines with a reliable supply with predictable composition, e.g. high carbohydrate-rich agro-food waste, protein-rich slaughterhouse waste, fat, oil and grease (FOG) waste from grease traps.

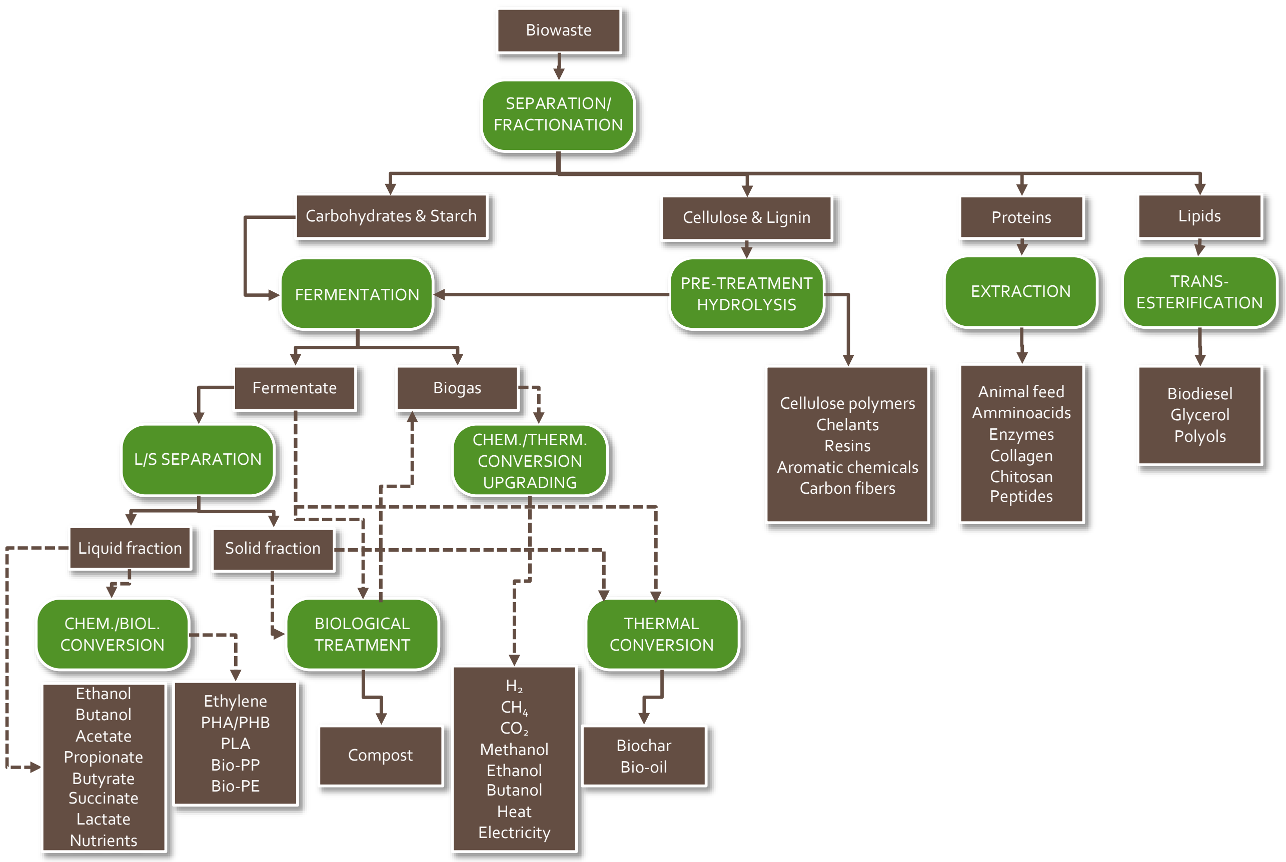

Figure 1. Layout for a multi-platform anaerobic biorefinery producing biofuels and biomolecules. Dashed lines represent alternative options. Green blocks represent processes and brown blocks represent materials.

The list of potential products presented in Figure 1 is not exhaustive, since further processing of intermediates and precursors may lead to additional products not specifically considered in the layout provided. Furthermore, in some cases (dashed lines in Figure 1), the bioproducts included in the proposed layout are considered alternative to each other, so that the individual treatment stages can be tailored towards the desired end products depending on the specific needs.

Full implementation of a multi-platform, multi-product scheme such as the one depicted in Figure 1 implies overcoming the bottlenecks associated with conversion processes from low-purity, heterogeneous materials such as organic residues. As a result, a transition period is unavoidable prior to the full development of the whole process chain. During the transition period, in the initial implementation stages the biorefinery concept can be applied and developed by adopting simplified configurations based on technologies that have already been developed and demonstrated at the full scale, to reduce uncertainties on process performance. This is meant to form a processing platform basis whose complexity can be progressively increased as soon as other, more advanced options become available for implementation. Such configurations can step up in the longer term into an integrated high-performance scheme. In this regard, a number of simplified layouts representing treatment trains with a short- to medium-term application horizon can be defined, which are deemed to have the potential of being more easily implemented within the waste management sector.

4.2 The role of dark fermentation in waste biorefineries

Potential simplified waste biorefineries models, with dark fermentation (production of H_2-based biogas and volatile fatty acids (VFAs) or alcohols) as the common initial stage followed by different treatment options depending on the target products, are outlined in Figures 2-6. Dark fermentation is the biohydrogen production option with the highest readiness for full-scale implementation (Lin *et al.*, 2018; Chandrasekhar *et al.*, 2015; Poggi Varaldo *et al.*, 2014). The relatively short retention time of dark fermentation implies small reactors that can be easily retrofitted into existing single-stage digestion plants even with limited space availability.

Regardless of whether H_2 is the targeted product, fermentation is central to processing carbohydrate streams. Protein and lipid-rich waste streams could also be directed through a fermenter if the competing routes and products shown in Figure 1 are not economically viable.

The layouts proposed in Figures 2-6 indicate the main (and most readily applicable) technological processes to maximise recovery of valuable products from the outflow of each stream, as well as the potential interconnections between treatment outflows. Dark fermentation plays the role of upfront treatment aimed at hydrolysing the complex starting waste materials, producing H_2 and providing simpler soluble compounds for downstream processes (De Gioannis *et al.*, 2013). More specifically, Option 1 (Figure 2) includes the following treatment stages: dark fermentation with H_2 production; a second methanogenic stage for CH_4 production; biogas treatment and upgrading to separate H_2, CO_2 and CH_4 for subsequent uses; liquid/solid separation of the digestate; biological stabilisation of the solid fraction of digestate to produce compost (or, alternatively, thermochemical treatment to produce either biochar or pyrolytic oil); and nutrient recovery from the liquid fraction of digestate. This represents the simplest and readily applicable waste biorefinery scheme that can benefit from the strong incentives that exist in several European countries to produce biomethane (Lombardi and Francini, 2020). The gaseous products (biohydrogen and biomethane) may then be used individually or as a mixture (hythane). Biomethane can also be used as a feedstock to more advanced processes, producing single-cell proteins or other high-value bioproducts (Strong *et al.*, 2016; Strong *et al.*, 2015).

The CO_2 in the biogas can be captured and supplied to industry or biologically converted to methane (Bajón Fernández *et al.*, 2015) by using hydrogen. Other promising alternatives include accelerated carbonation using alkaline industrial residues (Costa *et al.*, 2007; Sanna *et al.*, 2014) for both carbon sequestration and waste stabilisation purposes, biological reduction of CO_2 to VFAs in microbial electrochemical systems (Batlle-Vilanova *et al.*, 2017), or cultivation of autotrophic microorganisms such as cyanobacteria or algae which could be further exploited to produce pigments, lipids, biodiesel, bio-fertilisers or bioplastics (Duppeti *et al.*, 2017; Venkata Mohan *et al.*, 2015).

The liquid fraction of digestate can be treated to recover nutrients. The recovered nutrients can be used as fertilisers, in novel applications as the use of ammonium for biogas upgrading (Bavarella *et al.*, 2019) or for further H_2 production via chemical cracking (Lamb *et al.*, 2019).

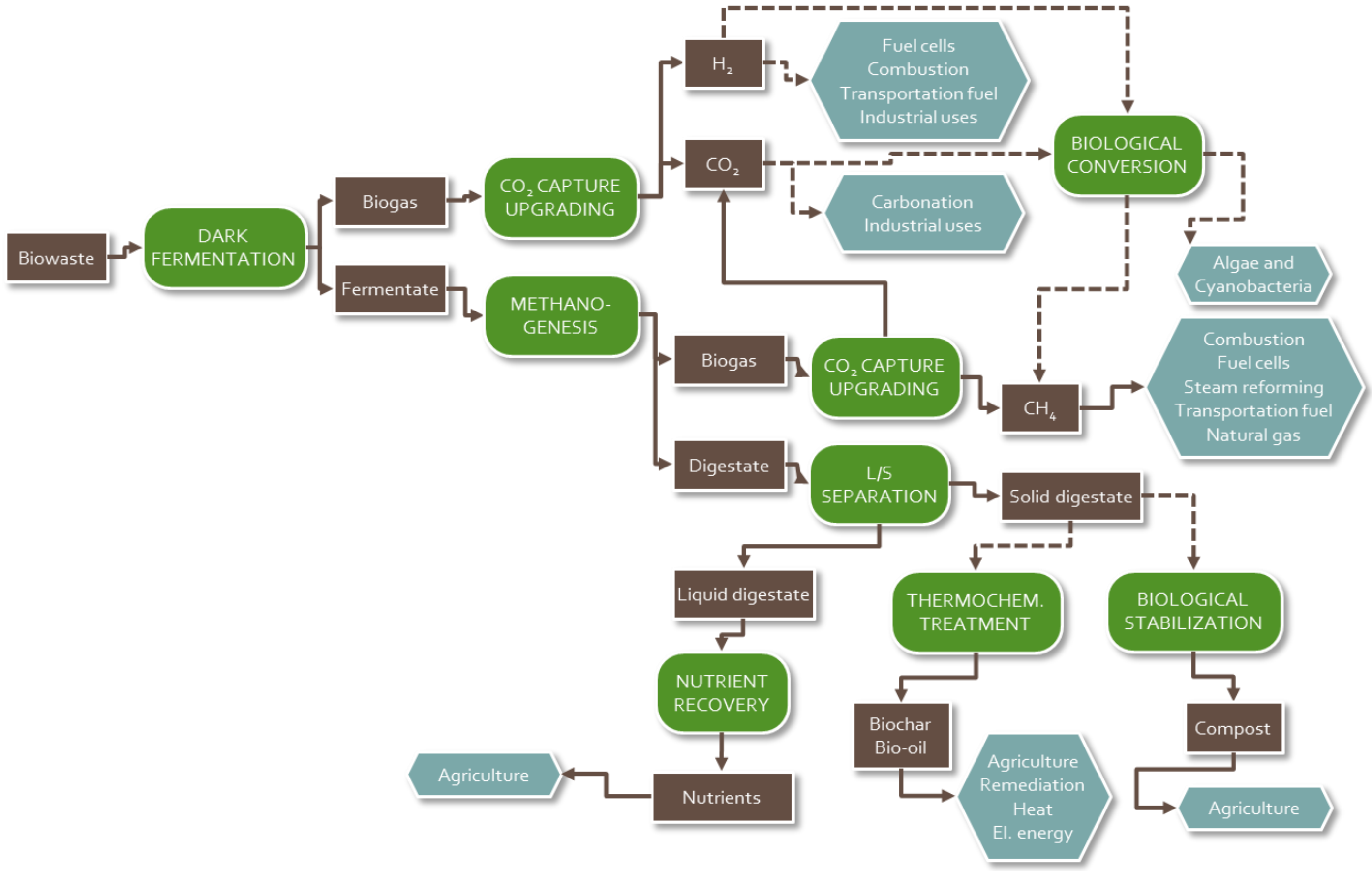

Figure 2. Simplified layout for an anaerobic waste biorefinery. Option 1: dark fermentation, methanogenesis, biogas (H_2, CO_2, CH_4) upgrading and digestate processing. Dashed lines represent

alternative options. Green blocks represent processes, brown blocks represent materials, light blue blocks represent final uses.

In option 2 (Figure 3) the dark fermentation stage is specifically oriented to VFA (with concomitant H_2 production) or bioethanol production and is therefore followed by a separation stage to fractionate and purify these compounds. Separation is the key challenge. The energy payback for alcohol is marginal if distillation is applied as a separation step. VFAs can also be directly extracted from the mixtures typically obtained via waste fermentation. Several technologies are commercially available for VFA purification from mixtures, including conventional (adsorption/desorption on ion exchange resins, liquid-liquid extraction), membrane-based (pertraction, nanofiltration) and electrochemical (electrodialysis) processes (Rebecchi *et al.*, 2016; Reyhanitash *et al.*, 2016; Outram and Zhang 2018; Xiong *et al.*, 2015; Jones *et al.*, 2017). However, none of them simultaneously allows high extraction efficiencies and selectivity at competitive price. Innovative separation methods for selective extraction of individual VFAs from mixtures are thus required to foster the economic sustainability of waste biorefineries. Methanogenesis can then be applied to the residual effluent resulting from the separation stage.

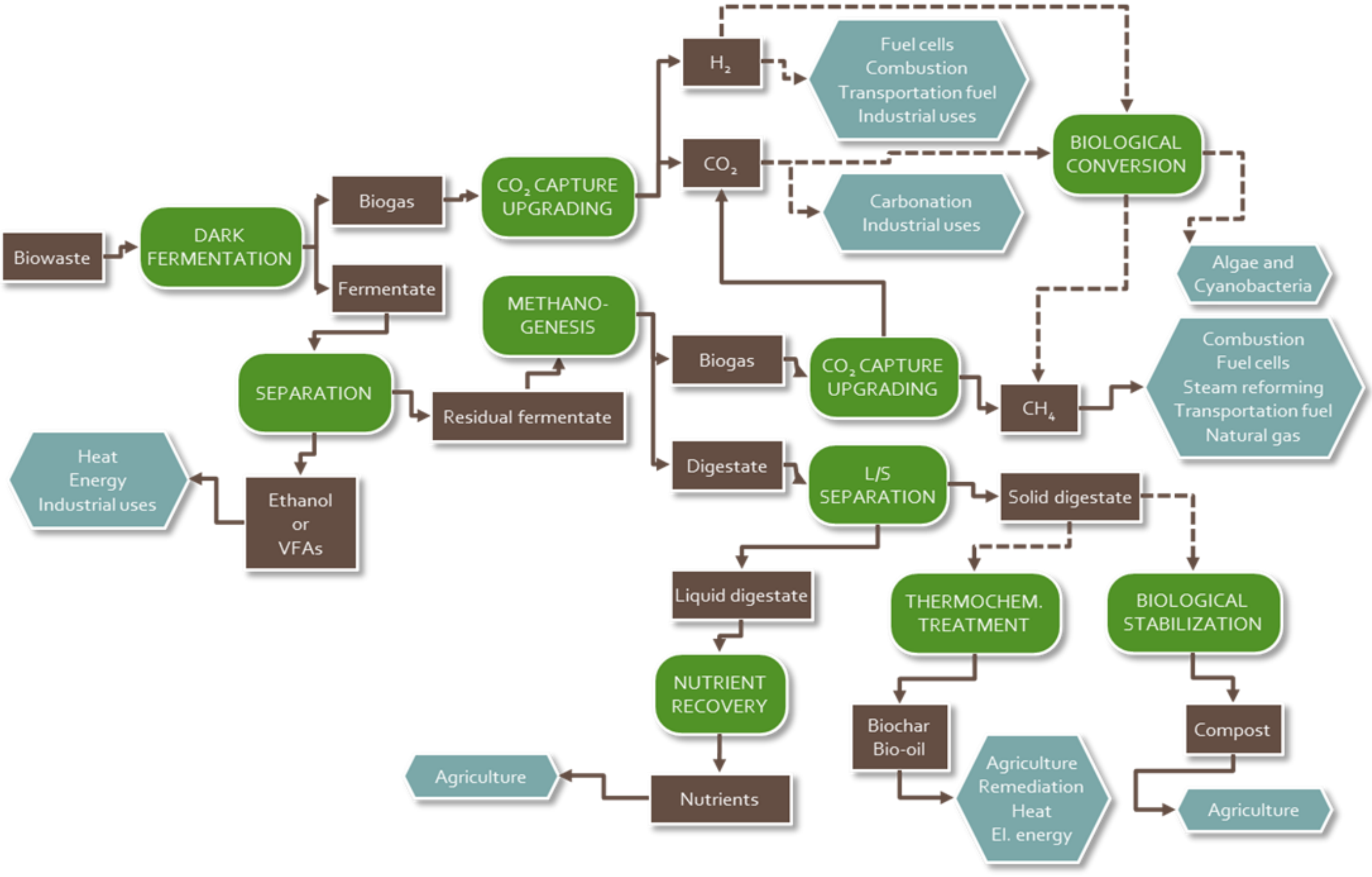

Figure 3. Simplified layout for an anaerobic waste biorefinery. Option 2: dark fermentation, ethanol/VFAs recovery, methanogenesis of the residual fermentate, biogas (H_2, CO_2, CH_4) upgrading and digestate processing. Dashed lines represent alternative options. Green blocks represent processes, brown blocks represent materials, light blue blocks represent final uses.

Option 3 (Figure 4) presents an integrated process in which H_2 becomes the main output of the biological treatment by coupling dark fermentation with photo-fermentation to enhance H_2 yields up to 7 mol H_2/mol glucose (Khetkorn *et al.*, 2017; Zhang *et al.*, 2017). In Option 4, (Figure 5), instead, the dark fermentation effluent, rich in VFAs, is further processed biologically to induce the accumulation of biopolymers (polyhydroxyalkanoates, PHA) within the bacterial cells, which are thereafter concentrated and extracted (Valentino *et al.*, 2017). Biopolymers can then be used in the bioplastic industry for a range of uses. Another potential alternative (Option 5; see Figure 6) involves coupling dark fermentation with an electrochemical process, that may be aimed at further H_2 production (through e.g. microbial electrolysis cells), or at electricity generation (through e.g. microbial fuel cells).

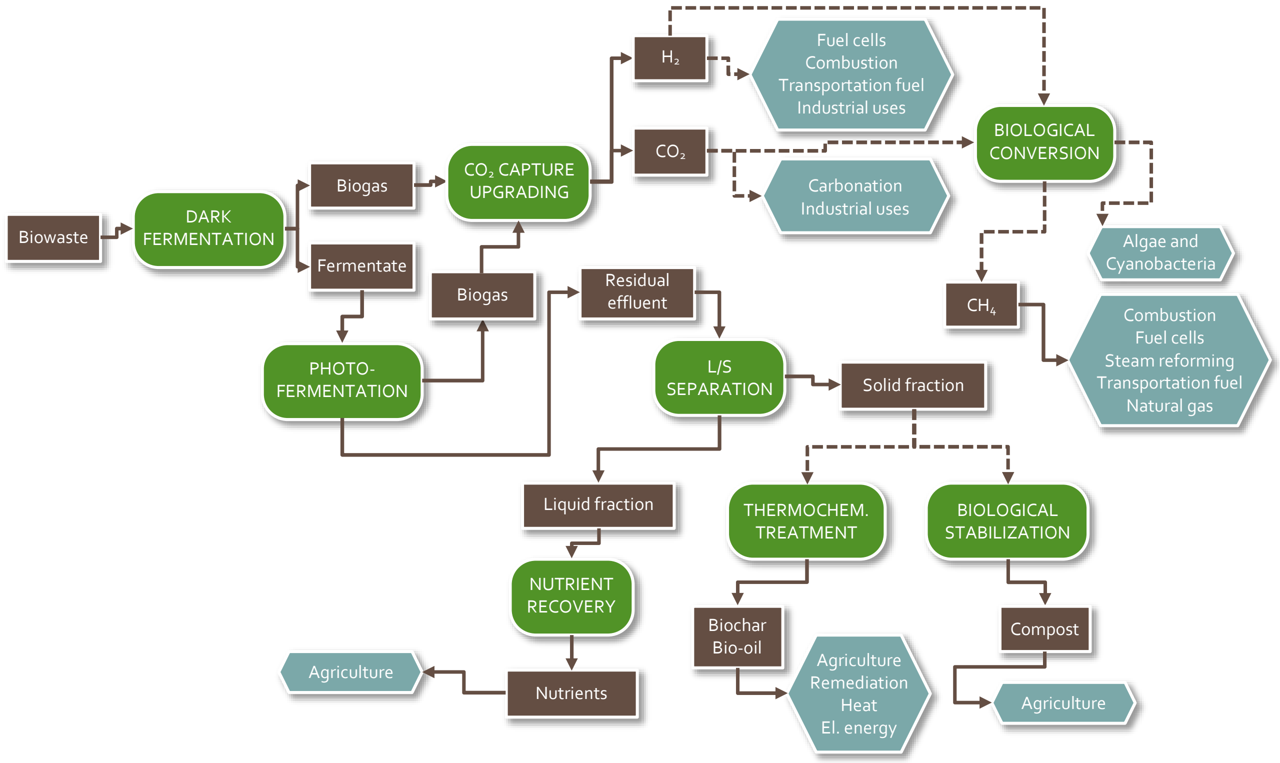

Figure 4. Simplified layout for an anaerobic waste biorefinery. Option 3: dark fermentation, photofermentation, biogas (H_2, CO_2) upgrading and digestate processing. Dashed lines represent alternative options. Green blocks represent processes, brown blocks represent materials, light blue blocks represent final uses.

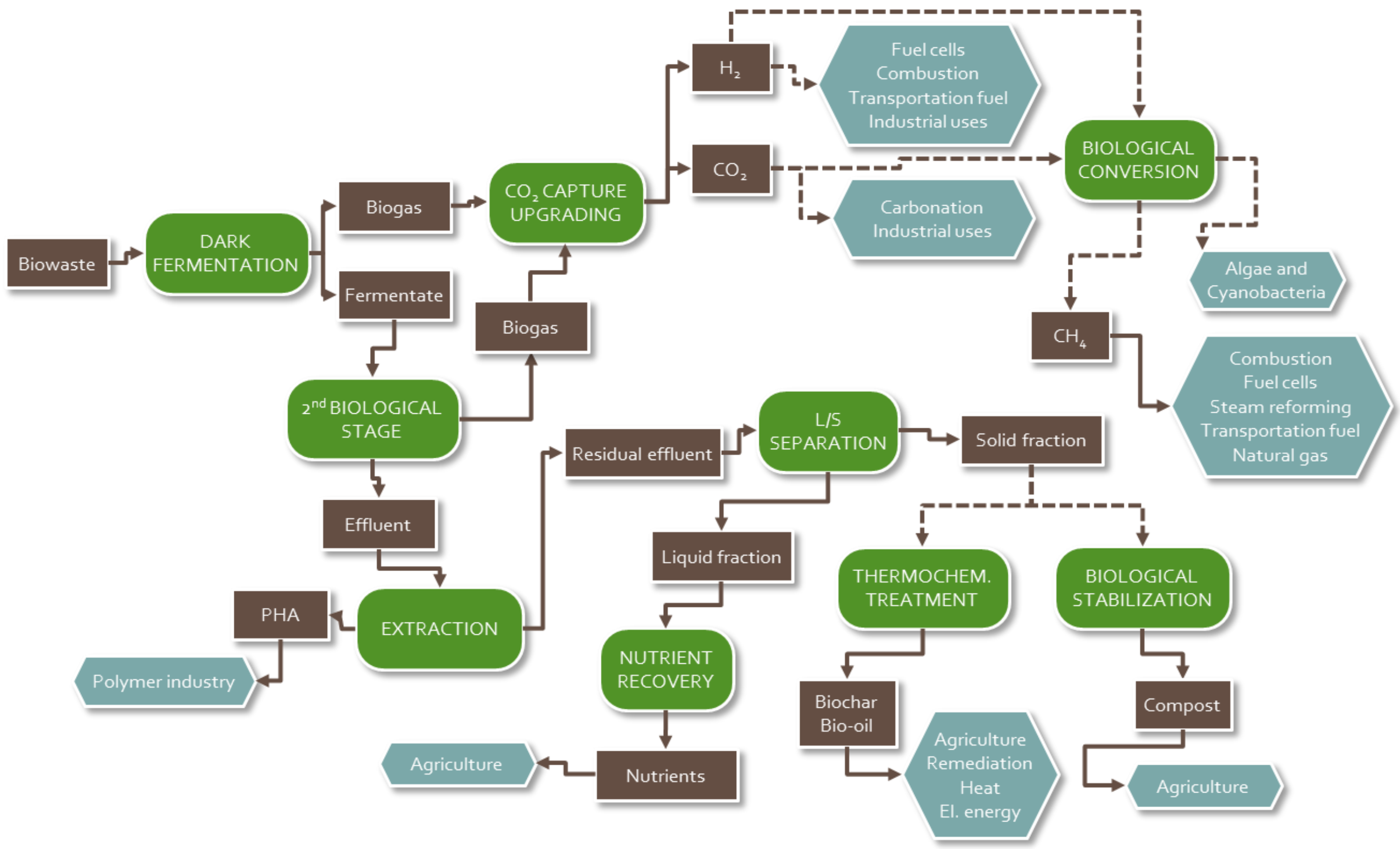

Figure 5. Simplified layout for an anaerobic waste biorefinery. Option 4: dark fermentation, biopolymer production, biogas (H_2, CO_2) upgrading and digestate processing. Dashed lines represent alternative options. Green blocks represent processes, brown blocks represent materials, light blue blocks represent final uses.

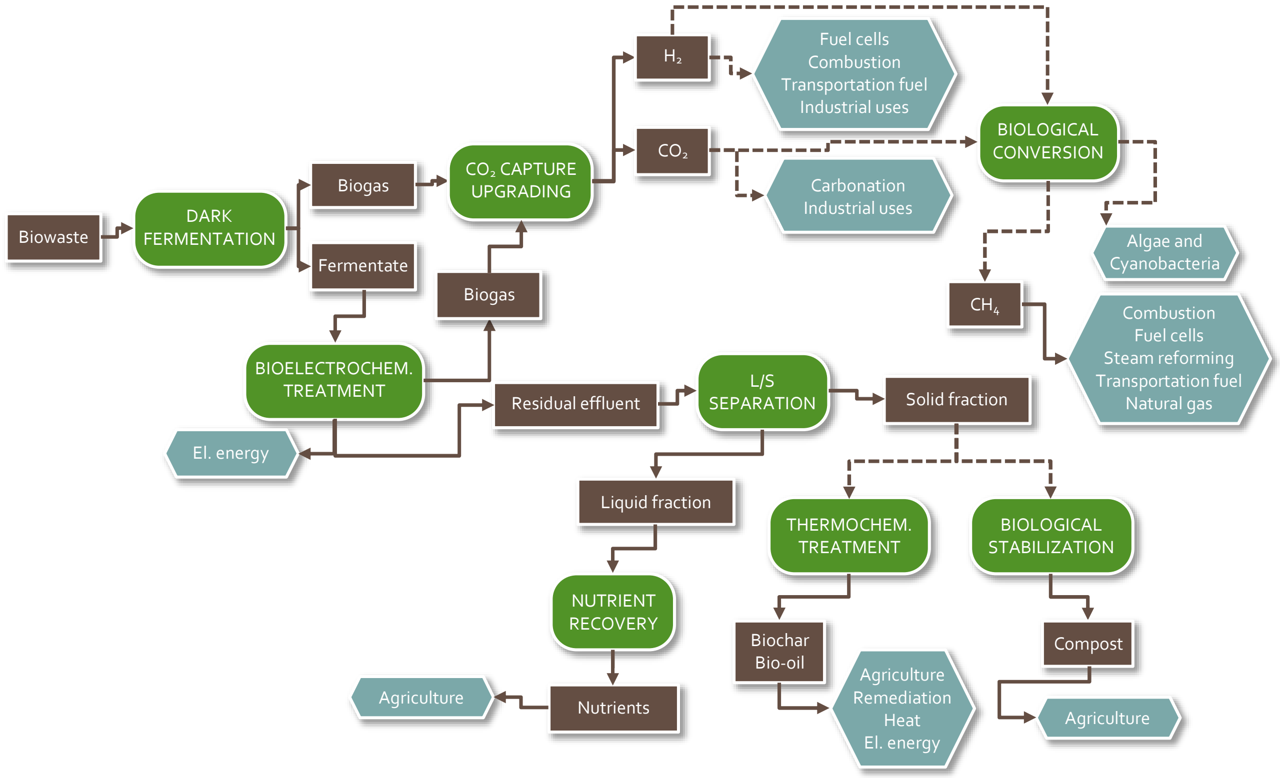

Figure 6. Simplified layout for an anaerobic waste biorefinery. Option 5: dark fermentation, electrochemical processing for enhanced H_2 production or electricity generation, biogas (H_2, CO_2) upgrading and digestate processing. Dashed lines represent alternative options. Green blocks represent processes, brown blocks represent materials, light blue blocks represent final uses.

4.3 Waste biorefinery output

A rough estimation of the potential outcomes of waste biorefineries can be derived from the observed ranges of bioproducts generation documented by literature studies. To this aim, H_2, CH_4, ethanol and PHAs were considered as examples among the several products presented in the biorefinery layouts described above thanks to a large availability of data. Since the reported yields are largely variable with respect to the specific characteristics of the waste treated, the type of conversion process applied and the operating conditions adopted, average values and deviations from literature data are shown in Figure 7.

On the basis of the reported market prices for each product of concern (Moscoviz *et al*., 2018), the following ranges for the economic value of the products that can be obtained from food waste (FW) in a biorefinery application were estimated: 0.24–15.5 €/t FW (average: 4.9) for H_2, 1.9–11.6 €/t FW (average: 7.3) for CH_4, 9.0–540 €/t FW (average: 229) for ethanol and 22–4500 €/t FW (average: 1510) for biopolymers. The revenues achievable from biowaste in a biorefinery would require deducting the capital and operating costs of the plant. Nonetheless, given the amount of food waste generated (in Europe, 46.5 and 41.1 Mt/y from municipal and industrial sources, respectively), as well as the incentives for the production of green chemicals and energy, considerable financial benefits are expected from the wide implementation of organic waste biorefineries.

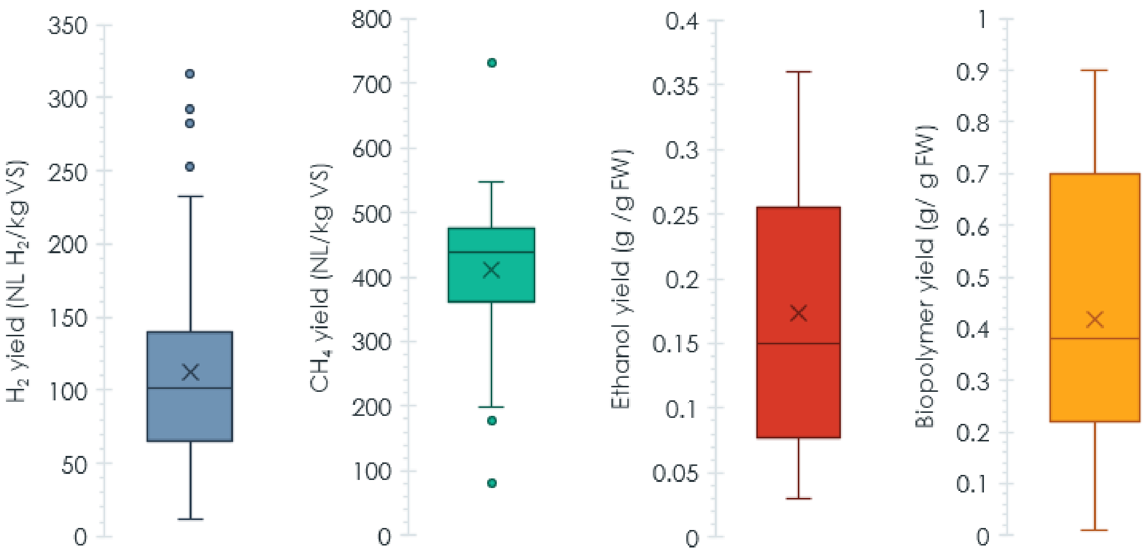

Figure 7. Yield ranges for H_2, CH_4, ethanol and biopolymers derived from literature references (Akhlaghi *et al.*, 2019; Braguglia *et al.*, 2018; Rodriguez-Perez *et al.*, 2018; Srisowmeya *et al.*, 2019; Tsang *et al.*, 2019; Uçkun Kiran *et al.*, 2014; Yadav *et al.*, 2020 and references therein). The cross and the line within the box show the average and median value, respectively, the box denotes the range of 50% of data, whiskers range from the lower to the higher value within 1.5 interquartile ranges and circles stand for outliers.

5. Conclusions and recommendations

The concept of organic waste biorefinery has the potential to open up a wide array of possibilities that may enable the waste management sector to improve the overall environmental, economic and social sustainability. Nevertheless, there are still numerous barriers and bottlenecks to overcome before the full implementation of biorefineries for waste management, which encompass environmental, technical, economic, social, logistic and legislative implications. From the technical standpoint, the waste biorefinery concept more and more requires that waste treatment is designed and operated industrially, with a high degree of technological development. To this aim, pre-treatments, bioreactors and downstream separation processes require development to produce bioproducts with consistent physical-chemical characteristics at feasible costs.

Measures are needed from the point of view of policy making to foster sustainable bio-based solutions for waste management. In this regard, suitable strategies should be defined to support the development of the industrial sector in this field by identifying priority streamlines, introducing systematic and comprehensive regulatory measures, involving potential stakeholders, setting technical standards for bioproducts and, where necessary, defining new incentive schemes. The identification of specific targets for bioproducts production, in accordance with the circular economy principles set in the EU action plan (European Commission, 2015), could drive industries to focus on priority streamlines and technological advancement. This could be further supported by economic incentives such as carbon trading, excises on fossil-based products and more direct forms of subsidies. Inevitably, the economy will increasingly rely on sustainable sources of materials and fuels as non-renewable stocks are depleted and fossil sources will have to remain in the ground. Exploration of the diversity of products than can be derived from waste will therefore become increasingly important.

ACKNOWLEDGEMENTS

This work was conducted in the framework of the activities of the "Waste Biorefinery" task group (for more information see https://www.tuhh.de/iue/iwwg/task-groups/waste-biorefinery.html), which is part of the International Waste Working Group (IWWG).

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