

1 **Organic waste biorefineries: looking towards implementation\***

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

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29

30 **Abstract**

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

49

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

52

53 **1. Introduction**

54 Organic waste treatment has traditionally been based on layouts involving a single bioprocess such  
55 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; Giroto *et al.*,

82 2015; Diacono and Montemurro, 2010). This has moved the frontiers of organic waste management  
83 towards more ambitious and articulated targets that may be fulfilled by the implementation of the  
84 waste biorefinery concept.

85 A number of definitions exists for biorefinery (Schieb *et al.*, 2015) but in essence all refer to a  
86 series of processes converting biomass into chemicals, material and fuels (Schieb *et al.*, 2015;  
87 Dubois, 2012; Cherubini *et al.*, 2009). An organic waste biorefinery can therefore be an evolution  
88 of the biorefinery notion to include waste as an alternative to dedicated biomass or to introduce a  
89 management practice enhancing the recovery of value from organic waste. The concept has raised  
90 great interest in the last years as technologies to recover value from waste feedstocks have been  
91 improved ensuring its environmental and economic sustainability (Cristóbal *et al.*, 2018; Go *et al.*,  
92 2019). The range of products from a biorefinery receiving organic waste may be limited by the  
93 variability of the waste stream, but organic waste can also be homogeneous waste such as  
94 agroindustrial by-products or surplus materials which can be as defined as dedicated crops (Caldeira  
95 *et al.*, 2020). In this paper, the terms organic waste or waste feedstock were used in the broadest  
96 sense to include any biogenic waste, effluent, by-product and production surplus (Fava *et al.*, 2015;  
97 Coma *et al.*, 2017).

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

101

## 102 **2. Scope and boundary conditions for organic waste biorefineries**

103 The purpose of waste biorefineries is to exploit the potential of organic residues from different  
104 sources to generate a range of bioenergy, biofuel and biochemical products (Cherubini *et al.*, 2010).

105 Waste biorefineries offer platforms for integrated utilisation of a wide range of resources in organic  
106 waste. The development and implementation of the waste biorefinery concept offer a range of  
107 economic, environmental, social and political benefits:

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

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

120

### 121 *2.1. Underlying principles of waste biorefineries*

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

134 the variability, heterogeneity and low purity of waste materials as opposed to dedicated biomasses  
135 (Duan *et al.*, 2020; Ubando *et al.*, 2020; Sadhukhan and Martinez-Hernandez, 2017).

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

139

## 140 *2.2. Technical and economic sustainability*

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

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

157 Organic wastes represent a plurality of substrates having different characteristics and whose  
158 availability changes significantly over time. In general, post-consumer organic waste is  
159 heterogeneous but less affected by seasonal availability, while waste at the food processing stage is

160 more homogeneous but affected by seasonality (Cristóbal *et al.*, 2018). Differences in origin and  
161 characteristics as well as seasonality drive production strategies, design, operation, and logistic  
162 choices for a biorefinery.

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

169 Transportation of the waste feedstocks to the biorefinery is another main logistic issue. Whilst more  
170 attention is usually given to the choice of the value recovery processes, the feasibility analysis  
171 should include also the management of the supply-chain (Caldeira *et al.*, 2020). Matching  
172 generation points and biorefinery location is a key factor that affects the viability of a biorefinery.

173 In this respect Cristóbal *et al.* (2018) considered two diametrically opposite scenarios while  
174 performing a techno-economic and profitability analysis of four food waste biorefineries for tomato,  
175 potato, orange, and olive processing waste. Fewer large biorefinery plants co-located with the food  
176 processing plants would be effective for processing wastes from harvested goods, but would not  
177 represent the optimum transport solution for harvesting wastes and rejects, while, a strategy based  
178 on numerous smaller plants would minimise the transport costs for these in-farm wastes. The  
179 analysis stressed that few large plants would be the most profitable scenario as this allows for  
180 concentrated production, takes advantage of economies of scale, and simplifies transport logistics  
181 (Cristóbal *et al.*, 2018). An economic analysis on a biorefinery treating citrus waste for the recovery  
182 of limonene, ethanol and biogas was performed by Lohrasbi *et al.* (2010). The ethanol production  
183 cost proved to be sensitive to the feedstock transportation costs. Increasing the transport cost from  
184 approximately 9 to 27 €/ton resulted in ethanol cost rising from 0.8 to 1.3 €/L, a feature reported  
185 also by Satari and Karimi (2018). The economic feasibility of biorefineries for food processing

186 waste is enhanced if the bio-refinery is co-located with the food processing plant, eliminating  
187 transport as a cost for the biorefinery (Caldeira *et al.*, 2020).

188

### 189 2.3. Environmental sustainability

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



211 Life cycle assessment (LCA) offers a systematic framework for evaluating the environmental  
212 consequences of waste management technologies and systems (e.g. ISO, 2006) with respect to a  
213 range of selected impact categories, such as climate change, resource depletion, eutrophication, and  
214 toxicity effects. Relatively few consistent LCA studies have been carried out with a focus on  
215 organic waste biorefineries, although a wider range of studies have addressed individual  
216 components such as anaerobic digestion and composting (e.g. Boldrin *et al.*, 2011; Eriksson *et al.*,  
217 2005), fuel production (e.g. Venkata Mohan *et al.*, 2016) and incineration (e.g. Astrup *et al.*, 2015).  
218 Most of the LCA studies in literature focusing on integrated biorefinery systems have evaluated  
219 combinations of traditional waste technologies, such as material recovery facilities, anaerobic  
220 digestion, pulping and incineration, with the recovery of specific biofuels or biochemicals (e.g.  
221 Tonini *et al.*, 2013; Sadhukhan and Martinez-Hernandez, 2017; Nizami *et al.*, 2017; Chen *et al.*,  
222 2017; Moretti *et al.*, 2017). As such, generic conclusions regarding the specific sustainability of  
223 organic waste biorefineries may be difficult to draw from existing literature due to variations in  
224 conditions and assessment approaches. However, biorefineries based on organic waste from  
225 households offer larger climate benefits compared to biorefineries that process industrial food  
226 industry (Tonini *et al.*, 2016).

227 Two different LCA perspectives may be applied when evaluating the environmental sustainability  
228 of organic waste biorefineries: (i) a “waste management perspective” focusing on comparing the  
229 waste biorefinery with other (traditional) waste management options such as composting or  
230 landfilling, or (ii) an “output perspective” focusing on comparing one or more waste biorefinery  
231 products with alternative (traditional) production options. The alternative management options are  
232 important in both of these perspectives: if the waste was otherwise landfilled, the environmental  
233 benefits of waste utilisation in a biorefinery may be significantly larger than if the alternative  
234 management was anaerobic digestion or energy recovery via incineration (Astrup *et al.*, 2015). This  
235 also relates to indirect effects, such as land-use-changes when crop markets are affected, *e.g.*  
236 organic waste fractions previously upgraded to animal feed products and now used as feedstock in

237 biorefineries with different target outputs. In this case, the environmental impacts associated with  
238 the animal feed products need to be accounted as well. As waste biorefineries are multi-output  
239 technologies per definition, the environmental consequences associated with all outputs should be  
240 considered.

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

252

#### 253 *2.4 Market potential*

254 The use of organic waste as a feedstock for biorefineries can be the nexus between environmental  
255 protection, bio-economy and circular economy promoted by EU policies (European Commission,  
256 2015). In particular, waste biorefineries could potentially exploit the untapped potential stored in  
257 approximately 130-151 million tonnes/year of biowaste estimated to be generated in the EU by  
258 2020 (European Commission, 2011). The latest data published by Eurostat (Eurostat, 2020) indicate  
259 an actual total (municipal + industrial) production potential of about 230 million tonnes/year of  
260 organic waste for EU28 in 2016, composed of ca. 42% of animal and vegetable waste, 26% of the  
261 organic fraction of municipal solid waste, 20% of wood waste and 9% of non-hazardous sludge  
262 from sewage treatment plants or food processing plants.

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

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

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

285

### 286 **3. Implementation of waste biorefinery systems**

#### 287 *3.1 From traditional biorefineries to waste biorefineries*

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

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

305

### 306 *3.2 Production strategies in waste biorefineries*

307 The simplest layouts of a waste biorefinery are those aimed at recovering low-added-value  
308 products, i.e. biofuels or energy carriers, soil improvers and fertilisers. A higher complexity is  
309 required to generate pure streams of platform chemicals for the production of biomaterials, where  
310 more specific technical standards must be met. The feasibility of a complex biorefinery with high-  
311 value outputs is linked to the availability and type of feeding residues, the market conditions and  
312 demand for these products and the possibility for a waste biorefinery to be integrated within the  
313 existing industrial system (Shahzad *et al.*, 2017). Indeed, some organic waste streams contain

314 appreciable quantities of substances whose value may be as high as 12,000 €/g, e.g. biophenols such  
315 as hydroxytyrosol and tyrosol (Tinikul *et al.*, 2018), or are suitable for conversion into profitable  
316 molecules and pivotal building blocks, e.g. lactic acid, acetic acid and ethanol (Moretto *et al.*, 2019;  
317 den Boer *et al.*, 2016). While biorefineries earn revenues from the sale of products, waste  
318 biorefineries can also earn income from gate fees. Gate fees strongly depend on the territorial  
319 context, the balance between demand and offer for waste treatment and local regulations. In an  
320 initial stage, gate fees can contribute to assuring a stable income for a waste management company  
321 to de-risk the uncertainties of a non-mature market for biofuels or bioproducts. In the long-term, the  
322 generation of high-value products might increase the profitability, allowing for reducing or even  
323 eliminating waste gate fees (Sadhukhan *et al.*, 2018).

324 It is generally acknowledged that, in order to generate high-value outputs and ensure environmental  
325 sustainability (what is commonly referred to as a second-generation biorefinery), the process should  
326 be arranged to comprise two or more platforms (Budzianowski and Postawa, 2016; Naik *et al.*,  
327 2010). According to the definition introduced by Task 42 of the IEA (IEA Bioenergy, 2012),  
328 analogous to the petrochemical industry, platforms are intermediates linking feedstocks and final  
329 products. The combined production of multiple platforms would ensure an optimised recovery of  
330 individual precursors from the feedstock. For instance, in order to make the selling price of biofuels  
331 competitive with that of fossil fuels, it is necessary to combine biofuel production with bioproducts  
332 that have high value and a sufficiently large market. In turn, producing multiple platforms requires  
333 the integration of a range of different treatment processes, the nature of which is a function of the  
334 characteristics of both the feeding waste to be exploited and the final products. Furthermore,  
335 adequate fractionation of individual waste components may be necessary to generate an array of  
336 outputs of different characteristics. To this regard, the selectivity, accuracy and yield of separation  
337 play a key role in view of full implementation of multi-platform biorefineries.

338

339 *3.3 Size-dependent waste biorefinery approaches*

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

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

362 Small scale biorefineries involve less complex treatment layouts with lower capital and operating  
363 costs, due to a reduced number of platforms and a smaller range of end products. Decentralised  
364 dedicated medium- to small-scale plants will use a reduced number of feedstocks, which are  
365 expected to be available at the local scale. At the same time, decentralised installations allow the

366 generated biofuels and biomolecules being tailored to the existing context, promoting close  
367 integration with other local industries in view of the circulation of materials and energy. The  
368 technological complexity and the industrial know-how of waste biorefineries is less developed than  
369 highly specialised chemical processing installations. It therefore appears more reliable, at least from  
370 a short-term development perspective, to conceive a waste biorefinery as a system producing  
371 intermediates, precursors or building blocks, which are then further processed beyond the  
372 boundaries of the biorefinery.

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

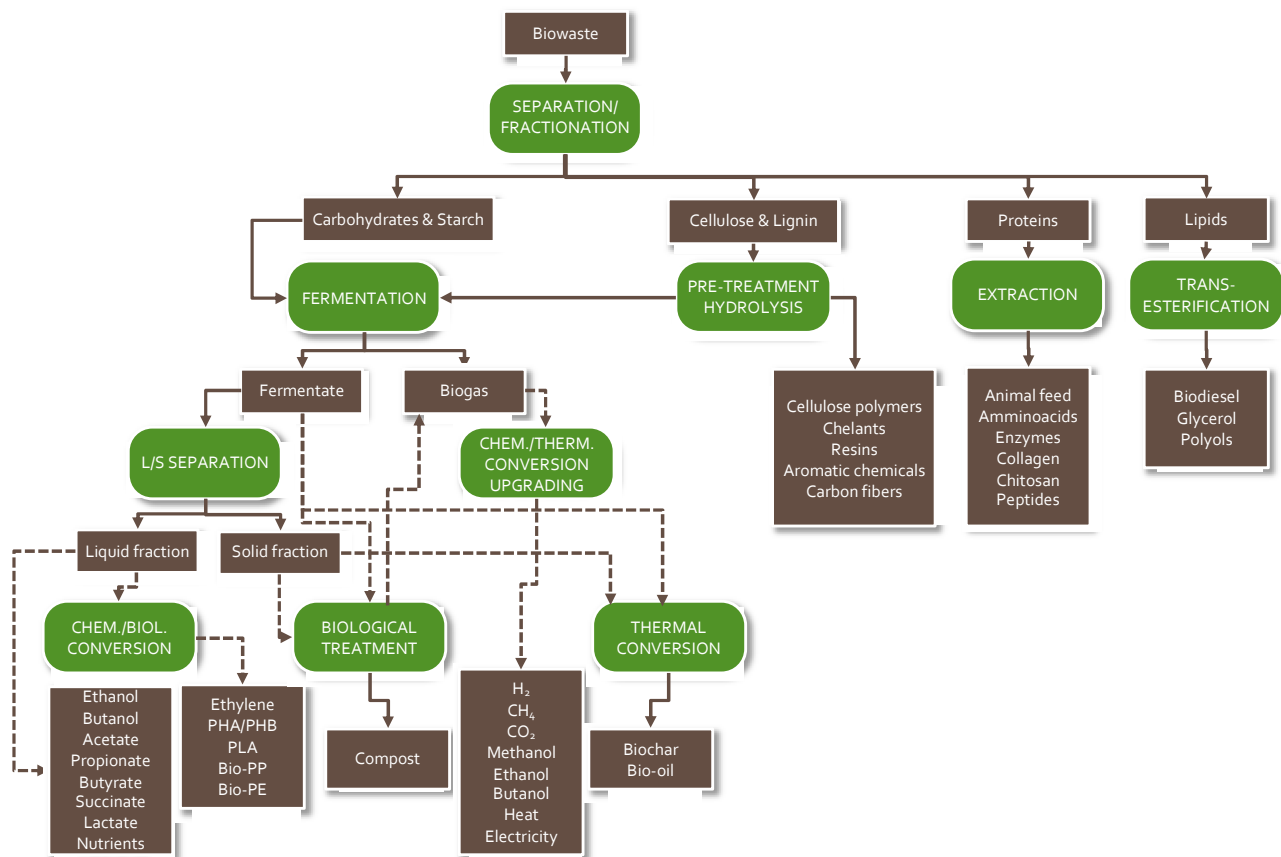
384

## 385 **4. Waste biorefinery configurations**

### 386 *4.1 Multi-platform waste biorefineries*

387 As shown in Section 3, a unique layout of the most suitable processes to be included in an organic  
388 waste biorefinery cannot be defined. The possible options on hand are related to the quantity and  
389 characteristics of the waste, the specific local conditions and constraints, market trends and  
390 legislative constraints. Nonetheless, in the authors' view, anaerobic digestion, being a well-  
391 established biological process currently adopted for complex and heterogeneous waste at large

392 scales, is regarded as a suitable candidate to play a central role in biorefinery schemes in the near  
 393 future. Stemming from this, a potential process layout for a multi-platform, multi-product  
 394 biorefinery integrating anaerobic digestion with other chemical, biochemical and thermochemical  
 395 treatment units is presented in Figure 1. The proposed layout includes an initial separation of the  
 396 individual components of the waste feed (carbohydrates, starch, cellulose, lignin, proteins and  
 397 lipids), followed by dedicated treatments of each component to maximise the yield of biofuels and  
 398 biomolecules recovery (Asunis *et al.*, 2019; Girotto and Cossu, 2019; Alibardi and Cossu, 2016).  
 399 The nature of the separation processes relies inherently on the composition and characteristics of  
 400 the input waste, and may involve processes such as washing and extraction (Ao *et al.*, 2020;  
 401 Matharu *et al.*, 2016), use of enzymes (Arbige *et al.*, 2019; Escamilla-Alvarado *et al.*, 2017) and  
 402 solid-liquid or membrane separation processes (Abels *et al.*, 2013; Huang *et al.*, 2008). Waste  
 403 fractionation by main chemical components enables parallel processing lines with a reliable supply  
 404 with predictable composition, e.g. high carbohydrate-rich agro-food waste, protein-rich  
 405 slaughterhouse waste, fat, oil and grease (FOG) waste from grease traps.



406



407 **Figure 1.** Layout for a multi-platform anaerobic biorefinery producing biofuels and biomolecules.

408 Dashed lines represent alternative options. Green blocks represent processes and brown blocks

409 represent materials.

410

411 The list of potential products presented in Figure 1 is not exhaustive, since further processing of

412 intermediates and precursors may lead to additional products not specifically considered in the

413 layout provided. Furthermore, in some cases (dashed lines in Figure 1), the bioproducts included in

414 the proposed layout are considered alternative to each other, so that the individual treatment stages

415 can be tailored towards the desired end products depending on the specific needs.

416 Full implementation of a multi-platform, multi-product scheme such as the one depicted in Figure 1

417 implies overcoming the bottlenecks associated with conversion processes from low-purity,

418 heterogeneous materials such as organic residues. As a result, a transition period is unavoidable

419 prior to the full development of the whole process chain. During the transition period, in the initial

420 implementation stages the biorefinery concept can be applied and developed by adopting simplified

421 configurations based on technologies that have already been developed and demonstrated at the full

422 scale, to reduce uncertainties on process performance. This is meant to form a processing platform

423 basis whose complexity can be progressively increased as soon as other, more advanced options

424 become available for implementation. Such configurations can step up in the longer term into an

425 integrated high-performance scheme. In this regard, a number of simplified layouts representing

426 treatment trains with a short- to medium-term application horizon can be defined, which are deemed

427 to have the potential of being more easily implemented within the waste management sector.

428

#### 429 *4.2 The role of dark fermentation in waste biorefineries*

430 Potential simplified waste biorefineries models, with dark fermentation (production of H<sub>2</sub>-based

431 biogas and volatile fatty acids (VFAs) or alcohols) as the common initial stage followed by

432 different treatment options depending on the target products, are outlined in Figures 2-6. Dark

433 fermentation is the biohydrogen production option with the highest readiness for full-scale  
434 implementation (Lin *et al.*, 2018; Chandrasekhar *et al.*, 2015; Poggi Varaldo *et al.*, 2014). The  
435 relatively short retention time of dark fermentation implies small reactors that can be easily  
436 retrofitted into existing single-stage digestion plants even with limited space availability.

437 Regardless of whether H<sub>2</sub> is the targeted product, fermentation is central to processing carbohydrate  
438 streams. Protein and lipid-rich waste streams could also be directed through a fermenter if the  
439 competing routes and products shown in Figure 1 are not economically viable.

440 The layouts proposed in Figures 2-6 indicate the main (and most readily applicable) technological  
441 processes to maximise recovery of valuable products from the outflow of each stream, as well as the  
442 potential interconnections between treatment outflows. Dark fermentation plays the role of upfront  
443 treatment aimed at hydrolysing the complex starting waste materials, producing H<sub>2</sub> and providing  
444 simpler soluble compounds for downstream processes (De Gioannis *et al.*, 2013). More specifically,  
445 Option 1 (Figure 2) includes the following treatment stages: dark fermentation with H<sub>2</sub> production;  
446 a second methanogenic stage for CH<sub>4</sub> production; biogas treatment and upgrading to separate H<sub>2</sub>,  
447 CO<sub>2</sub> and CH<sub>4</sub> for subsequent uses; liquid/solid separation of the digestate; biological stabilisation of  
448 the solid fraction of digestate to produce compost (or, alternatively, thermochemical treatment to  
449 produce either biochar or pyrolytic oil); and nutrient recovery from the liquid fraction of digestate.

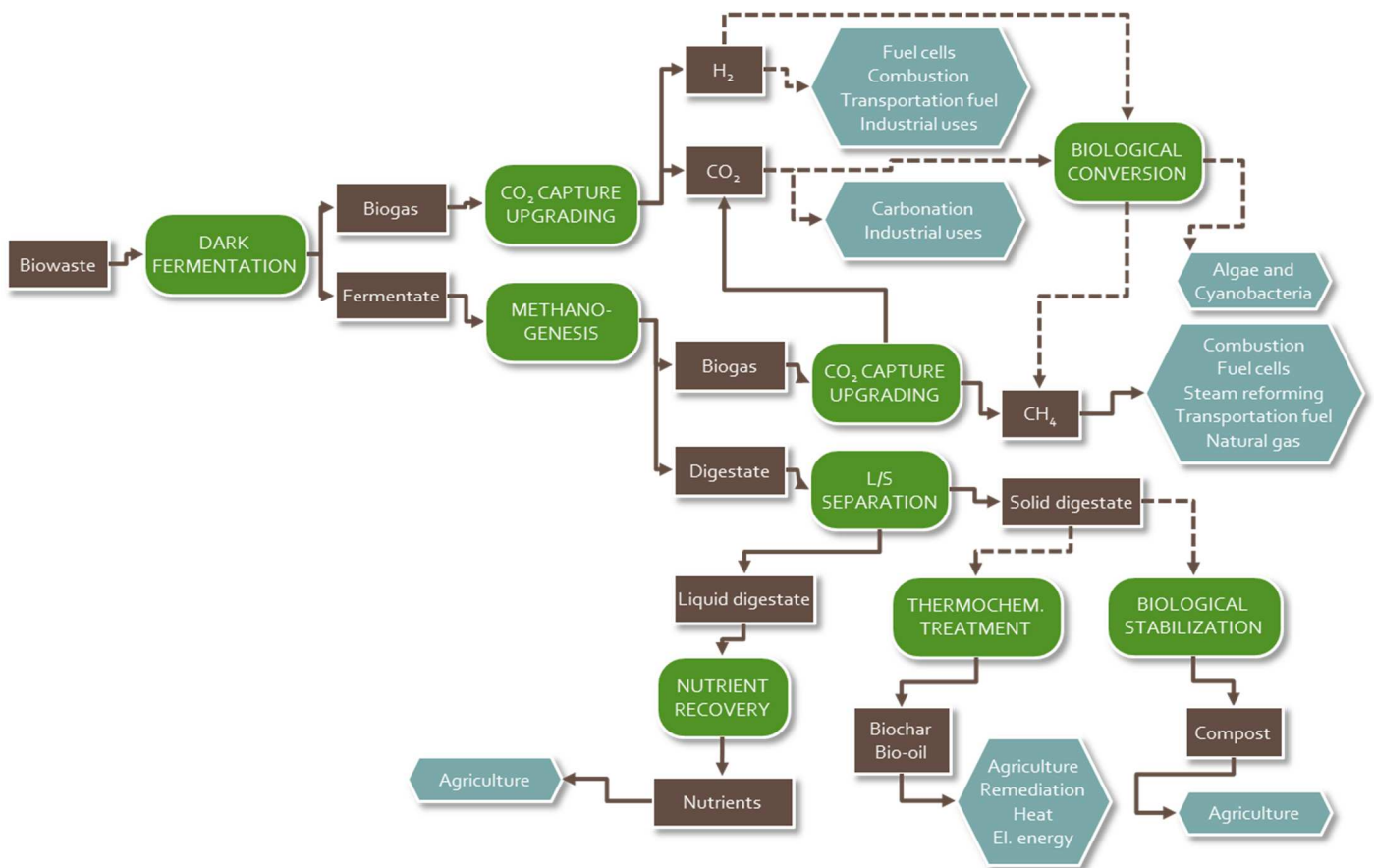
450 This represents the simplest and readily applicable waste biorefinery scheme that can benefit from  
451 the strong incentives that exist in several European countries to produce biomethane (Lombardi and  
452 Francini, 2020). The gaseous products (biohydrogen and biomethane) may then be used  
453 individually or as a mixture (hythane). Biomethane can also be used as a feedstock to more  
454 advanced processes, producing single-cell proteins or other high-value bioproducts (Strong *et al.*,  
455 2016; Strong *et al.*, 2015).

456 The CO<sub>2</sub> in the biogas can be captured and supplied to industry or biologically converted to  
457 methane (Bajón Fernández *et al.*, 2015) by using hydrogen. Other promising alternatives include  
458 accelerated carbonation using alkaline industrial residues (Costa *et al.*, 2007; Sanna *et al.*, 2014) for

459 both carbon sequestration and waste stabilisation purposes, biological reduction of CO<sub>2</sub> to VFAs in  
 460 microbial electrochemical systems (Batlle-Vilanova *et al.*, 2017), or cultivation of autotrophic  
 461 microorganisms such as cyanobacteria or algae which could be further exploited to produce  
 462 pigments, lipids, biodiesel, bio-fertilisers or bioplastics (Duppeta *et al.*, 2017; Venkata Mohan *et al.*,  
 463 2015).

464 The liquid fraction of digestate can be treated to recover nutrients. The recovered nutrients can be  
 465 used as fertilisers, in novel applications as the use of ammonium for biogas upgrading (Bavarella *et*  
 466 *al.*, 2019) or for further H<sub>2</sub> production via chemical cracking (Lamb *et al.*, 2019).

467



468

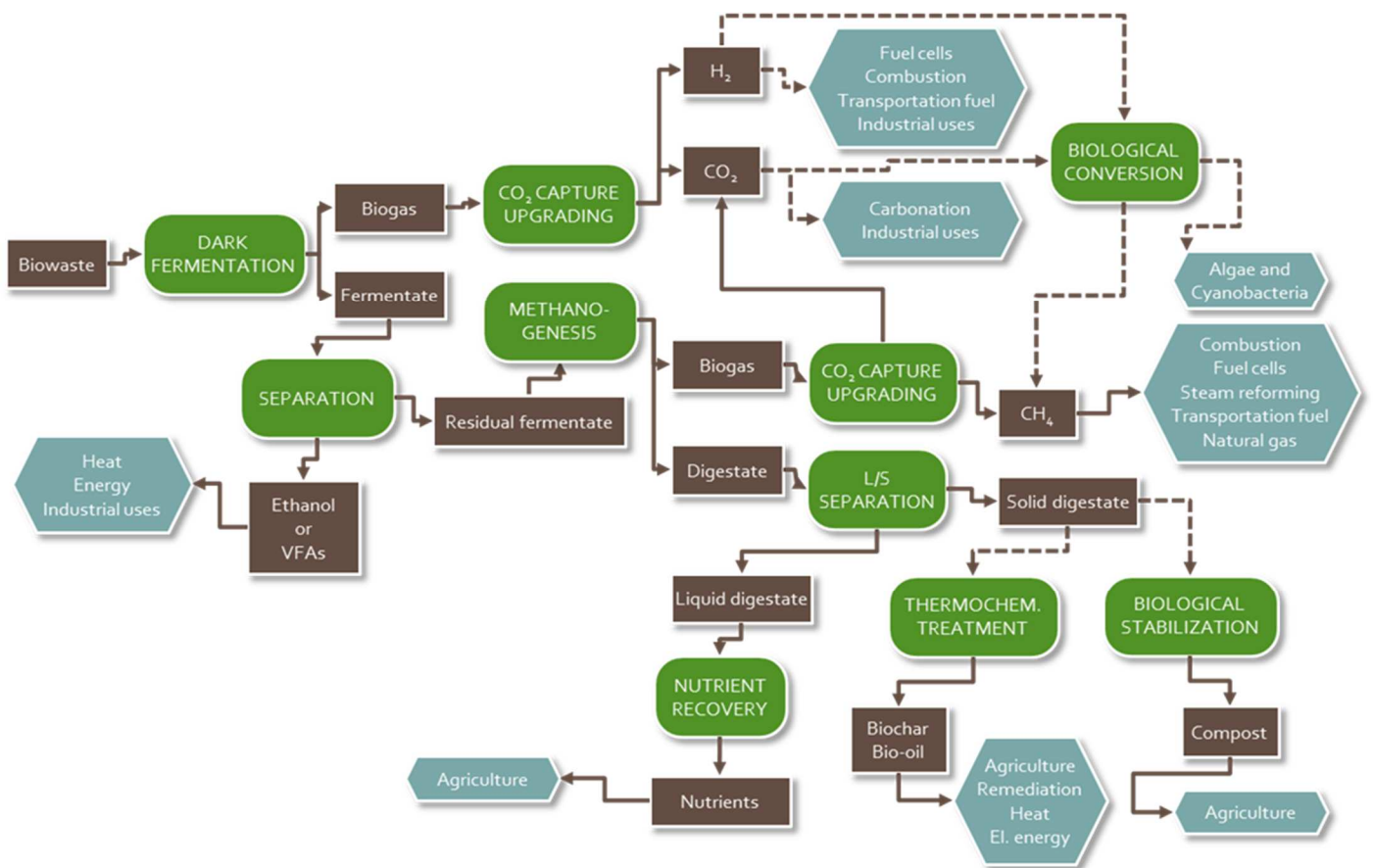
469

470 **Figure 2.** Simplified layout for an anaerobic waste biorefinery. Option 1: dark fermentation,  
 471 methanogenesis, biogas (H<sub>2</sub>, CO<sub>2</sub>, CH<sub>4</sub>) upgrading and digestate processing. Dashed lines represent

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

474

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



488

489 **Figure 3.** Simplified layout for an anaerobic waste biorefinery. Option 2: dark fermentation,  
 490 ethanol/VFAs recovery, methanogenesis of the residual fermentate, biogas (H<sub>2</sub>, CO<sub>2</sub>, CH<sub>4</sub>)  
 491 upgrading and digestate processing. Dashed lines represent alternative options. Green blocks  
 492 represent processes, brown blocks represent materials, light blue blocks represent final uses.

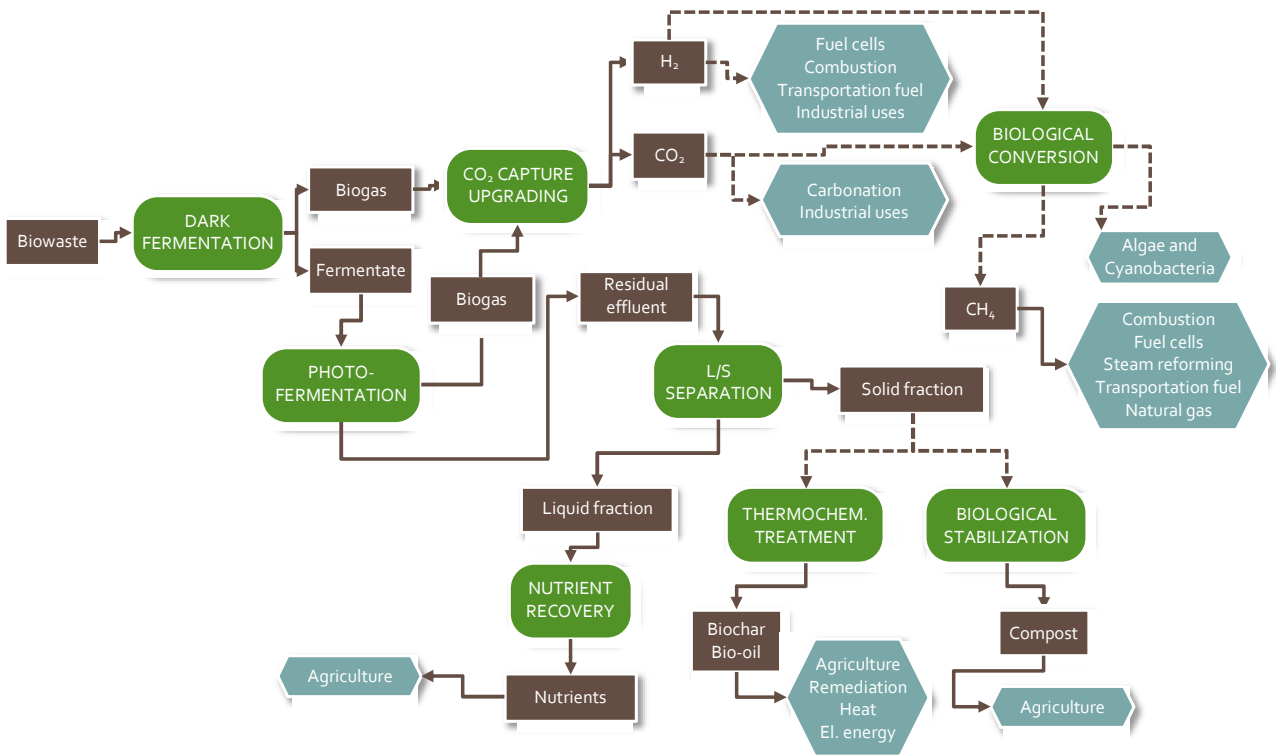
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494

495 Option 3 (Figure 4) presents an integrated process in which H<sub>2</sub> becomes the main output of the  
 496 biological treatment by coupling dark fermentation with photo-fermentation to enhance H<sub>2</sub> yields  
 497 up to 7 mol H<sub>2</sub>/mol glucose (Khetkorn *et al.*, 2017; Zhang *et al.*, 2017). In Option 4, (Figure 5),  
 498 instead, the dark fermentation effluent, rich in VFAs, is further processed biologically to induce the  
 499 accumulation of biopolymers (polyhydroxyalkanoates, PHA) within the bacterial cells, which are  
 500 thereafter concentrated and extracted (Valentino *et al.*, 2017). Biopolymers can then be used in the  
 501 bioplastic industry for a range of uses. Another potential alternative (Option 5; see Figure 6)

502 involves coupling dark fermentation with an electrochemical process, that may be aimed at further  
 503 H<sub>2</sub> production (through e.g. microbial electrolysis cells), or at electricity generation (through e.g.  
 504 microbial fuel cells).

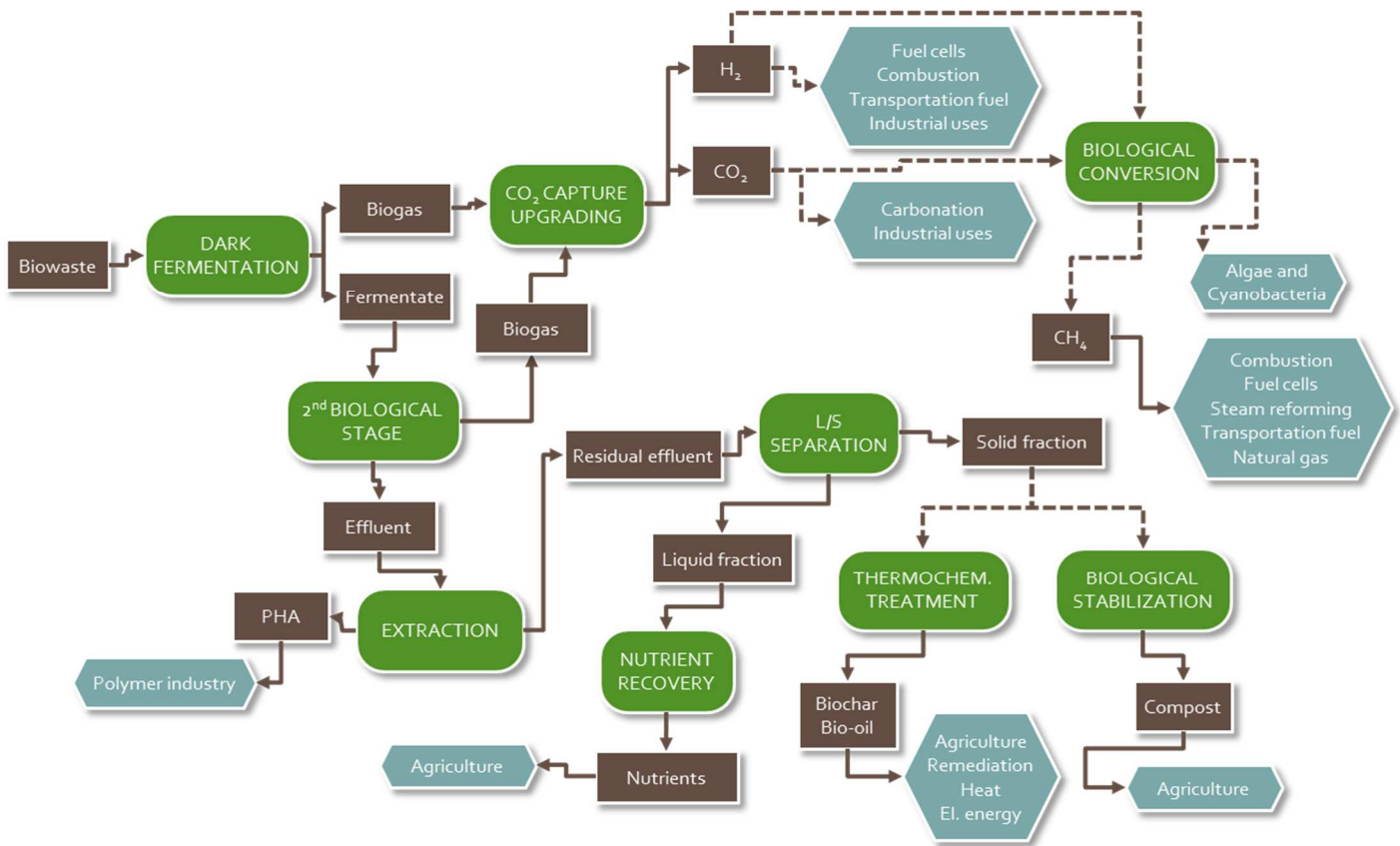
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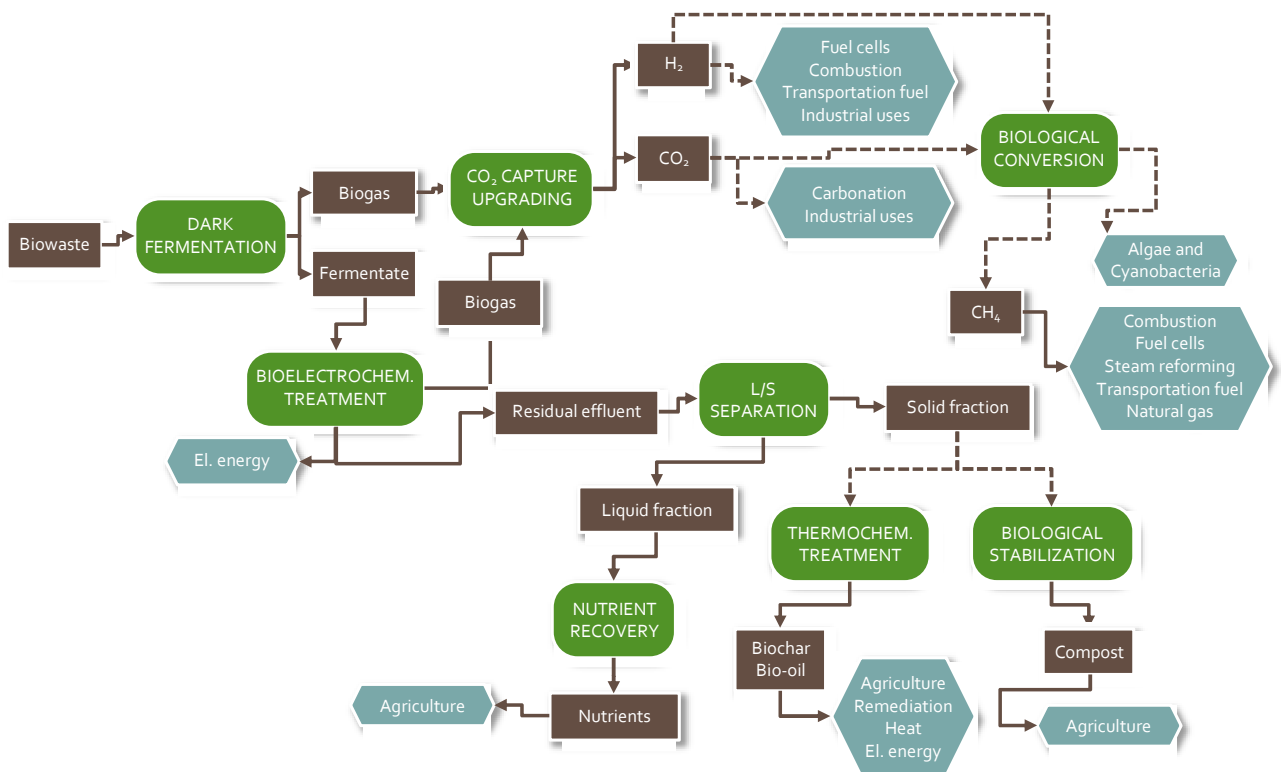
507

508 **Figure 4.** Simplified layout for an anaerobic waste biorefinery. Option 3: dark fermentation,  
 509 photofermentation, biogas (H<sub>2</sub>, CO<sub>2</sub>) upgrading and digestate processing. Dashed lines represent  
 510 alternative options. Green blocks represent processes, brown blocks represent materials, light blue  
 511 blocks represent final uses.



512

513 **Figure 5.** Simplified layout for an anaerobic waste biorefinery. Option 4: dark fermentation,  
 514 biopolymer production, biogas (H<sub>2</sub>, CO<sub>2</sub>) upgrading and digestate processing. Dashed lines represent  
 515 alternative options. Green blocks represent processes, brown blocks represent materials, light blue  
 516 blocks represent final uses.



518

519 **Figure 6.** Simplified layout for an anaerobic waste biorefinery. Option 5: dark fermentation,  
 520 electrochemical processing for enhanced H<sub>2</sub> production or electricity generation, biogas (H<sub>2</sub>, CO<sub>2</sub>)  
 521 upgrading and digestate processing. Dashed lines represent alternative options. Green blocks  
 522 represent processes, brown blocks represent materials, light blue blocks represent final uses.

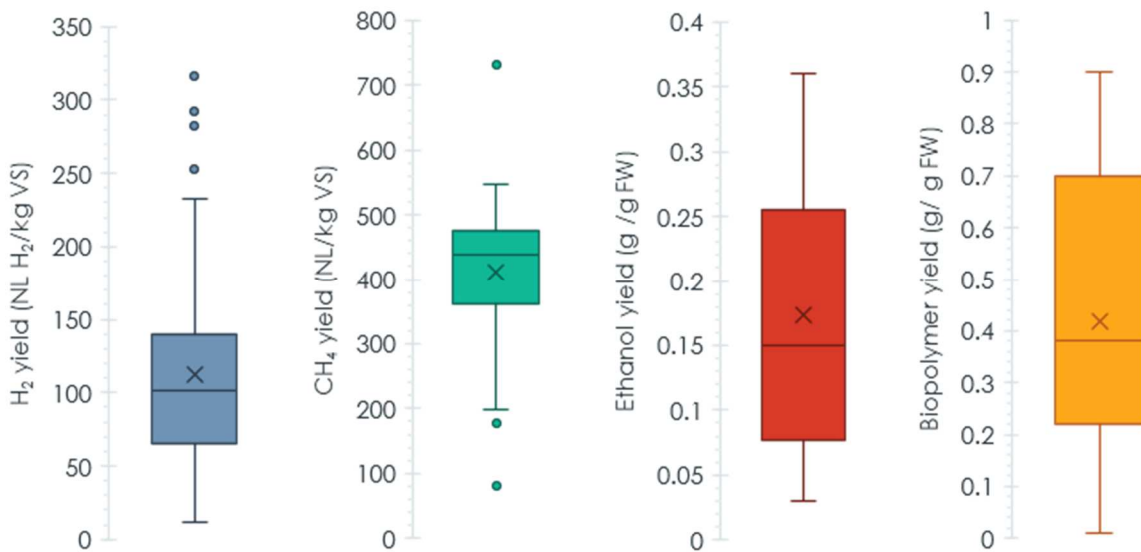
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#### 524 4.3 Waste biorefinery output

525 A rough estimation of the potential outcomes of waste biorefineries can be derived from the  
 526 observed ranges of bioproducts generation documented by literature studies. To this aim, H<sub>2</sub>, CH<sub>4</sub>,  
 527 ethanol and PHAs were considered as examples among the several products presented in the  
 528 biorefinery layouts described above thanks to a large availability of data. Since the reported yields  
 529 are largely variable with respect to the specific characteristics of the waste treated, the type of  
 530 conversion process applied and the operating conditions adopted, average values and deviations  
 531 from literature data are shown in Figure 7.



532 On the basis of the reported market prices for each product of concern (Moscoviz *et al.*, 2018), the  
 533 following ranges for the economic value of the products that can be obtained from food waste (FW)  
 534 in a biorefinery application were estimated: 0.24–15.5 €/t FW (average: 4.9) for H<sub>2</sub>, 1.9–11.6 €/t  
 535 FW (average: 7.3) for CH<sub>4</sub>, 9.0–540 €/t FW (average: 229) for ethanol and 22–4500 €/t FW  
 536 (average: 1510) for biopolymers. The revenues achievable from biowaste in a biorefinery would  
 537 require deducting the capital and operating costs of the plant. Nonetheless, given the amount of  
 538 food waste generated (in Europe, 46.5 and 41.1 Mt/y from municipal and industrial sources,  
 539 respectively), as well as the incentives for the production of green chemicals and energy,  
 540 considerable financial benefits are expected from the wide implementation of organic waste  
 541 biorefineries.  
 542



543  
 544 **Figure 7.** Yield ranges for H<sub>2</sub>, CH<sub>4</sub>, ethanol and biopolymers derived from literature references  
 545 (Akhlaghi *et al.*, 2019; Braguglia *et al.*, 2018; Rodriguez-Perez *et al.*, 2018; Srisowmeya *et al.*, 2019;  
 546 Tsang *et al.*, 2019; Uçkun Kiran *et al.*, 2014; Yadav *et al.*, 2020 and references therein). The cross  
 547 and the line within the box show the average and median value, respectively, the box denotes the  
 548 range of 50% of data, whiskers range from the lower to the higher value within 1.5 interquartile ranges  
 549 and circles stand for outliers.

550 **5. Conclusions and recommendations**

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

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

571 Exploration of the diversity of products than can be derived from waste will therefore become  
572 increasingly important.

573

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577 which is part of the International Waste Working Group (IWWG).

578

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