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Review

Innovative Circular Biowaste Valorisation—State of the Art and Guidance for Cities and Regions

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Abstract: The management of the organic fraction of municipal solid waste (OFMSW), also called urban biowaste, and urban wastewater sludge (UWWS) represents a challenge for cities and regions, which want to adopt innovative urban bioeconomy approaches for their treatment and production of high-added-value products beyond the traditional anaerobic digestion (AD) and compost. This adoption is often restricted by the availability and maturity of technologies. The research object of this manuscript, based on the findings of EU Horizon 2020 project HOOP, is the identification of state-of-the-art circular technologies for material valorisation of OFMSW and UWWS, following a novel screening methodology based on the scale of implementation (tested at least at pilot scale). The screening resulted in 25 technologies, which have been compared and discussed under a multidisciplinary assessment approach, showing their enabling factors and challenges, their current or potential commercial status and their compatibility with the traditional technologies for urban biowaste treatment (composting and AD). The bioproducts cover market sectors such as agriculture, chemistry, nutrition, bioplastics, materials or cosmetics. Therefore, the results of this review help project promoters at city/region level to select innovative technologies for the conversion of OFMWS and UWWS into high value products.

Keywords: bioproducts; biowaste; circular economy; municipal waste; technology readiness level; urban bioeconomy; urban wastewater sludge

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1. Introduction

In the last decades, the world has experienced a sharp population growth, especially in urban environments. This population increase and concentration, combined with the prominence of a linear economic model (According to [1], only 8.6% of the world economy is estimated to be circular), has inevitably led to a scenario of increased exploitation of resources, pollution and municipal waste generation. Municipal waste is the waste produced mainly by households, small business activities and restaurants, offices, public institutions and by maintenance of public spaces. This municipal waste includes materials such as plastic, glass, cans, paper, textiles, and an organic fraction, among others. Such an organic fraction of municipal solid waste (OFMSW), which is also called urban biowaste, is composed of biodegradable material, including food waste, kitchen waste and—in many cases—leaves, grass clippings, flower trimmings, and yard waste. **OFMSW** is sourced from three main streams:

- **Separately collected biowaste**. This includes all kind of biowaste collected through a specific channel. It includes separate collection in household, HoReCa sector and markets. Food waste and garden waste (plants, leaves, grass) are its main streams, but its nature depends on the system of collection, as household garden waste sometimes goes through a different channel.

- **Specific separate collection**. In this category might be included specific waste, such as used cooking oils or, for instance, waste from fruits and vegetables.

Green waste. This refers to waste produced during the maintenance of parks, gardens and public spaces. Although it has certain homogeneity, the presence of easily biodegradable matter and wooden parts might affect the potential biological degradation

Apart from these sources, there is also an organic fraction in the mixed municipal waste, which refers to the waste from households or similar without sorting, also called "rest fraction". This fraction can be separated through a mechanical process, normally as one part in the mechanical–biological treatment (MBT). This organic fraction is treated mainly by composting in the MBT, yielding a stabilised material with low quality, which represents a challenge of management.

Another important biological waste of urban origin (but not considered municipal waste) is the solid residue generated in the plants for treatment of urban wastewater, known as urban wastewater sludge (UWWS). **UWWS** entails the solid, semisolid, or slurry residual material that is produced as a by-product of wastewater treatment processes. Sludge is rich in nutrients such as nitrogen and phosphorus and contains organic matter. Therefore, it is used as fertiliser or soil improver for soils with low fertility or degraded. Depending on the water treatment, the composition of UWWS might have variations in terms of water content, nutrient content and availability, organic matter stability, etc.

Most of the 225 million tons of municipal waste generated in Europe in 2019 were disposed through landfilling (24.4%) or were treated with incineration (26.2%), with less than half being recycled (29.8%), composted (17.3%), or treated with other technologies [2]. Landfilling of municipal waste can cause major environmental problems because of the production of greenhouse gases, especially methane, during decomposition and the potential contamination of soil and groundwater, if technical measures such as sealing, leachate collection, or landfill gas capture are not taken. Therefore, the Council Directive 1999/31/EC on the landfill of waste obliged European Members to reduce the amount of biodegradable municipal waste that they landfilled (to 75% by July 2006, to 50% by July 2009, and to 35% by July 2016) which has significantly reduced this problem [3]. The latest update through European Directive 2018/850 sets that by 2030 no waste suitable for recycling or other recovery shall go to landfill. In addition, it sets that not more than 10% of the municipal waste shall go to landfill by 2035 [4]. Moreover, incineration remains as a pressing environmental issue. Although incineration with energy recovery does not have a specific target on reduction, it implies high requirements on air pollution control, involving the implementation of systems for removal of acid gases, dioxins, dust, NOx and other pollutants. These emission requirements are clearly stated in the Industrial Emissions Directive (2010/75/EU), which also sets specific procedures for permits with the application of Best Available Technologies [5]. The management of by-products such as bottom ash are also another important consideration. Apart from this, the presence of biowaste decreases the efficiency of energy recovery in incineration due to the high moisture of biowaste and the decrease in the heating value of the waste [6]. Therefore, this makes that from many points of view incineration is not a suitable method for biowaste treatment.

Assuming that biowaste can represent up to approximately 50% of municipal solid waste [7], there can be up to 33% of total municipal waste, which is biowaste that it is not recycled or upcycled [2]. For using biowaste as a resource in a circular way, separate collection is highly convenient because it keeps the levels of impurities (plastics, glass, stones, inorganic fine material, etc.) and contamination (heavy metals, persistent organic pollutants, PAH, PFAS, microplastics) as low as possible and enables its use as a valuable secondary resource. Such collection should have been implemented in the European Union no later than 31 December 2023, according to the Waste Framework Directive (2008/76/CE). Treatment of biowaste coming from mixed municipal waste, such as the organic fraction from MBT stabilized by composting, will not be considered recycling from 2027 [8]. Therefore, although this organic fraction could have potential as feedstock for valorisation technologies, European legislation does not promote this route. Moreover, the targets for preparation for reuse and recycling of municipal waste are 55% for 2025 and 65% for 2035, according to the updated Waste Framework Directive [8].

In the case of UWWS, more than 4 million tons on a dry basis were produced in the EU in 2019. Land application is the main route for material valorisation in the European Union (EU) directly, after composting, or as a digestate of anaerobic digestion (AD). About 41% of UWWS is spread on agriculture soils, 41% is incinerated, and 6% is disposed in landfills [9]. The remaining 12% is disposed of through other methods, such as storage, reuse in green areas and forestry, and landfill cover [10]. It is important to notice that although these values are given on a dry basis for a better control, the actual volume is much higher due to the water content. This is especially critical in landfills, as their space limitations and growing environmental concerns, such as groundwater pollution by landfill leachate, odour emission and soil contamination, have encouraged the investigation of alternative disposal or valorisation routes.

Governments around the world are becoming aware of the challenge faced by cities and regions related to increasing population and generation of waste in a global context of climate change, conflicts and environmental degradation. It is thus clear that a change in the current urban biowaste management system is needed and that the approach must be circular, where the value of waste is retained in the production cycle for as long as possible, reducing waste generation and the impact on the ecosystems to the minimum; this is the only possible way to achieve a sustainable, low-carbon, resource-efficient, and competitive economy [11]. At the international level, the path to a sustainable economy is led by the 2030 Agenda presented by the United Nations in 2015, which includes 17 Sustainable Development Goals (SDGs), among which circular economy is presented as a priority and essential area for their attainment. At the European level, the direction towards circular economy was initiated following the adoption of the first circular economy Action Plan in 2015 [12]. The new Action Plan [11], adopted in 2020, is one of the main pillars of the European Green Deal, considered the new European agenda for sustainable growth [13]. Within the general term of circular economy and sustainability applied at cities/region level, and as discussed by Yang and Yang (2022) [14], the concept of urban circular bioeconomy (UCBE) has emerged as a powerful solution to facilitate the transition using bioeconomy at local level. According to these authors, it can be understood as an economic system that consists of bioeconomic components in an urban environment with the aim of generating a broad positive impact.

The above context shows clearly the high urgency in providing solutions for biowaste management that promote the transition to a circular economy. This makes research into new ways of valorising urban biowaste into high-value products imperative. It offers an unprecedented opportunity for cities and regions to improve the management of urban biowaste and associated issues but also shifts the existing business model, which results in high economic cost to another one in which territories become producers of high value products which have the potential of being monetised. Actually, the OFMSW and UWWS are types of waste that, if properly managed, can play an important role in the circular economy due to their potential as source of nutrients, energy, and production of bio-based products. Both are rich in nutrients and other organic compounds and, in a similar way as nature does, they have the potential to bring new life and new products if treated by suitable technologies, some of which are also inspired by nature.

In order to implement UCBE approaches, we need new and sound technologies to deal with the OFMSW and UWWS, and here is where EU initiatives, such as the Horizon 2020 (H2020) HOOP project (https://hoopproject.eu/, accessed on 21 August 2024), come into play. HOOP aims to assist project developers in European cities and regions in deploying UCBE projects. The main focus of HOOP, bringing together partners and technologies from other H2020 projects—VALUEWASTE, WAYSTUP!, and SCALIBUR—is to provide assistance on the latest technologies available for the material valorisation of the OFMSW and UWWS into added-value products.

The adoption and deployment of state-of-the-art and sound technologies is challenging for a number of reasons that are outlined below. The first barrier is related to the technology maturity, which in most cases is very low for such technologies to be adopted (at least, they need to have been scaled up to pilot). This technology maturity is usually measured by the technology readiness level (TRL), a parameter ranking how the degree of development starting from the idea (TRL 1) to the fully availability on commercial scale (TRL 9). Another limitation is related to existing infrastructures, which in most cases are related to composting and anaerobic digestion, which in turn represent the main technologies for the valorisation of urban biowaste. Composting is a biological treatment transforming the solid biowaste into a stabilised material for soil amendment. Anaerobic digestion is another biological treatment to produce a gas (biogas) formed mainly by methane (CH_4) and carbon dioxide (CO_2), which is normally energetically valorised or upgraded into biomethane. Both are well-established technologies but have limitations. For compost, it is generally due to the low market price and, in some areas, low applicability or low social acceptance. In the case of anaerobic digestion, the sensitivity to the quality of the biowaste might act as limitation. In general terms, biowaste quality is defined as the content of organic matter in the biowaste, excluding improper materials such as plastics, papers or stones. The higher the degree of awareness of the citizens, the higher the quality/purity of the biowaste separately collected. Quality can be critical for anaerobic digestion, making necessary the implementation of more or less costly pre-treatments to remove the improper materials.

Feedstock availability and quality represents a major limitation as the OFMSW and UWWS vary regionally, seasonally and depends on socio-economic factors. In addition, the social acceptance of derived bioproducts and their low value in the market have also to be considered. Inherent to the market potential is the fact that the uptake of innovative solutions strongly depends on the adopter sectors, who are often hesitant to explore new valorisation systems due to the difficulty in quantifying risks (mainly related to TRL and bioproduct market) and potential benefits. Last but not least, international conflicts and associated instability have also affected the choices for the preferred valorisation routes.

Although the offer of innovative technologies coming from scientific articles, research projects, start-ups and technology-providers (solution developers) is wide, only few of them are ready to be adopted. In a context of boosting territorial bioeconomy by providing solutions for the valorisation of the OFMSW and UWWS into high value products [15], and to the best of the authors' knowledge, there is a clear need to identify, analyse, and compare between suitable technologies available which have the potential of being adopted. Therefore, this manuscript features a review of the state-of-the-art technologies for the production of high-value bio-based products from the OFMSW and UWWS to be considered in innovative circular bioeconomy processes.

As conveniently described in the Section 2 (Methodology), the selection is restricted to those technologies with at least TRL 5, with a strong focus on H2020- or Horizon-EU-funded projects, such as VALUEWASTE, SCALIBUR, and WAYSTUP!, which teamed up to form the HOOP project. Thus, the manuscript intends to empower project developers from cities and regions by featuring a portfolio of innovative technologies for valorisation of the OFMSW and UWWS and a tool for the identification of potential paths and opportunities linked to such valorisation in a context of circular bioeconomy. In addition, we present assessment guidelines for the compilation and selection of mature technologies for biowaste valorisation. Our final aim is to help adopters to bet on diverse solutions and to inform technology developers on adopter's expectations, contributing to foster UCBE and to create high added value through technologies using biowaste as feedstock. The assessment also provides the reader with an overview on the most known and widely used traditional technologies: composting and anaerobic digestion.

2. Methodology

2.1. Identification and Selection of Technologies

The state-of-the-art of technologies is based on the screening of different sources to identify innovative methods for valorisation of urban biowaste. These sources comprise EU funded projects from different calls, such as Horizon 2020 (VALUEWASTE, SCALIBUR, WaysTUP!), LIFE, BBI-JU and Interreg, patent databases, scientific journals, websites and correspondence with technology-providers. For the consideration of technologies and processes in the portfolio, the following criteria have been followed:

- Focus on material valorisation (energy valorisation and biofuels were out of the scope);
- Target biowaste produced at local/regional level, which includes the OFMSW, UWWS and other streams (i.e., parks and garden waste, markets, HoReCa);
- Technology Readiness Level of at least 5. There are numerous scientific publications with potential methods of treatment of biowaste. However, few of them have been scaled up to pilot scale. Therefore, technologies which have not reached at least a pilot scale were not considered;
- It needs to be specifically a technology for biowaste management. From this point of view, processes such as the production of construction materials from UWWS cannot be considered as such, because it relies on the application of existing industrial processes from other sectors;
- Cope with the heterogeneity and variability of the expected feedstock and with the fact that the amounts might not be as large as the ones from specific industrial biowaste producers.

2.2. Technology Analysis and Comparison

Once identified, the technologies were described and the most relevant bioproducts highlighted. This process was followed by the analysis and comparison of technologies, taking the following multidisciplinary criteria into account:

- Techno-environmental;
- Economic;
- Social;
- Legal.

The **techno-environmental** criteria consider indications on which conventional product might be replaced and main environmental impact of the process, like impacts on greenhouse gases (GHG) production, other emissions, and waste generation. Moreover, this analysis reports and assesses the TRL, as defined by the European Commission (EC) in Annex G of the General Annexes of Work Program 2016–2017 for H2020 [16], shown in Table 1. To understand how to apply the technology for a circular approach, this analysis provides information on the biowaste feedstock that inputs each process as well as raw material consumption and residual waste produced.

The **economic analysis** is meant to preview information on the profitability and economic feasibility of all technologies, including those with the lowest TRL. Data on the investment cost (capital expenditures, CAPEX), operational costs of the plant (operational expenditures, OPEX), and market price of the bioproducts were considered. However, this kind of information is very difficult to obtain for technologies whose TRL is lower than 7. It is important to notice that, especially when treating OFMSW or UWWS, the business model plays an important role, as the cashflows are not only dependent on the marketability of the bioproducts, treatment services being another potential source of income.

In terms of **social analysis**, it is important to consider that bio-based products and processes constitute a key element of UCBE. Therefore, ensuring widespread social acceptance for them is a challenge that stakeholders involved need to tackle to truly establish a market for their bioproducts. Wüstenhagen distinguishes three basic dimensions of social acceptance: community acceptance, socio-political acceptance and market acceptance [17]. Our analysis is focused on **community acceptance** and **consumer acceptance**. Community acceptance refers to the behavioural responses within communities, which are affected, for example, by the placement of a bio-based production plant close to their home (Not-In-My-Back Yard, NIMBY concept), and consumer acceptance is related to the willingness of consumers to adopt or buy a particular bioproduct.

Table 1. Definition of Technology Readiness Levels [16].

TRL	Definition
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

The **legal analysis** studies the regulatory feasibility of the proposal based on the current regulatory framework. Circular bioeconomy technologies are subject to regulations both considering the nature of the raw material, the characteristics of the process in some cases and the market sector towards the bioproducts are oriented. In any case, general guidelines and considerations are indicated, as most technologies require a tailored regulatory analysis.

The detailed description of the technologies and the development of the different steps in the multidisciplinary assessment has required the analysis of 462 references, from which there are 320 scientific articles, 78 websites, 32 technical reports, 15 books, 9 regulations, and 3 theses. This diversity in sources is explained because in general, issues such as economic data or the actual implementation of the technology on large scale are rarely considered in scientific articles. Moreover, some articles might refer to more than one technology, making unrepresentative a quantitative breakdown of the references.

3. Current Status of OFMSW and UWWS Valorisation Methods

As discussed, waste management at local/regional level represents a major concern and, at the same time, an opportunity. On one hand, the evolution of new technologies and the evolution of legislation make it possible to create economic value out of biowaste. On the other hand, biowaste disposal is a serious concern that requires a solution to reduce its environmental impact, making OFMSW and UWWS the perfect candidate to implement UCBE models.

The traditional treatment methods for OFMSW and UWWS are **composting and anaerobic digestion (AD)**. However, it is important to notice that these methods generate **by-fractions**, like the rejections from composting plants or digestate outcoming anaerobic digestion, which might represent a challenge of management.

Composting is a widely used technology, typically applied to process separately collected OFMSW to stabilise the organic fraction after MBT and to stabilise digestate after anaerobic digestion. It is an aerobic process that involves biological decomposition of organic matter under controlled conditions to provide a humic stabilised material (**compost**) that can be used as a fertiliser, soil conditioner, or growing media constituent. The process works best with an adequate mixture of biodegradable constituent, such as food waste, animal manure, or garden waste. During the composting process, microorganisms consume oxygen and release mainly CO_2 and heat as a result of their activity. Compost provides a range of environmental benefits, including improving soil health and recycling nutrients. Compost from separately collected OFMSW is normally one of the key elements for the implementation of circular bioeconomy. However, there are some areas or countries where biowaste-based compost has a low applicability. The main problem is generally its low market value, which depends on demand but also on the quality of the final product. Therefore, it is important to create a demand for compost which, in turns, builds upon the quality of the input feedstock.

Anaerobic digestion is a multi-step biological process carried out in closed vessels where different microbial species decompose organic matter in absence of oxygen, through a cascade of various metabolic paths. A wide range of different feedstocks, such as UWWS, animal manure, food industry waste, energy crops and harvesting residues and the OFMSW [18], can be used as substrates for AD. As shown in Figure 1, the outputs of AD are **biogas** and **digestate**, both of great value to implement a circular economy model. The digestate can be separated into a liquid and a solid fraction. More detailed information about these fractions can be found in Appendix A, the metabolic steps involved in the digestion, thermal pretreatments [19–22], enzymatic pretreatments treatments [23], and potential applications [24–28].

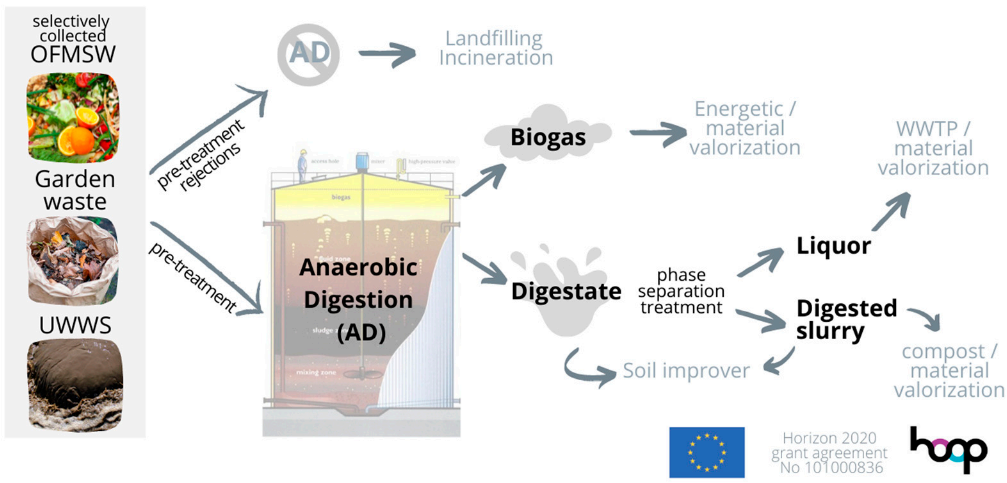


Figure 1. Scheme of anaerobic digestion process.

The main drawback of AD is that the process is very sensitive to the quality of the feedstock to keep the balance between the different stages in the digestion. This means that the concentration of impurities should be as low as possible to avoid technical problems which might stop the digester.

Although well established, composting and AD have inherent drawbacks, and their level of success is not the same in all the geographical circumstances. This limited number of alternatives for the valorisation of OFMSW and UWWS cause many cities and regions to want to find new processes in order to obtain either bioproducts with higher added value or more robust and stable processes to cope with the heterogeneity of the waste in a sustainable way. Therefore, there is a clear need for these new technologies to be implemented on commercial scale as alternative to the traditional composting and AD.

Apart from the environmental challenges, European Union is poor in many natural resources currently necessary and not replaceable in many value-chains, which need to be imported from other continents—for example, phosphorus for agriculture, crude oil for chemistry, protein-rich vegetables for animal and human nutrition. This dependence is a serious concern that could be partially overcome if renewable, underutilised, and ubiquitously available resources—like the OFMSW and UWWS—could be used as alternative raw materials.

In recent years, several new processes for producing new materials and products from OFMSW and UWWS have received significant attention, with the main objective of taking advantage of their conversion into high-added-value bioproducts.

Biorefineries are the processing facilities in which biomass is converted into valuable products such as chemicals, biofuels, food and feed ingredients, biomaterials or fibres [29]. Integrated biorefineries combine the production of bio-based products and energy from biomass. Biorefineries use different types of organic feedstocks, including OFMSW and UWWS. According to the European Commission, there are 803 biorefineries in Europe, of which 136 are based on waste streams [30].

These novel processes have interesting economic prospects based on the expected income from the production of high value-added products and a clear environmental benefit. Moreover, they have a potentially strong bankability because they meet the criteria of suitability for private and public green finance tools.

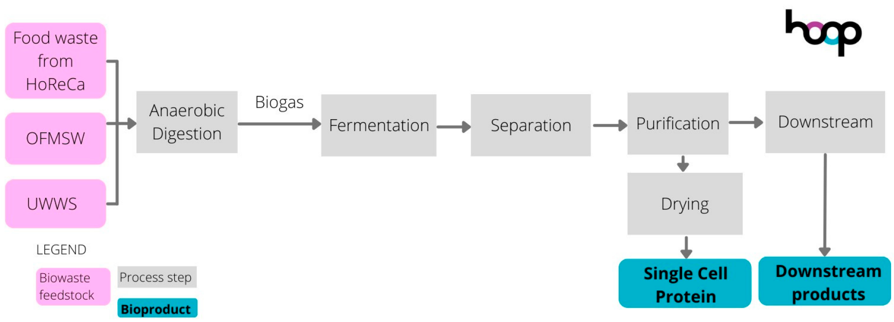
4. Innovative Technologies for Biowaste Valorisation

Summaries, descriptions, and main bioproducts obtained from the technologies identified as a result of the state-of-the-art review are provided in Table 2. The table shows that many of the technologies have been designed for a kind of biowaste, but by definition, they are applicable to other biowaste. This is clearly shown in technologies based on hydrolysis, where the term “any other hydrolysable biowaste” is systematically used, as their purpose is being used as source of sugars for growth medium. A similar case is observed with biowaste which can be potentially treated by AD. Flowcharts are provided for each technology.

Table 2. State-of-the-art technologies identified.

<table>
<tr><th>Technology</th><th>Description, Bioproducts, and References</th></tr>
<tr><td>1. Bioprocess involving methanotrophic bacteria using biomethane arising from the AD of the OFMSW</td><td>

Waste treated: Any treated by AD
Type of technology: Biological (fermentation)
Description. This technology is based on the use of methane from biogas in AD as a carbon and energy source for the growth of methanotrophic bacteria in a fermentation reactor. Methanotrophic bacteria are fed with biogas, oxygen (because these bacteria are aerobic) and nutrients to efficiently transform methane to protein-rich biomass, which is normally concentrated, and to products both derived from biomass fractionation or from their metabolic production. The downstream of the bacterial biomass requires normally the cell disruption and the removal of nucleic acids, especially for nutrition applications. Biomass fractionation and the recovery of products from metabolic production require treatments to liberate the intracellular constituents into the external fluids. These metabolic products include ectoine, sucrose, biofuels, polyhydroxybutyrate, and glycogen since methanotrophic bacteria accumulate osmolytes, phospholipids, and biopolymers, among others. Other cell components, such as surface layers, metal chelating proteins, enzymes, or heterologous proteins might produce methanobactin or monooxygenase, which might be also used to produce new materials. Other products can be obtained if bacteria are genetically modified. In any case, the downstream needs to be tailored to the target bioproduct.

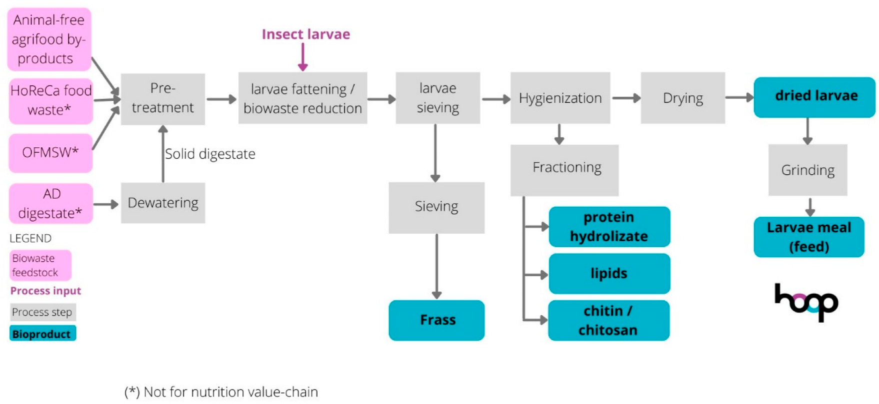


Bioproducts: Single-cell protein (feed supplement), bacterial protein isolates and concentrates, nucleic acids. Others: biopolymers, surface layers, lipids, methanol, organic acids, ectoine, vitamin B12, sucrose, copper-binding proteins (methanobactin).
Market sector: Nutrition (feed), others (pharma, environment, cosmetic, materials, energy)
References: [31–57]
</td></tr>
</table>

Table 2. *Cont.*

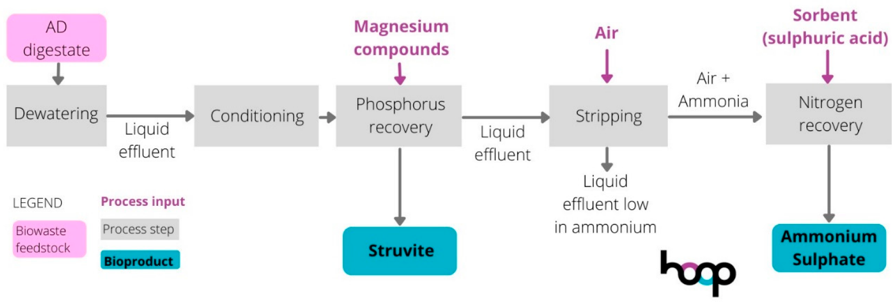
<table>
<tr><th>Technology</th><th>Description, Bioproducts, and References</th></tr>
<tr><td>2. Insects breeding</td><td>

Waste treated: OFMSW. Digestate AD *.
Type of technology: Biological (animal).
Description: Valorisation of the fresh separately collected OFMSW and/or AD digestate through insect larval feeding activity. Most technologies consist in growing larvae in trays with the biowaste, where they eat for several days in their development stages, transforming the feedstock into biomass (the larvae) and frass (the excreta). Larvae or further stages (pre-pupae, pupae) are sacrificed, hygienised and dried. Few of them are saved to become adults for reproduction. Depending on the target product, a downstream process can be implemented for fractionation into protein, fats and chitin. Protein can be hydrolysed into biostimulants. One of the most appreciated species is the black soldier fly (Hermetia illucens), whose larvae convert a wide range of feed sources into valuable products. This same concept can be applied to other insect species, such as yellow mealworm (Tenebrio Molitor). Black soldier fly larvae (BSFL) have higher fat content than other fly larvae, what makes them valuable as fat and protein source in animal feed and for the production of biodiesel. Adults do not travel far, implying very low ecologic impact in case of insect escape. They also do not feed or bite and are therefore not considered a source of disease transmission.



Bioproducts: Dried larvae. Sequential extraction products: lipids, proteins and chitin. Hydrolysed protein into biostimulants.
Market sectors: Nutrition (feed), others (agriculture, cosmetic, energy, pharma)
References: [53–55,57–100]
</td></tr>
<tr><td>3. Nutrient recovery (struvite, ammonium sulphate)</td><td>

Waste treated: Digestate AD, UWWS, wastewater.
Type of technology: Chemical.
Description: The technology treats the digestate liquid fraction from AD, which is rich in phosphorus and nitrogen. Nitrogen (ammonium) and phosphorus (phosphate) can be simultaneously recovered by precipitation of struvite ($NH_4MgPO_4{\cdot}6H_2O$) with addition of a source of magnesium. Struvite is a novel P-based circular fertiliser authorised as EU fertiliser and organic fertiliser. More details on sustainable P-based products can be found on the European Sustainable Phosphorus Platform (ESPP). In the case of nitrogen, the stripping–scrubbing of ammonia in the digestate is the most common method to obtain a circular fertiliser, ammonium sulphate ($(NH_4)_2SO_4$). It consists of releasing ammonia using air as carrier gas and scrubbing the air with sulfuric acid to form an ammonium sulphate solution. It is also possible to obtain solid ammonium sulphate through crystallization.



Bioproducts: Struvite, ammonium sulphate.
Market sector: Agriculture.
References: [101–115]
</td></tr>
</table>

Table 2. *Cont.*

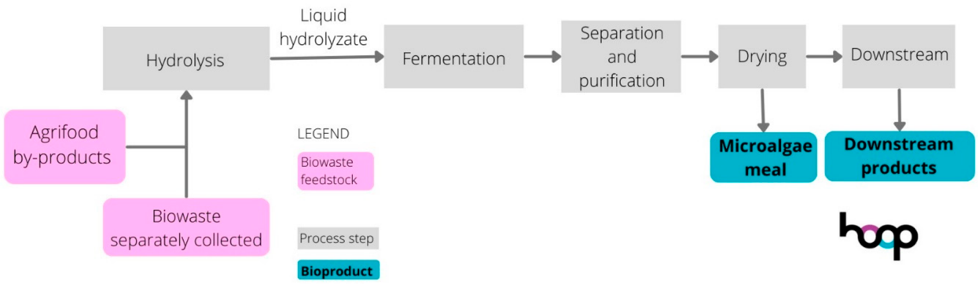
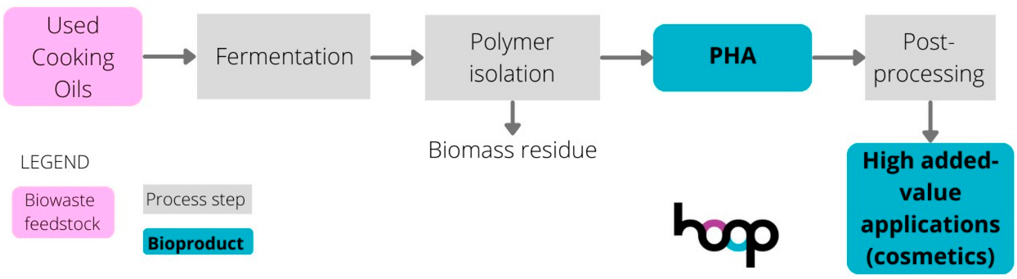
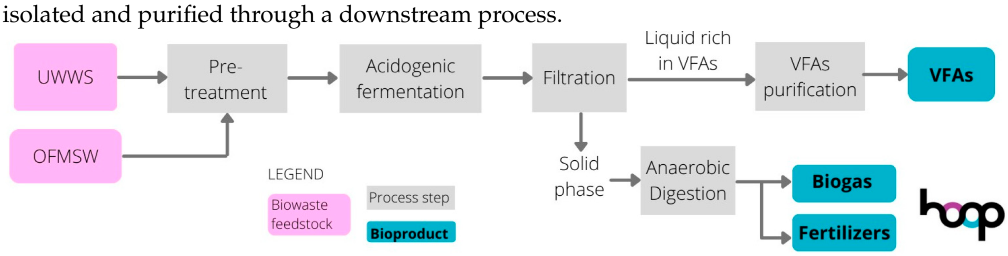
Technology	Description, Bioproducts, and References
4. Microalgae cultivation	**Waste treated:** OFMSW *. Other hydrolysable biowaste. **Type of technology:** Biological. **Description:** Microalgae can use the nutrients from biowaste or wastewater as growth medium, the approach being different depending on the nature of the microalgae species (heterotrophic of phototrophic). Heterotrophic microalgae can be grown from hydrolysate of agrofood by-products or kitchen waste. Phototrophic microalgae are being widely investigated in wastewater treatment applications, due to their excellent ability to grow in complex media and capture nutrients from waste streams, normally in open raceway ponds, but also with photobioreactors using CO_2. Microalgae have an important protein content, sometimes higher than animal or plant sources, and also present a large number of minerals and vitamins. In addition, microalgae such as Spirulina, Chlorella, Dunaliella or Scenedesmus have shown to have an attractive taste when they are correctly processed and incorporated into different types of food. As an alternative to its use in the food industry, microalgae produced from the liquid fraction of digestate can be integrated into a biorefinery to produce biochemicals, biofuels, aquaculture feeds, and soil conditioners.  **Bioproducts:** Animal feed (fish and mollusks), biofuels, cosmetics, nutraceuticals, biostimulants. **Market sector:** Nutrition. Others (cosmetic, environment, energy, agriculture). **References:** [38,116–137]
5. Fermentation of used cooking oils into biodegradable polymers	**Waste treated:** Used cooking oils (UCOs) **Type of technology:** Biological (fermentation) **Description:** The technology consists in the fermentation of used cooking oils using bacteria that accumulate the biopolymers polyhydroxyalkanoates (PHAs), which are later separated and purified. Unlike biofuels, PHAs are a high-added-value product, as they are biodegradable and biocompatible, making them a sustainable substitute for conventional plastics derived from fossil resources. One of the most interesting applications are in cosmetics, biomedicine, sustainable packaging and agriculture, with special interest on the cosmetic sector, where they can act as substitute of microplastics.  **Bioproducts:** Biopolymers (PHA). **Market sector:** Cosmetic. Others: pharma, biomedical, packaging, agriculture. **References:** [138–144]

Table 2. *Cont.*

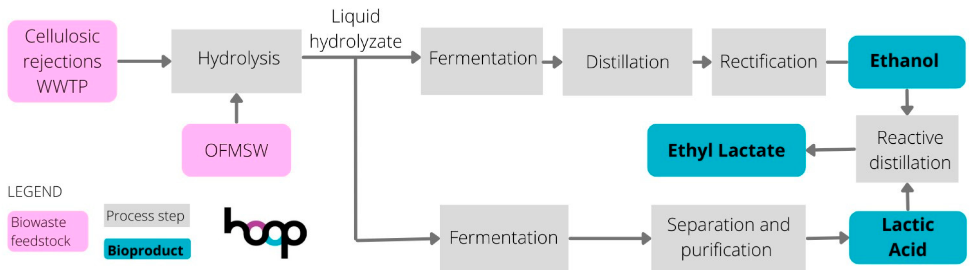
<table>
<tr><th>Technology</th><th>Description, Bioproducts, and References</th></tr>
<tr><td>6. VFAs production from UWWS anaerobic fermentation</td><td>

Waste treated: UWWS. OFMSW. Other biowaste suitable for AD.
Type of technology: Biological (fermentation)
Description: VFAs are short-chain carboxylic acids (acetic, propionic, butyric, isobutyric, valeric, isovaleric) that, thanks to their properties, are of interest for different applications. Even though mixed VFAs have been used in different approaches, such as biological nutrient removal, bioplastics and biodiesel among others, each individual VFA has specific uses in different industries. The technology to produce volatile fatty acids (VFAs) is an integration of different commercial processes of proven robustness, whose technological core is anaerobic fermentation. This main process is coupled to different up and downstream treatments which directly affect the type of VFAs obtained and the efficiency of the process. The technology consists in driving the AD into the acidogenic step and stopping there. At that point, the VFAs obtained as metabolite are isolated and purified through a downstream process.



Bioproduct: Volatile fatty acids.
Market sector: Chemistry.
References: [113,114,145–177]
</td></tr>
<tr><td>7. Ethanol and other biosolvents from cellulosic rejections of WWTP and OFMSW</td><td>

Waste treated: Cellulosic rejections WWTP. OFMSW. Other hydrolysable biowaste.
Type of technology: Biological (fermentation)
Description: Urban wastewater has a high quantity of cellulose fibres, mainly generated from toilet paper. This cellulose obtained in wastewater treatment plants (WWTP) can be hydrolysed into sugars which can be used as growth media in the production of ethanol by fermentation (bioethanol). These sugars can be also obtained from separately collected OFMSW or any feedstock that can be hydrolysed into sugars. Bioethanol is then isolated and purified. Bioethanol can be employed as biofuel or as an extremely versatile building block for biorefinery processes, such as the production of biomaterials, biosolvents, and biochemicals. One example of biosolvent is ethyl lactate, which is obtained by reactive distillation of bioethanol and lactic acid (see next technology). Ethyl lactate and other lactic acid esters are employed as toxic-free biodegradable biosolvents, and they had been proven to be suitable as additives in foodstuffs. Moreover, it is also possible to transform bioethanol into bioethylene.



Bioproducts: Bioethanol, biosolvents (ethyl lactate), ethylene.
Market sector: Chemistry, energy.
References: [11,38,178–204]
</td></tr>
</table>

Table 2. *Cont.*

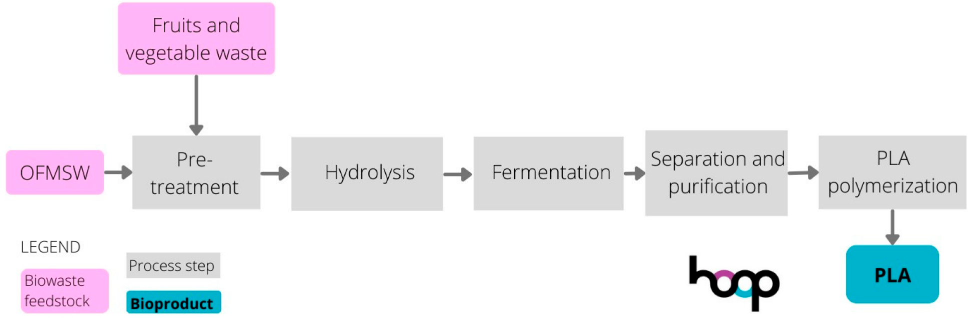
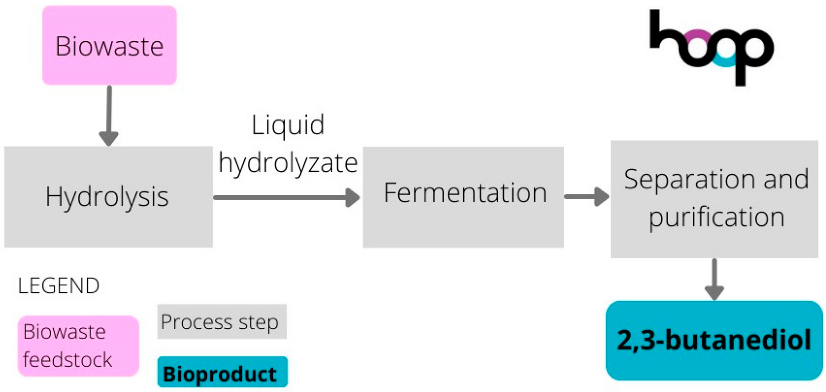
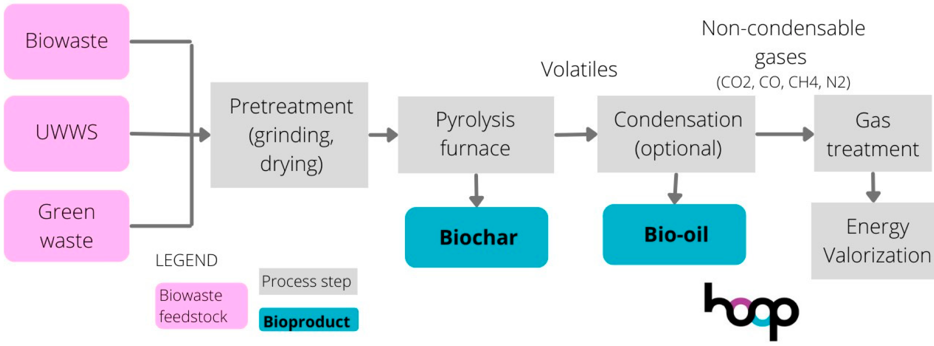
Technology	Description, Bioproducts, and References
8. PLA production from fruits and vegetables	**Waste treated:** Fruits and vegetables waste. OFMSW. Other hydrolysable biowaste. **Type of technology:** Biological (fermentation) **Description:** The technology consists in the hydrolysis of vegetal biowaste into simple sugars and subsequent fermentation to obtain lactic acid, which needs to be isolated and purified. The lactic acid from biowaste is subsequently polymerised to obtain polylactic acid (PLA), a biopolymer that is biocompatible and biodegradable and presents thermoplastic properties similar to polyethylene terephthalate (PET). PLA is compostable under controlled temperature conditions (higher than 58 °C) and fully recyclable.  **Bioproduct:** Polylactic acid (PLA). **Market sector:** Polymers (packaging, pharma). **References:** [55,180,193,205–224]
9. Bioprocess production 2,3-Butanediol from OFMSW, garden and UWWS	**Waste treated:** OFMSW, UWWS, garden waste, other hydrolysable biowaste. **Type of technology:** Biological (fermentation). **Description:** 2,3-Butanediol (2,3-BDO) is a valuable chemical building block with a wide variety of applications in sectors such as chemistry, energy, food or polymers. 2,3-BDO is produced industrially from fossil raw materials using chemical methods, which require high energy intensity and the use of expensive catalysts. This technology produces 2,3-BDO through fermentation with bacteria, such as Enterobacter cloacae, Klebsiella oxytoca, and Serratia marcescens using sugars coming from vegetal feedstocks: garden waste, vegetables and fruit waste. Food additives, aviation fuel, solvents, polymers and cosmetics, drugs, and lotions, among other products, can be obtained from 2,3-BDO using different chemical reactions.  **Bioproduct:** 2,3-Butanediol. **Market sector:** Chemistry. **References:** [113,223–229]

Table 2. *Cont.*

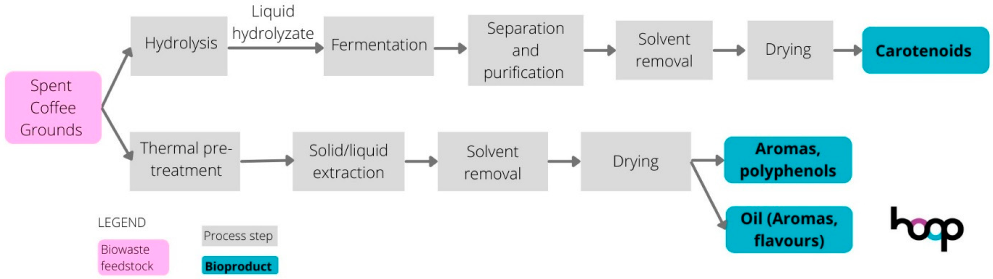
<table>
<tr><th>Technology</th><th>Description, Bioproducts, and References</th></tr>
<tr><td>10. Slow pyrolysis</td><td>

Waste treated: UWWS. Any other biowaste.
Type of technology: Thermal.
Description: Pyrolysis is a thermal treatment for organic matter such as biowaste, garden waste or wastewater sludge. Pyrolysis uses high temperatures and absence of air to transform the waste into three fractions: (i) a porous charcoal-like solid (biochar), (ii) liquid, and (iii) gases. The main advantages of pyrolysis are the production of biochar, the avoidance of decomposition of organic matter and the destruction of potential pathogens. Gases and eventually liquids are normally burnt to obtain energy to support the process. The characteristics of biochar depend both on the starting material and the process conditions followed. Although pyrolysis is not a novel process, the applications of the products obtained are new. Biochar has relevant properties as soil amendment and as carbon storage in the soil, as it keeps a significant amount of the nutrients from the starting feedstock, especially phosphorus. Biochar has other potential uses, such as active carbon for pollution removal or its application as additive in construction materials. Most of the application depend on the starting material and the operation conditions.



Bioproducts: Biochar.
Market sectors: Agriculture, others (environment, materials).
References: [230–241]
</td></tr>
<tr><td>11. Fermentation of SCGs</td><td>

Waste treated: Spent coffee grounds (SCGs), other hydrolysable biowaste.
Type of technology: Chemical. Biological (fermentation).
Description: SCGs are rich in high value molecules and organic compounds which still remain in the solid part after the preparation of the beverage. Therefore, SCGs are an optimal feedstock for the recovery of valuable products such as polysaccharides, lipids, protein, minerals and bioactive secondary metabolites including diterpenes, sterols, chlorogenic acids, flavonoids and caffeine. This technology applies two approaches, one is the extraction of existing compounds using solvents and the other is the use of the fibre matrix as source of sugars for fermentation after hydrolysis. Aromatic flavour components (diacetyl and acetaldehyde) and oils can be extracted from SCGs through physical and chemical methods. Another product is a polyphenol-rich extract with important antioxidant properties. In addition, carotenoids can be obtained through fermentation using the hydrolysed SCG or their fibre matrix. Carotenoids are organic pigments used commercially as food colorants, animal feed supplements, nutraceuticals, and cosmetics and pharmaceutical purposes.



Bioproducts: Coffee oil, aromas, polyphenol-rich extract, carotenoids.
Market sectors: Cosmetics, nutrition.
References: [113,242–254]
</td></tr>
</table>

Table 2. *Cont.*

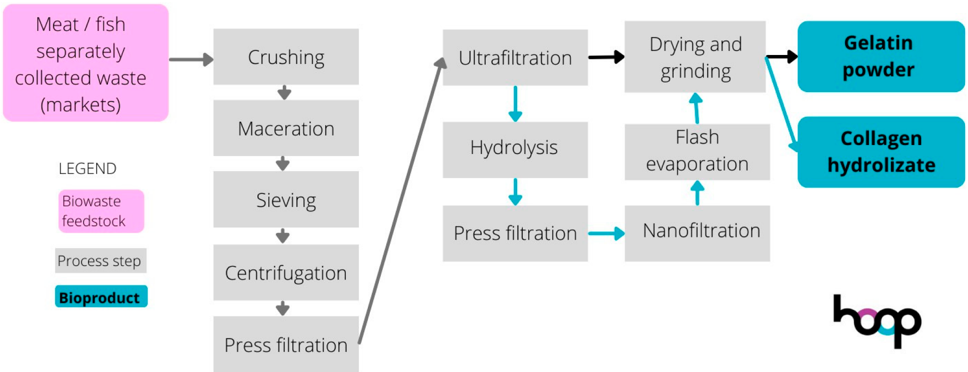
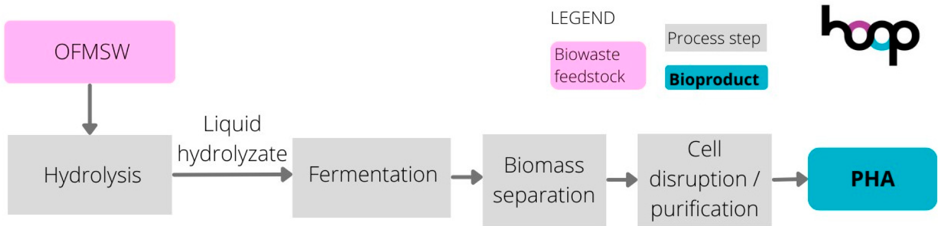
Technology	Description, Bioproducts, and References
12. Biochemical production of functional ingredients from animal by-products	**Waste treated:** Animal by-products. **Type of technology:** Chemical. **Description:** Fish and meat by products are a good resource to consider for the production of hydrolysed collagen and gelatine. Hydrolysed collagen is a product of great value in the cosmetic industry due to the presence of bioactive peptides (short chain), which stimulate production of collagen in the body if ingested. It has beneficial effects on the skin, strengthens joints, nails, bones and hair. Gelatine can be also obtained and has shorter peptide chains than collagen. This technology proposes chemical hydrolysis of animal by-products from markets (mainly from meat or fish) to obtain the collagen. Further hydrolysis can be used to obtain functional peptides. Downstream processes using membranes in cascade fractionate the peptides according to their size and provide a wide range of qualities of peptides.  **Bioproducts:** Hydrolysed collagen, gelatine, active peptides. **Market sector:** Cosmetic, nutraceutical. **References:** [114,221,255–258]
13. Biochemical conversion of OFMSW to bioplastics	**Waste treated:** OFMSW. Other hydrolysable biowaste. **Type of technology:** Biological (fermentation). **Description:** The technology consists in using OFMSW as a source of sugars via hydrolysis. The liquid hydrolysate is used later to grow yeast and/or specialised bacteria able to accumulate biopolymers, typically PHA. PHA is recovered by a downstream process and purified. The applications of PHA have been mentioned in the section about fermentation of UCOs.  **Bioproducts:** Biopolymers (PHA). **Market sector:** Cosmetic. Others: pharma, biomedical, packaging, agriculture. **References:** [209,259–266]
14. Production of Biopesticides from OFMSW	**Waste treated:** OFMSW. Other hydrolysable biowaste. **Type of technology:** Biological (fermentation). **Description:** The bacteria Bacillus Thuringiensis (Bt) is one of the most well-known biological agents for selective control of pest insects and is included in the list of biological pesticides of the EU according to the Commission Implementing Regulation (EU) 540/2011. The traditional production of Bt is relatively expensive due to the utilisation of high-priced feedstocks, especially as growth medium. The technology consists in the same concept described in previous technologies based on hydrolysis of OFMSW and fermentation using the hydrolysate as growth medium.

Table 2. *Cont.*

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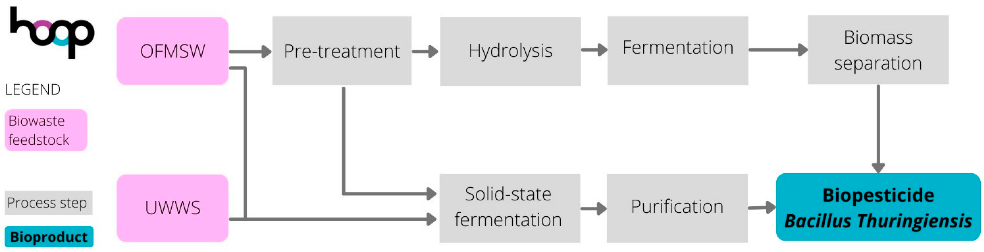
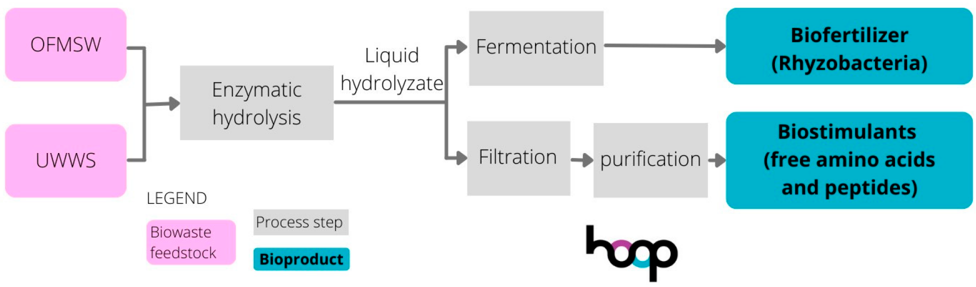
<tr><th>Technology</th><th>Description, Bioproducts, and References</th></tr>
<tr><td>14. Production of Biopesticides from OFMSW</td><td>


Bioproducts: Biopesticides (Bacillus Thuringiensis).
Market sector: Agriculture.
References: [260,267–269]
</td></tr>
<tr><td>15. Production of biofertilisers and biostimulants</td><td>
Waste treated: OFMSW. Other hydrolysable biowaste.
Type of technology: Biological (fermentation).
Description: The process involves the enzymatic hydrolysis to release the sugars of OFMSW, using enzymes such as proteases, cellulases, ligninases, lipases, and pectinases, which are responsible for the hydrolysis of protein, cellulose, lignin, lipids, and carbohydrates, respectively. This step brings to either the obtention of a bioproduct itself (protein hydrolysate biostimulants) or the obtention of an adequate nutrient broth for the selected plant-growth-promoting rhizobacteria (PGPR) strain to be cultivated. PGPR are bacteria that, applied to the soil, enhance plant growth by increasing the availability of essential nutrients and by regulating the production of compounds involved in plant growth, making plants more resistant to abiotic stress and limited water availability.



Bioproducts: Biofertilisers, phytohormones, biostimulants.
Market sector: Agriculture.
References: [112,263,270–283]
</td></tr>
<tr><td>16. Bioconversion of UWWS: CO_2 fermentation with bioelectrochemical systems</td><td>
Waste treated: Any waste treated by AD.
Type of technology: Biological (fermentation).
Description: This technology is based on a hybrid system of biotechnology and electrochemistry, known as bioelectrochemical system (BES), to transform CO_2 from biogas upgrading into chemical building blocks like acetate, ethanol or short-chain fatty acids. This means that some specific bacteria use CO_2 and electricity for the production of organic molecules through their own metabolism. The first step is the upgrading of biogas produced from AD of UWWS or OFMSW into biomethane by absorption of CO_2 with water. This water with CO_2 is fed to the bioelectrochemical reactor, where the bacteria make the transformation. The organic molecules produced by the BES are later isolated and purified. The BES provides two effects. On one hand, the quality of the biogas increases by removal of the CO_2, and on the other hand, the CO_2 transforms into a series of chemical building blocks. Similar BES technology can find applications in wastewater treatment coupled to energy generation, salinity removal, and hydrogen production treatment of toxic and recalcitrant pollutants, among others.
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Table 2. *Cont.*

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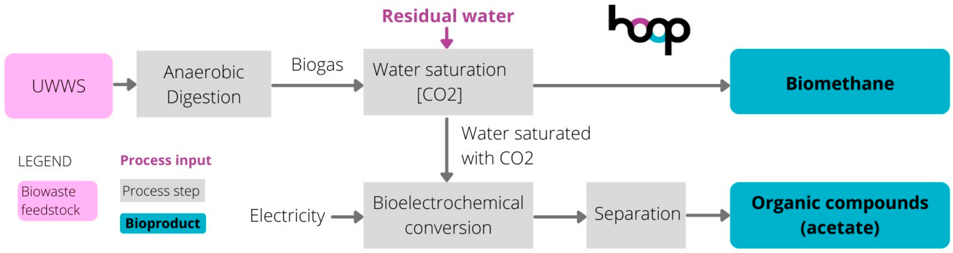
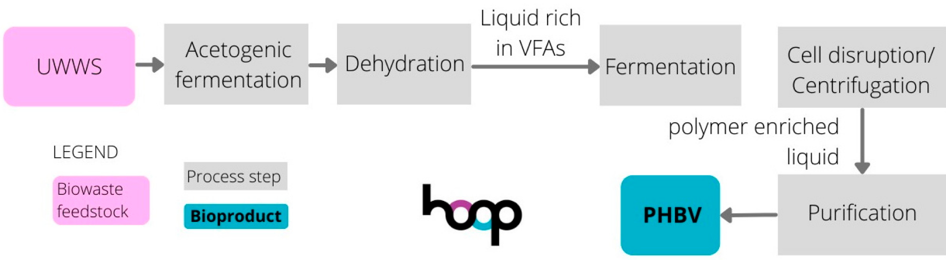
<tr><th>Technology</th><th>Description, Bioproducts, and References</th></tr>
<tr><td>16. Bioconversion of UWWS: CO_2 fermentation with bioelectrochemical systems</td><td>



Bioproducts: Acetate, ethanol, butyrate, short-chain fatty acids.
Market sector: Chemistry.
References: [263,284–289]</td></tr>
<tr><td>17. Bioconversion of UWWS: production of PHBV and other PHAs</td><td>**Waste treated:** UWWS, other biowaste suitable for AD.
Type of technology: Biological (fermentation).
Description: This technology is based on the ability of certain species and strains of microorganisms to accumulate PHAs as metabolite under certain conditions. The technology is based on the interruption of the chain of reactions of AD of UWWS in the part of volatile fatty acids. These VFAs are then used as nutrients to cultivate bacteria for the biotechnological production of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), but the process is easily adaptable to the obtention of other PHAs. The remaining digestate can go on to the following AD steps. The process is coupled to wastewater treatment. The applications of PHA have been mentioned in the section about fermentation of UCOs.



Bioproducts: Biopolymers (PHVB and other PHAs).
Market sector: Cosmetic. Others: pharma, biomedical, packaging, agriculture.
References: [55,263–267,290–296]</td></tr>
<tr><td>18. Hydrothermal carbonization (HTC)</td><td>**Waste treated:** UWWS, OFMSW.
Type of technology: Thermal.
Description: HTC is a thermal technology for treatment of waste and biomass consisting of heating in the absence of air, but—in the presence of a significant amount of water either from its natural moisture content or added—is enough to increase pressure. The reaction results in a carbon-rich solid normally known as hydrochar and wastewater rich in organic intermediate compounds and nutrients. The resulting slurry needs to be cooled down and separated into a water cake through filterpress. The hydrochar can be further dried and used either as fuel or as biofertiliser. It is important to mention that HTC is not the same as pyrolysis. If the same process is carried out at higher temperatures, the products can shift into the formation of oils or into gas in a similar way as it happens with pyrolysis. HTC is attractive to the treatment of waste with high moisture content, such as UWWS, AD digestate, or manure, as the volume is significantly reduced, and clean water might be produced after treatment. However, it has been also tested with urban biowaste and agrofood waste. Nutrient recovery might be coupled to the process in order to recover both P and N present in the water.</td></tr>
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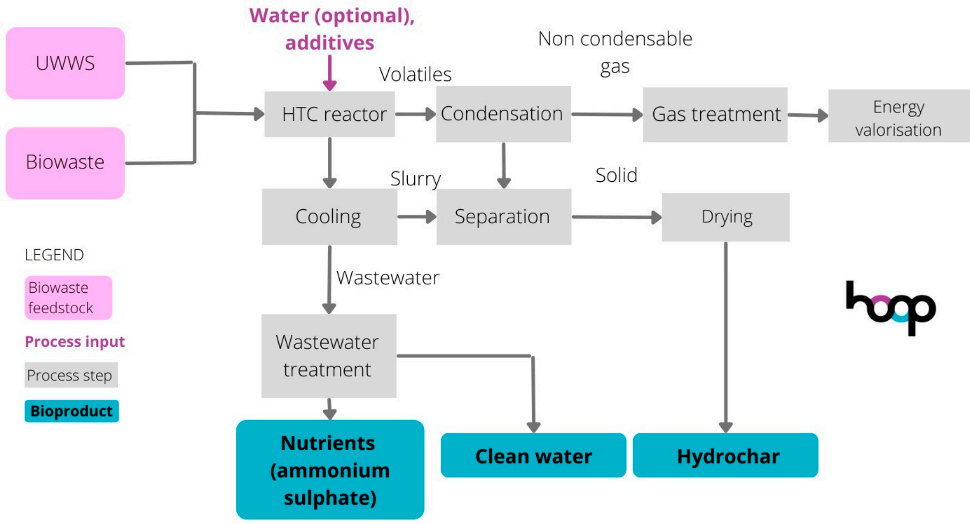
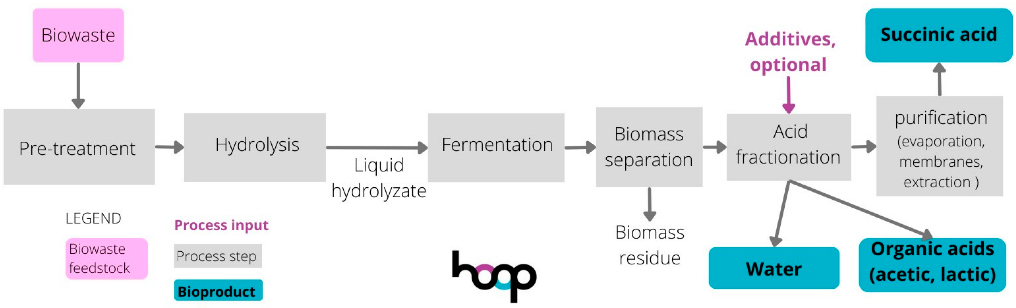
<tr><th>Technology</th><th>Description, Bioproducts, and References</th></tr>
<tr><td>18. Hydrothermal carbonization (HTC)</td><td>

Bioproducts: Hydrochar, water, and ammonia salts.
Market sector: Agriculture.
References: [297–320]</td></tr>
<tr><td>19. Succinic acid production</td><td>**Waste treated:** OFMSW. Other hydrolysable biowaste.
Type of technology: Biological (fermentation).
Description: The process consists in a combination of hydrolysis to release nutrients in biowaste and a subsequent fermentation for the production of succinic acid, a promising chemical building block. This product needs to be isolated and purified by downstream, for which multiple strategies are followed involving membranes and evaporation steps. Succinic acid is a chemical building block which can be used as starting point for many products in the sector of chemistry and polymers, especially for the production of polybutylenesuccinate (PBS) or polybutylenesuccinate terephthalate (PBST). In addition, succinic acid finds applications as acidity regulator, antimicrobial and flavouring agent and as additive for green solvents and plant growth stimulation. It is also used in the production of antibiotics, aminoacids and vitamins, shampoos, creams, detergents, surfactants, corrosion inhibitors, and chelators.


Bioproducts: Succinic acid
Market sectors: Chemistry, polymers, nutrition, pharma, cosmetics
References: [113,177,200,321–352]</td></tr>
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Table 2. *Cont.*

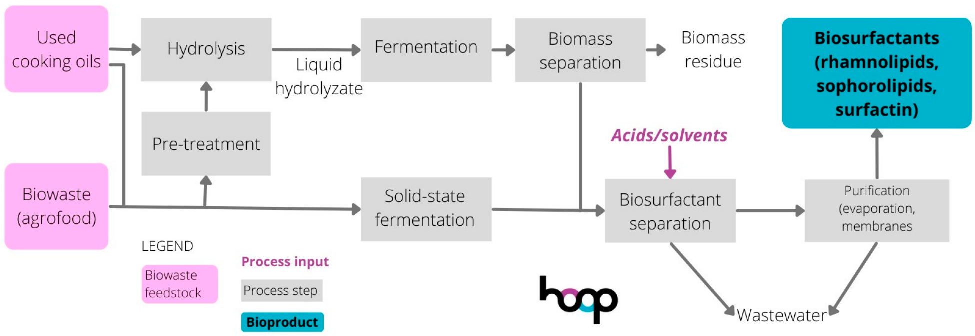
Technology	Description, Bioproducts, and References
20. Production of biosurfactants	**Waste treated: OFMSW (food waste). UCOs. Other hydrolysable biowaste.** **Type of technology:** Biological (fermentation) **Description:** The main bioproducts are surfactants, which are amphoteric molecules. This means that they have one polar part and another non-polar polar, providing them with properties of application in multiple sectors such as food, detergents, or cosmetics. The most common microbial biosurfactants are rhamnolipids and sophorolipids. Bioproduction of surfactants can take place by submerged fermentation in a sugar rich medium and by solid state fermentation. Submerged fermentation uses sugars from hydrolysed biowaste and waste oils as growth media for the bacteria used in the production of biosurfactants. Solid-state fermentation takes place directly on the solid biowaste. Solid-state fermentation has more advantages in terms of costs but is more challenging for the recovery of the product. The microorganisms used for the fermentation depend on the target type of biosurfactants, the most frequent being *Pseudomonas* sp., *Candida* sp, *Starmerella bombicola*, and *Bacillus subtillis*. Biosurfactants are recovered and further isolation steps (acid precipitation, liquid-liquid solvent extraction and membrane filtration) are required in order to purify the biosurfactants. The main application of biosurfactants is enhanced oil recovery (EOR), for making emulsions able to increase the yield of oil wells. Biosurfactants can be used also for the treatment of oil spills and bioremediation. This kind of applications do not require a high level of purity. Moreover, biosurfactants are an emerging agent in crop disease management due to the antimicrobial and antifungal properties of many of them and their biodegradability. Biosurfactants can be also used for cosmetic, pharmaceutical or personal care applications as substitute of fossil-based surfactants due to their biodegradability. These applications are much more stringent and have higher purity requirements.  **Bioproducts:** Biosurfactants (rhamnolipids, sophorolipids). **Market sectors**: Oil industry, environment, chemistry, cosmetics, agriculture, pharma. **References:** [353–386]
21. Mycelium production	**Waste treated:** Green waste, lignocellulosic waste. **Type of technology:** Biological (fungi). **Description:** Mycelium is the filamentous structure produced by the cells of fungi. Organic agrofood by-products or lignocellulosic waste are used for growing the mycelium, using different feedstock depending on the target products. Growth occurs either in moulds or an airborne environment. According to the target characteristics, the strain, the conditions of growth, and the time are tailored. The typical equipment for the production of mycelium is vertical modular cultivation. For instance, the substrate for the mycelium-based foams always uses lignocellulosic waste since fungi can preferentially degrade cellulose or lignin in plant biomass. Additives might be also added to produce a biocomposite, such as glass, to increase fire resistance. Construction materials such as insulation panels against noise and thermal can be produced based on mycelium. This can be also used in the production of foams. In addition, mycelium can provide biodegradable packaging substituting polystyrene. Leather substitute can be produced from a layer of airborne grown mycelium with subsequent treatment to improve durability. Apart from this, mycelium can also be used in the food sector as vegan meat, especially as a bacon substitute.

Table 2. *Cont.*

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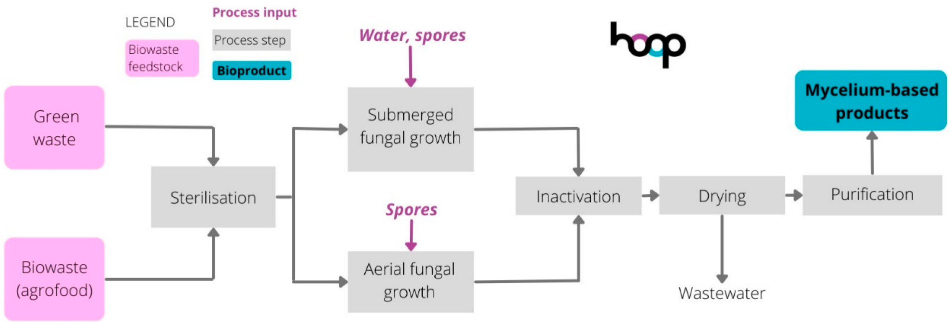
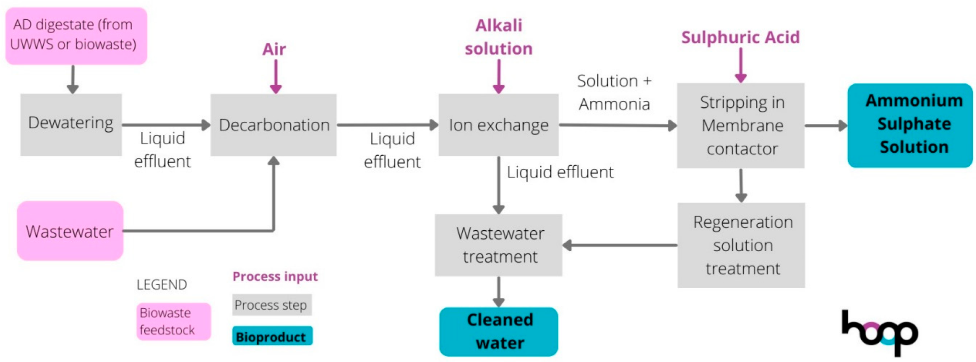
<tr><th>Technology</th><th>Description, Bioproducts, and References</th></tr>
<tr><td>21. Mycelium production</td><td>


Bioproducts: Insulation panels, foams, packaging, vegan leather, vegan bacon.
Market sectors: Packaging, construction, textile, nutrition.
References: [387–410]</td></tr>
<tr><td>22. Nitrogen recovery with ion exchange and membrane contactors</td><td>**Waste treated:** OFMSW, UWWS, wastewater.
Type of technology: Chemical.
Description: This technology recovers nutrients in wastewater, especially nitrogen in its ammonium form. The technology involves two main units: an ion-exchange step for ammonium concentration and a membrane contactor unit for ammonia recovery by stripping and absorption with a liquid in order to produce a marketable fertiliser (this step is similar to the one described in 3. Nutrient recovery). Both ion exchange and membranes have been applied separately and together with different feedstocks, such as manure, AD supernatant, landfill leachate, or urine. The final product of this treatment train is an ammonium salt solution which can be used as fertiliser or as an intermediate product for fertiliser production.


Bioproducts: Ammonium sulphate solution, ammonia water solution.
Market sector: Agriculture.
References: [411–428]</td></tr>
<tr><td>23. Bacterial cellulose production</td><td>**Waste treated:** OFMSW, other hydrolysable biowaste.
Type of technology: Biological (fermentation).
Description: Bacterial cellulose (BC) is a natural fibre that is an excellent raw material for the manufacture of composite materials that offer unique and improved properties such as high crystallinity, resistance, non-toxicity, biodegradability, high degree of purity (absence of hemicellulose or lignin), making it an interesting substitute for vegetable cellulose. The technological process of BC production is based on the hydrolysis of biowaste to release sugars used later as growth medium for bacteria rich in cellulose. The fermentation can be carried out under static or aerated and/or agitated conditions in a fermenter. Once a good production of BC (in sheet or pellet) is reached, it is harvested and bleached. After bleaching, the biopolymer is available for use in wet format in sheets, wet in crushed suspension, or dry in powder form (after drying by spray dryer or other similar techniques). The final format of the product depends directly on the type of application for which it is intended.</td></tr>
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Table 2. *Cont.*

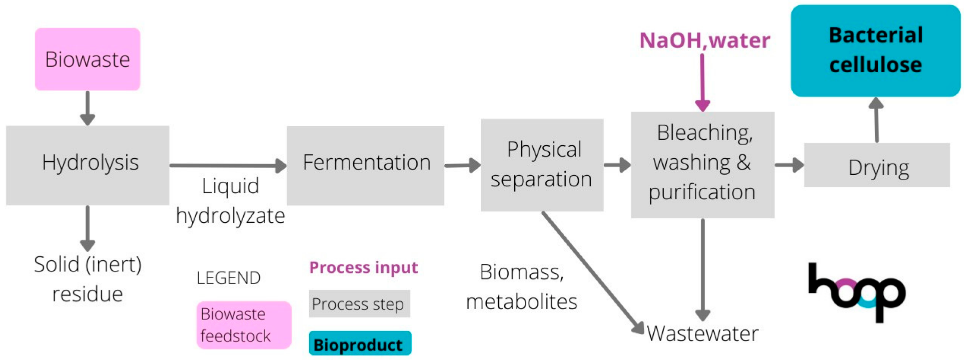
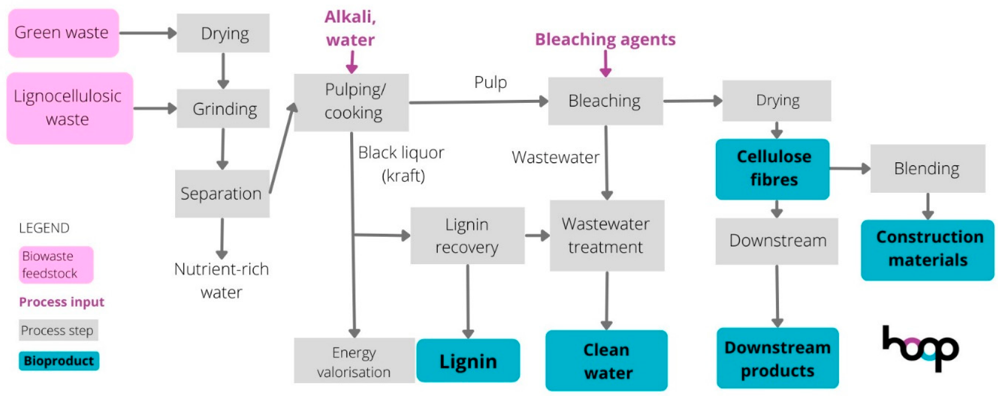
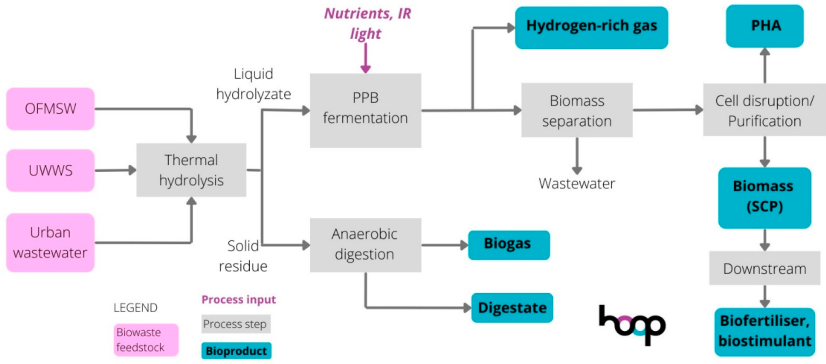
Technology	Description, Bioproducts, and References
23. Bacterial cellulose production	 **Bioproducts:** Bacterial cellulose. **Market sectors**: Cosmetics, biomedical, paper, nutrition, electronics. **References:** [13,429–448]
24. Isolation of fibres from green waste	**Waste treated:** Green waste (parks, garden). **Type of technology**: Chemical. **Description:** Green waste from maintenance of public spaces, rich in lignocellulosic-based materials, can be used as source of fibres. The dried biomass is milled, sieved and sent to the process to obtain the fibres. Following an approach similar to the kraft process for pulp production, cooking and bleaching are the processes used for the cellulose isolation from lignocellulosic sources. The fibres can be valorised as high-added-value products using a downstream process. This implies the application of mechanical and chemical processes for the obtention of nanocellulose (cellulose nanofibres, microfibrillated cellulose, and cellulose nanocrystals). With the acidification of the black liquor the lignin could be precipitated and purified, obtaining a second bioproduct from green waste. Cellulose fibres coming from the biomass can be used in the paper-making industry or combined and extruded to create biocomposites. Elements such as traffic signs, urban furniture, or isolation panels can be prepared. The cellulose fibres can be also used as reinforcement in construction material such as green concrete, with applicability as noise insulation barriers in roads.  **Bioproducts:** Cellulose fibres, others (biocomposites, paper, cellulose nanofibres, microfibrillated cellulose, cellulose nanocrystals) **Market sectors**: Materials, paper, construction. **References:** [449–452]

Table 2. *Cont.*

Technology	Description, Bioproducts, and References
25. Purple photobiotrophic bacteria	**Waste treated:** UWWS, wastewater, OFMSW. **Type of technology:** Biological (fermentation). **Description:** A process for fermentation with purple phototrophic bacteria (PPB) treats simultaneously OFMSW and urban wastewater by means of a two-step process. The first step is thermal hydrolysis with water. After this first step, the solid residue from hydrolysis is sent to AD, but the liquid hydrolysate, rich in saccharides and nutrients, goes to an anaerobic photobioreactor for fermentation with PPB. These bacteria use the infrared radiation from sun to grow, producing an enriched biomass. Depending on the conditions, the fermentation can be used for the production of PHAs by accumulation. Moreover, the bacterial biomass, which is high in proteins, can be used for the production of fertilisers through downstream processing (hydrolysis). In addition to these bioproducts, the fermentation also generates biohydrogen. However, the high concentrations of ammonium required to maximise the yield of protein inhibit the production of biohydrogen, so the amounts obtained are low.  **Bioproducts:** PHAs, biostimulants, hydrogen. **Market sector**: Biopolymers, energy, agriculture. **References:** [453–460]

* Nutrition value-chain. Animal-based biowaste must be avoided.

Apart from the above-referred-to technology list, technologies from related H2020 projects out of the scope of this review have also been identified. In general, they represent variations of the technologies reported in Table 2 in terms of feedstock or downstream processes into bioproducts. In addition, it is worth mentioning the database of technologies [461] for biowaste treatment developed in the project Tech4Biowaste [462], which provides a very useful overview of general trends in biowaste valorisation and a starting point for their analysis.

5. Technology Assessment and Discussion

This review manuscript has an eminent applied approach as it intends to be useful for project promoters towards the adoption of technologies to deal with the OFMSW/UWWS, providing high value product. Once the traditional and state-of-the-art technologies have been presented and described, it is our aim to assess and compare them, this being the objective of this Section 5, covering key aspect such as the test of the solutions under real-life conditions, their enabling factors and considerations and the compatibility with existing systems.

5.1. Use of the Technologies Identified under Real-Case Conditions

This subsection includes the experiences and conditions where such real-life experiences have taken place, as well as the level of maturity of the technology. Together with this information, it is important to know the feedstock that has been used. Table 3 summarises the status of the technologies, providing information on examples of existing pilots, demonstration plants and implementation at commercial level. Moreover, Table 3 also describes the results of the techno-environmental analysis (see Section 2. Methodology) in an aggregated manner, providing significant enabling factors as well as considerations for each one of the technologies identified in the previous section.

Table 3. Comparative table: current status of the state-of-the-art technologies, enabling factors and considerations.

Technology	Current Status, Enabling Factors, and Considerations
1. Bioprocess involving methanotrophic bacteria using biomethane arising from the AD of the OFMSW	**Current status: TRL 8** **Examples of existing pilots:** VALUEWASTE (60 t SCP/year) **Comments on commercial scale implementation:** Technology established with natural gas. Tested in the Soviet Union (10,000 t/year) [463]. At least 5 companies operating plants in different countries (UK, USA, Russia, Denmark) with different capacities (6000 t SCP/year [51], 20,000 t SCP/year [463]). Interest in the technology has been lost due to the priority on energy use of biogas.
	Enabling factors • The feedstock required can be obtained from any biogas flow from anaerobically digested urban biowaste. • High TRL (7–9) for use as protein feed for animals. • No special additional raw materials are needed. • Waste produced are liquid effluents, which are rich in salts and nutrients and toxic-free. No specialised waste treatment needed. Waste produced can be treated in a waste treatment plant, which is generally an inexpensive process, or partially reintroduced in the fermenter. • The approach employs CH_4 for material valorisation, avoiding the CO_2 emission associated to the energetic valorisation of biogas (burning). • GHG emissions are being avoided as biowaste is not diverted in landfills. **Considerations:** • Single-cell protein (SCP) is not suitable for human consumption because of the high content of nucleic acids (nitrogen-rich diets cause nephritic stress) and a fractionation downstream would be necessary to remove them. • In the case of fractionation this would imply extra steps for the separation process (i.e., membrane filtration). • Lower interest in material valorisation of biogas due to international geopolitical situation. • Emissions are expected directly due to fuel consumption for generation of heat/steam during the process (drying, sterilisation or temperature control) and indirectly due to electricity consumption (i.e., pumping in membrane separations, in case of fractionation).
2. Insects breeding	**Current status: TRL 7–9** **Examples of existing pilots:** VALUEWASTE (1 t/d), SCALIBUR. **Comments on commercial scale implementation:** Commercial installations inside EU [464] with a capacity up to 60,000 t waste/year [465,466] and outside EU [467–469]. The trend in Europe is to avoid the nutrition value-chain and focus on downstream.
	Enabling factors • Only grinded biowaste is required for feedstock. • The process is very robust for bad quality biowaste: improper materials (plastics, metals, glass, etc.) are simply left aside by the larvae and do not affect their metabolism. • High TRL. Worldwide (non-EU countries), the production of BSFL for feed, oil and frass can be found on TRL 9. • If the quality of the separately collected biowaste is excellent, the residue associated to the bioprocess would be 0%. • In case of ammonia (NH_3) generation, for eventually unoptimised conditions during the fattening phase, the quantity is too small to require air treatment or to imply environmental concerning. • Emissions avoided in raw material fertiliser fabrication when frass is used for agriculture. • Applicability to agri-food by-products **Considerations** • In case of further processing into, for instance, protein hydrolysate or chitosan is done, chemicals and/or enzymes might be required as additional raw material. • Regulatory constraints for the use in nutrition sector when insects fed with biowaste • The formation of ammonia-like odours during the fattening phase of larvae can take place if the process is not optimised. Other residual streams might be formed in case of further processing into hydrolysates (i.e., solvents, effluents from hydrolysis).

Table 3. *Cont.*

Technology	Current Status, Enabling Factors, and Considerations
3. Nutrient recovery (struvite, ammonium sulphate)	**Current status: TRL 8–9** **Examples of existing pilots:** VALUEWASTE, LIFE ENRICH. **Comments on commercial scale implementation:** Implementation on commercial scale (2.5 t/d, TRL 9) with wastewater and other specific waste as UWWS digestate [470] for both struvite and ammonium sulphate. Several patented technologies.
	Enabling factors • The process is currently on a TRL 9 for both struvite and ammonium sulphate recovery. • Variety of waste. • Avoided use of phosphate rock for fertilisers. • Struvite and ammonium sulphate included in Fertiliser Products Regulation • Emissions avoided due to the avoided manufacture of N and P mineral fertilisers, due to the use of the solid digested fraction (directly or previously composted) in agriculture. • Comparing the fertiliser nutritional value (5.7% N, 26% P_2O_5 and 13% MgO) present in 1 ton of struvite with equal quantity of mineral fertiliser, CO_2 can be saved between 4 to 6 tons. • For 1 m^3 of biowaste treated 5–7.5 kg of CO_2 is saved, or for 10 m^3/h biowaste treated, 500 tons CO_2/year are saved. **Considerations** • The residue is wastewater, which could be used to irrigate agriculture crops. Otherwise, the residue is diverged to a wastewater treatment plant for urban wastewater (no industrial treatment required, no concern about toxic additives, metals, etc.). • Use of sulphuric acid for ammonia absorption. • Direct emissions due to the burning of biogas generated in AD that is used to heat the digester (CH_4, N_2O, SO_2). • Indirect emissions due to the consumption of electrical energy in the process: The related GHG are purely the ones originating from the production of the needed power consumption. • Direct emissions due to the consumption of fuels to generate heat/steam in the process—for example, in product drying stages. • Direct emissions from the composting of the solid fraction of the digested (NH_3, N_2O, CH_4), if this is carried out. • Direct emissions (NH_3, N_2O, CH_4) due to the application of the solid fraction of the digest (directly or previously composted) as a source of N and P.
4. Microalgae cultivation	**Current status: TRL 5–6** **Examples of existing pilots:** Bergen/NORCE (10 m^2, capacity 520 kg/year). **Comments on commercial scale implementation:** Bioproduct established (324 dry ton/year in Europe), with different levels of development depending on the microalgae species [471] but not from waste.
	Enabling factors • The residue from hydrolysis might be used as feedstock for further processes, as for instance composting. This residue might be also used as organic fertiliser. • Saving in emissions by using CO_2 for microalgae cultivation (only autotrophic microalgae) and avoidance of landfilling emissions. • TRL 5 (validated) or 6 (demonstrated). • Important advantages compared to the production of microalgae from fermentable sugars for heterotrophic species. **Considerations** • For hydrolysis, either enzymes (enzymatic hydrolysis) or steam and high pressure (thermal hydrolysis) are required. CO_2 is not required for heterotrophic microalgae • Solid residue from the hydrolysis.

Table 3. *Cont.*

Technology	Current Status, Enabling Factors, and Considerations
5. Fermentation of used cooking oils into biodegradable polymers	**Current status: TRL 8–9** **Examples of existing pilots:** WAYSTUP!, Nafigate (1 t PHA/year). **Comments on commercial scale implementation:** Commercial plant in Ostrava (Czech Rep.) (45,000 L/year producing 35 t PHA/year, expected to increase to 227,500 L/year producing 175 t PHA/year).
	Enabling factors • Waste cooking oil does not need any specific pre-treatment before entering the basic production process. • High TRL: TRL 9 for up-stream process (USP), TRL 8 for down-stream process (DSP). • Waste cooking oil of any type can be used, even coffee oil made from spent coffee grounds. • Residues (biomass) are directly used for energy production (biogas station), which is part of the technological process. • According to life cycle assessment (LCA) results, depletion of fossil fuels and marine aquatic ecotoxicity impact categories as well as global warming potential impact category strongly support production of PHAs from UCOs instead of production with low density polyethylene (LDPE) and polylactide granulate. • High potential for the substitution of microplastics in the cosmetic sector **Considerations** • In the case of coffee oil, prior to its use in a fermentation process, the oil was sterilised at 121 °C for 40 min to prevent contamination. The temperature of the coffee oil was maintained above 60 °C after sterilisation. • Additional raw materials are used: air, water, and mineral nutrients. • Used cooking oils still remain categorised as animal by-product, and there might be limitations on their applicability. • Competition with biodiesel industry for the same feedstock.
6. VFAs production from UWWS anaerobic fermentation	**Current status: TRL 7–8** **Examples of existing pilots:** CIGAT Ourense (Spain) (1 t VFA/year), Twence. **Comments on commercial scale implementation:** Demo plant (ChainCraft) from waste in Amsterdam (20,000 t waste/year to produce 2000 t VFA/year) [472], TRL 7–8 [174].
	Enabling factors • VFAs production is possible without a pre-treatment process, except for those typical of AD. • Relatively high TRL (7–8), according to the literature [174]. • For bio-based VFAs production, different waste streams could be used as feedstock. • Solid phase from the acidogenic fermentation broth still contains organic matter, so this can be exploited to produce biogas by complete AD. In addition, the remaining solid fraction can be used in agriculture due to its fertiliser properties. • If the energy used in the process is obtained from renewable sources, carbon neutrality can be achieved. **Considerations** • The UWWS used as a substrate for this technology is produced during the aerobic fermentation process necessary for water treatment. Therefore, as the core VFA production process is anaerobic fermentation, additional sludge containing anaerobic bacteria is used as inoculum in addition to sodium hydroxide (NaOH). • The solid fraction of the fermentation, if not properly valorised, can be considered as residue waste. • The main GHG emissions derive from the different chemical reactions that require an energy input. Other minor sources of emissions include the methane liberation from sludge degradation and due to an incomplete inhibition of methanogenesis. • VFA production through fermentation and their recovery is an emerging technology and there is no conclusive information about the environmental performance so far, although it can be affirmed that its environmental performance improves with respect to the conventional production method.

Table 3. *Cont.*

Technology	Current Status, Enabling Factors, and Considerations
7. Ethanol and other biosolvents from cellulosic rejections of WWTP and OFMSW	**Current status: TRL 8 (ethanol); TRL 5–7 (ethyl lactate)** **Examples of existing pilots:** WAYSTUP!, PERCAL. Perseo (25 t waste/d). **Comments on commercial scale implementation:** Commercial production of ethyl lactate both with bioprocesses from fermentable sugars or from petrochemical origin depending on the production of ethanol and lactic acid. Growing interest in the production of ethanol.
	Enabling factors • The organic solid produced as output can be used as (depending on its composition): • Valuable feedstock for biomethanisation to produce biomethane and biofertiliser (AD). • High-calorific-value organic material for heat and electricity production through a cogeneration process (waste to energy). • Organic material with low content of inert materials to produce a biofertiliser (composting). • High TRL for ethanol production. **Considerations** • Pre-treatment is needed for the feedstock before entering the process. Available methods could be mechanical, mechanical-chemical, chemical, or biological. • Additional raw materials—sulphuric acid, acetaldehyde, bioethanol—are needed in order to transform the lactic acid into ethyl lactate. • After the saccharification and fermentation process organic solid is produced as output.
8. PLA production from fruits and vegetables	**Current status: TRL 5–6** **Examples of existing pilots:** VAMOS (15 m^3) **Comments on commercial scale implementation:** Bioproduct established on commercial scale (TRL 9), but based on fermentable sugars [473]. Due to the difficulties in biodegradability, the interest in PLA is decreasing. The same technology might focus more on lactic acid production.
	Enabling factors • Regarding vegetal biomass (i.e., fruits and vegetables) there is no need for pre-treatment. • Compostable plastic. • Important advantages compared to the production of lactic acid from fermentable sugars. **Considerations** • Polymerisation needed as final step to produce PLA. This adds an extra step in comparison with PHA. • The overall yield of the biotechnological process for obtaining PLA is low. There is still a long way to go in this technology [474]. • Additional raw materials: Lactobacillus in fermentation; additionally, for enzymatic activity: Celluclast®, Novozyme 188®, and Pectinex Ultra SP-L®. • PLA production process produces greenhouse gases CO_2 and CH_4. However, the emission of gases from this biotechnological process is 50% less than the production process of PLA from fossil resources.
9. Bioprocess production 2,3-Butanediol from OFMSW, garden and UWWS	**Current status: TRL 6–7** **Examples of existing pilots:** CENER Spain (1–3 m^3). Demonstration plant in Korea for bioprocess (300 t 2,3-BDO/year) [475], but not from waste **Comments on commercial scale implementation:** Not available yet in commercial 2,3-Butanediol with biologic origin
	Enabling factors • Remains of seeds, bagasse and lignocellulosic vegetables that have not been able to degrade during the process can be valorised (compost, AD) and are not toxic. • Flexible chemical building block. **Considerations** • Additional raw materials: • Enterobacter ludwiggii: Facultative anaerobic gram-negative bacteria. • Sulphuric acid (H_2SO_4): is an extremely corrosive chemical compound. • Enzymes. • TRL variations depending on the provider (2–7). • Need to consider potential pathogenicity of the bacteria. • The bioproduct itself does not have high value and depends on the existence of industries for the production of derived products.

Table 3. *Cont.*

Technology	Current Status, Enabling Factors, and Considerations
10. Slow pyrolysis	**Current status: TRL 7–9** **Examples of existing pilots:** WAYSTUP! (7.2–9.6 t waste/year). **Comments on commercial scale implementation:** Commercial plants with biomass and waste. P4S Almere [476]. Large-scale projects in construction (Futerra 200,000 t biomass/year [477], Ireland 75,000 t/year). Significant problems in pyrolysis plants from municipal waste in the past [235].
	Enabling factors • There is no pre-treatment before feedstock enter into the slow pyrolysis of the process, although drying is recommendable for UWWS. • The pyrolysis eliminates pathogens, stabilises heavy metals and reduces the bioavailability of minerals. So, in theory, there are no microorganisms and chemical solvents needed for this process. • Solid waste (biochar) is the bioproduct. • Biochar amendment is conductive to promote carbon sequestration, enlarging soil carbon pools, and lessening the emission of greenhouse gases. • Biochar is included in fertiliser product regulation. **Considerations** • Energy required to reach the temperature might require burning the gas. • Off-gas management system. • Important differences in the process and feedstock suitability between technology providers • Limitations in the feedstock for the production of biochar under EU fertiliser product regulation.
11. Fermentation of SCGs	**Current status: TRL 7** **Examples of existing pilots:** WAYSTUP! (2.6–5.2 t waste/year). **Comments on commercial scale implementation:** Production of carotenoids might be independent of the specific feedstock, but not oil and aromas, which require a source of coffee.
	Enabling factors • No pre-treatment before the SCGs enters the fermentation process. • TRL 7 for the SCG process for oils and aromas. • The residue generated can be employed to feed insects in order to obtain insect protein. **Considerations** • Additional raw materials: hexane (oils process), ethanol (aromas process), • Carotenoids fermentation process additional compounds: $(NH_4)_2$ SO_4, KH_2PO_4, $MgSO_4$, glucose, sulphuric acid, commercial enzyme. • Liquid residue waste expected. Wastewater treatment will be needed. • Challenges with feedstock availability.
12. Biochemical production of functional ingredients from animal by-products	**Current status: TRL 7** **Examples of existing pilots:** WAYSTUP! (52–260 t waste/year). **Comments on commercial scale implementation:** Gelatine production based on food industry and slaughterhouse by-products [255].
	Enabling factors • No special pre-treatment of biowaste is needed except for crushing and grinding. • Hydrolysed collagen TRL 7. **Considerations** • Additional raw materials: Filtration grounds, water, enzymes (commercial), sulphuric acid. • Liquid residue expected. Wastewater treatment will be needed. • Feedstock needs to be carefully selected to comply with animal by-product regulation.

Table 3. *Cont.*

<table>
<tr><th>Technology</th><th>Current Status, Enabling Factors, and Considerations</th></tr>
<tr><td rowspan="2">13. Biochemical conversion of OFMSW to bioplastics</td><td>Current status: TRL 7
Examples of existing pilots: SCALIBUR.
Comments on commercial scale implementation: Several patented technologies. Commercial plants from fermentable sugars with high capacity which needed to downscale due to market size. Some companies based on waste (5000–10,000 t/year) [478].</td></tr>
<tr><td>Enabling factors
• Biodegradable and compostable bioplastic (reduced GHG emissions compared to fossil-derived plastics).
• Potentially higher robustness due to previous hydrolysis.
• TRL 7 for PHA.
Considerations
• Costs might be higher due to the use of enzymes.</td></tr>
<tr><td rowspan="2">14. Production of Biopesticides from OFMSW</td><td>Current status: TRL 6–7
Examples of existing pilots: SCALIBUR.
Comments on commercial scale implementation: Bioproduct commercially established in the global market. Estimation of more than 32 companies [479]. Large-scale production not from waste.</td></tr>
<tr><td>Enabling factors
• The production of biopesticides will contribute to reduce GHG emissions from the extraction of raw materials for conventional pesticide production.
Considerations
• Specific pre-treatment needed before the fermentation process.
• Additional raw materials: Bacillus thuringiensis, water content, and nutrient adjustment.</td></tr>
<tr><td rowspan="2">15. Production of biofertilisers and biostimulants</td><td>Current status: TRL 6
Examples of existing pilots: SCALIBUR.
Comments on commercial scale implementation: Estimation of 60 bioproducts available in the global market from different strains [480,481] but not from waste.</td></tr>
<tr><td>Enabling factors
• The solid waste from hydrolysis might be used as feedstock for further processes as, for instance, insect breeding or as organic fertiliser.
• The production of biofertilisers will contribute to reduce GHG emissions from the extraction of raw materials for conventional fertilisers production.
• Decreased cost and environmental impact compared to the production from fermentable sugars.
Considerations
• Additional raw materials: Enzymes such as proteases, cellulases, ligninases, lipases, and pectinases for the hydrolysis process. Endoglucanases and exoglucanases or cellobiohydrolases.
• Limited number of microorganisms accepted.</td></tr>
<tr><td rowspan="2">16. Bioconversion of UWWS: CO_2 fermentation with bioelectrochemical systems</td><td>Current status: TRL 5
Examples of existing pilots: SCALIBUR.
Comments on commercial scale implementation: Emerging technology focused mainly in wastewater treatment. Lower development for chemical building blocks [482]. The technology was not successfully validated on a pilot scale.</td></tr>
<tr><td>Enabling factors
• The input of the process is the CO_2 produced from the AD of UWWS.
• The anaerobic digestate (coming from the AD) can be direct applied to soil.
• No specific pre-treatment is needed.
• Direct CO_2 sequestration from the technology implementation.
Considerations
• Additional raw materials: Enriched homoacetogens.
• Relatively low TRL 5.
• Issues with feasibility.</td></tr>
</table>

Table 3. *Cont.*

Technology	Current Status, Enabling Factors, and Considerations
17. Bioconversion of UWWS: production of PHBV and other PHAs	**Current status: TRL 7** **Examples of existing pilots:** URBIOFIN (10 t MSW/d); RES URBIS (30 kg PHA), Phario (500 L), Mountain View (USA, 2 t waste/d). **Comments on commercial scale implementation:** Commercial technologies provided by companies, mainly SMEs [478].
	Enabling factors • The PHA production plants are generally designed as a side-stream process of WWTP. • The waste expected can be managed together with primary and secondary sludge from WWTP. • Biodegradable and compostable bioplastic (reduced GHG emissions compared to fossil-derived plastics). **Considerations** • Common configuration of a WWTP for the production of PHA associated with the same plant, may include treatments such as primary settling followed by an activated sludge system; primary sludge and waste activated sludge are then separately thickened. Methane production from AD of the sludges is partially replaced by PHAs production for UWWS valorisation. • Additional raw materials: fermented organic waste as VFA feedstock, bacteria that are able to accumulate PHBV/PHA. • Limitations in the applications due to pollutants.
18. Hydrothermal carbonisation	**Current status: TRL 8–9** **Examples of existing pilots:** Valencia (14 kt/year OFMSW, UWWS, agrofood). Heinola (Finland, 16 kt/year UWWS, pulp sludge). Jining (China, 21 kt/year UWWS). **Comments on commercial scale implementation:** Mainly applications to UWWS. The hydrochar in most cases is used for energy purposes. Nutrient recovery required in water effluent.
	Enabling factors • High volume and mass reduction for UWWS and other biowaste with high moisture content. • Potential to obtain clean water from UWWS. • Lack of pre-treatments. **Considerations** • Nitrogen is mainly transferred to the water phase. Nutrient recovery is required. • Hydrochar has lower quality than biochar for agriculture application. • Energy demanding process. • Off-gas management system.
19. Succinic acid production	**Current status: TRL 5** **Examples of existing pilots:** PERCAL (pilot OFMSW). Cassano (Italy, 10 kt/year). Sarnia (Canada, 30 kt/year). **Comments on commercial scale implementation:** Several patented technologies. Commercial plants from fermentable sugars with high capacity. Most companies needed to stop production due to excess of capacity for the market demand. Other two plants not operative in Montmeló (Spain, 10 kt/year) and Lake Providence (USA, 15 kt/year).
	Enabling factors • Wide range of derived products in a biorefinery context. • Important experience on industrial scale. **Considerations** • Separation and purification process very demanding in economic terms. • The bioproduct itself does not have high value and depends on the existence of industries for the production of derived products. • Industrial-scale experiences have stopped in many cases.

Table 3. *Cont.*

Technology	Current Status, Enabling Factors, and Considerations
20. Production of biosurfactants	**Current status: TRL 7** **Examples of existing pilots:** Amphistar Food waste (Gent, Belgium). Holiferm (Wirral, UK) **Comments on commercial scale implementation:** Most technologies are based on fermentable sugars. The isolation and purification step is the most important. A commercial plant is in planning in Lupca (Slovakia).
	Enabling factors • Substitution of fossil-based surfactants. • Wide range of products. • Biodegradability. • Market sector with low regulatory restrictions. **Considerations** • Not as high TRL using waste as feedstock. • Challenges in the isolation and purification of the bioproduct. • Need to consider potential pathogenicity of the bacteria.
21. Mycelium production	**Current status: TRL 7–9** **Examples of existing pilots:** Arnhem (leather). Green Island (USA, 1.5 kt mycelium/year) US. Colorado (USA, 22.5 kt mycelium/year). **Comments on commercial scale implementation:** High diversity in the range of bioproducts with different degree of development. The plants have a trend to modularity. The plant capacity is defined in terms of surface. The development is taking place mainly in USA. Vegan leather and food are the applications attracting the most investments.
	Enabling factors • Wide range of products in diverse market sectors. • Relatively simple technology. • Biodegradability of the bioproduct. • Good isolation properties. • Substitute of high environmental impact products. **Considerations** • Treatments required in several cases to achieve the final functionality (vegan leather, increase in structural strength). • Need of feedstock with good quality, as in some cases (construction) it remains in the final product.
22. Nitrogen recovery with ion exchange and membrane contactors	**Current status: TRL 5–6** **Examples of existing pilots:** WALNUT (OFMSW), Münster WWTP. **Comments on commercial scale implementation:** Münster WWTP had a pilot for nitrogen recovery with membrane contactors which has ceased activity. There was also a pilot in Maribor (Slovenia).
	Enabling factors • Similar fundamental as ammonia absorption. • Flexibility. The solution can adapt to different feedstock inputs due to its modularity. • Easier wastewater treatment. • Removal of other pollutants such as heavy metals through ion exchange. • Ammonium sulphate solution with high purity. **Considerations** • Important interferences in effluents with high concentrations of other cations (calcium, magnesium). • Use of chemicals and need for the treatment of the regeneration solution. • Monitoring of the ion exchange cycles and planning of use and regeneration steps. • The bioproduct is normally a solution that needs to be used not far from the production point.

Table 3. *Cont.*

Technology	Current Status, Enabling Factors, and Considerations
23. Bacterial cellulose production	**Current status: TRL 7–8** **Examples of existing pilots:** Cellulose Lab 96,000 m^2/year (Fredericton, Canada). Cellugy 3 m^3 (Søborg, Denmark). Polybion 102,000 m^2/year (Guanajuato, Mexico). **Comments on commercial scale implementation:** Most commercial scale technologies are based on fermentable sugars. Industrial scale with applications to biomedicine in Canada. Commercial scale BC is used in food industry from South-East Asia based on coconut by-products. Commercial plant for vegan leather in Mexico based on agrofood waste.
	Enabling factors • Special properties not found in vegetal cellulose. • Smaller plant size. • Lower environmental impact, as it does not use virgin wood or chemicals. **Considerations** • High costs, not competitive to vegetal cellulose. • Limitations in application depending on the feedstock.
24. Isolation of fibres from green waste	**Current status: TRL 8–9** **Examples of existing pilots:** Upcycle Centre Almere (1.2 kt/year), CELESA 19 kt/year fibres (Tortosa, Spain). Borregaard 1 kt/year microfibres (Sarpsborg, Norway). VAMOS, CAFIPLA. **Comments on commercial scale implementation:** High TRL for fibre isolation, but lower for applications. Growing market of biocomposites based on natural fibres for diverse applications as in construction and automotive sector [483]. Companies in process of developing processes on large scale to valorise fibres from waste [451]. Value chain inside forestry biorefineries including also lignin valorisation.
	Enabling factors • Circular solution to green lignocellulosic waste normally energetically valorised. **Considerations** • Use of polluting chemicals. • Very variable quality depending on the feedstock and processing conditions. • Marketability depends on derived products.
25. Purple photobiotrophic bacteria	**Current status: TRL 7** **Examples of existing pilots:** DEEP PURPLE 350 m^3/d (Linares, Spain). **Comments on commercial scale implementation:** Flexible production depending on the operation conditions.
	Enabling factors • Flexibility in bioproducts. • Possibility to produce hydrogen. **Considerations** • Large area required. • Important investment in the photobioreactor. • Sensitive fermentation conditions. Increasing yield in biomass decreases yield in hydrogen.

In terms of **TRL**, a wide range from 5 to 9 can be observed. This is very related to the nature of the pilot found. Many of the pilots are related to projects of innovation actions with TRL of 6 or projects of demonstration, which can increase the TRL into 8, as for instance in the case of ethanol production. It is also important to notice that a same technology might be found at different TRL depending on the downstream. A clear example of this is the production of ethanol in comparison with the production of ethanol-based biosolvents. In general, when there is a company behind the technology TRL is higher and this is the case in those technologies showing TRL 9. The range shown in the TRLs is related to the fact that several technology providers might represent the same technology, or the same technology provider might work with different feedstock at a different degree of maturity.

It must be noted that several of the presented technologies have not been developed from scratch, but **adapted from other sectors** that traditionally employ other kind of feedstock. This means that some of them are already tested, but the uncertainty coming from the change of feedstock gives them a lower TRL. For example, methanogenic bacteria have been used for the production of single cell protein (SCP) from natural gas, and nutrients recovery by means of struvite precipitation and ammonium sulphate has a higher level of development in the wastewater value-chain [470]. Several technologies involving fermentation come from already existing biotechnological processes based on fermentable sugars (i.e., PLA production, bioethanol). In some cases (i.e., microalgae cultivation, bacterial cellulose), the success of using a cheap raw material (biowaste) would imply considerable changes in their economic feasibility. There are also some technologies, such as pyrolysis, gelatine production, and isolation of fibres, with a long background, but new applications (e.g., biochar) and downstream processes (e.g., active peptides) have been found. Some of the bioproducts are already consolidated in the market, but coming from different feedstocks: bioethanol, polylactic acid (PLA), biopesticides, biostimulants (PGPR), or gelatine and active peptides. There is also the case of emerging bioproducts with very important trend of growth, but which have not reached yet its full potential (i.e., struvite, PHA, mycelium or microalgae). In this case, struvite, insects or mycelium have increased their impact in the last two years with regulatory advances and important investments.

It is also important to notice the **flexibility** of some of the technologies, which allow the treatment of different types of biowaste. However, differences might be found in the pre-treatments. One clear example is the production of bioethanol from cellulosic materials. This feedstock requires different pre-treatments than if the same technology were applied directly to OFMSW. Moreover, one type of bioproduct can be obtained from very different technologies and feedstocks. This is the case for PHA (fermentation of used cooking oils, bioconversion of OFMSW, fermentation with PPB).

Most of the **techno-environmental enabling factors and considerations** shown in Table 3 are related to the general mass balances of each of the technologies. One of the aspects appearing in most technologies is their requirements in terms of **additional raw materials** and energy. The raw materials are related mainly with the chemical processes implied, as for instance the addition of magnesium in nutrients recovery or the use of solvents in the production of functional ingredients from SCGs. However, the enzymes or the chemicals used for the hydrolysis also play an important role in this balance of additional raw materials.

In terms of **energy**, the sustainability depends much on the source of energy needed, as most technologies required heat, pumping, stirring and other kind of electrical consumption associated. The source of the energy has an important influence on the impacts. It is important to notice that some of the technologies are generating emissions by themselves, as for instance pyrolysis or the ammonia released from insects, which need also to be taken into consideration. From a technical point of view, some bioproducts do not have a market by their own, but they require further steps to come into marketable products; such is the case for 2,3-butanediol and succinic acid.

In terms of **residues**, it can be seen that almost all the technologies based on hydrolysis produce a solid residue and a biomass that need to be further managed. In most cases, these materials are suitable for AD, composting or insect feeding, which means that the impacts and benefits associated to those treatment can be also accounted. Actually, in most cases, the most beneficial impact of the technologies is related to the substitution of a fossil-based product (bioplastics, biosurfactants, fertilisers) which has a much higher impact that those generated by the processes based on biowaste. Apart from the impacts in terms of raw material extraction, the bioproducts usually are biodegradable, which is a key advantage. In terms of hydrolysis, the impacts avoided from the sugar production are considered in most of the technologies where the biowaste or by-products are the source of a growth medium.

In terms of **landfill reduction**, there are two aspects that determine the impact of technologies. The first aspect is related to the ability to treat a broader range of waste. This means that the technology would divert a larger amount of waste from landfill or incineration. The second aspect is the generated residue, as this will require further management. Technologies generating less by-product/residue will contribute more to landfill reduction. From this point of view, insect breeding and pyrolysis are the technologies with the highest impact as they both provide management for the feedstock to the process and for the biomass generated. This integral management does also take place in some cases of mycelium production. In the case of technologies based on hydrolysis, both a solid fraction from hydrolysis and biomass from fermentation steps are generated. Therefore, another method of management of these streams is required. Other technologies, such as nutrients recovery and bioconversion of CO_2 with BES, treat a very small amount of the starting feedstock residue.

In terms of **greenhouse gas emissions**, it is difficult to evaluate the impact of the technologies, as these also depend on the energy consumption and the type of local electricity source. The avoidance of emissions either from landfill or from incineration should be considered, but also the savings from substitution of the fossil raw material or its process (i.e., processing of phosphate rock, petroleum-based plastics, etc.). Some technologies have greenhouse gases as feedstock. These are the bioprocesses involving methanotrophic bacteria (transforming methane and CO_2 into biomass), microalgae cultivation (in case of autotrophic algae), and bioconversion of CO_2 with BES.

It should be noted that the list of aspects included in Table 3 is not exhaustive and mainly depicts the current knowledge and practical experience of the developers of each technology. More detailed information (LCA, economic data) can be found in the references provided in Table 2 for each technology. However, although LCA [50,95,96,203,358,384,399,403] has been one of the key elements considered in the environmental analysis, unfortunately not all the technologies have it available. Results might differ depending on the methodology used, the territorial energy mix, the feedstock and the final application of the bioproduct. In addition, some of the described technologies can be considered as emerging, making it challenging to offer conclusive information on their environmental performance.

Last but not least, authors encourage the reader to keep updated with the European pilot and demo infrastructures on the Europe-wide network and database of open access multipurpose for the European bio-economy "Pilots4U Open Access Database" [484].

5.2. Compatibility of the Technologies Identified with Composting and Anaerobic Digestion

The adoption of innovative technologies, such as the ones identified in this review depends, among other factors, on the existing waste management system. Some of these factors are separate collection of urban biowaste from households, mechanical–biological treatment for mixed municipal waste, and the availability of existing pilots of circular bioeconomy technologies. Cities and regions with these pilots might be more open to upscaling or promoting these existing technologies rather than starting from scratch.

Regarding composting and AD, those technologies able to find synergies with these existing treatments or complement them have an advantage from a point of view of potential adoption, this being the main objective of this subsection.

But before evaluating those synergies and complementarities, these technologies need to be grouped and classified according to diverse criteria. From the analysis of the technologies and in agreement with Suarez et al., 2023 [485], it can be concluded that many of them share common steps and approaches which allow them to be classified under four main categories. These categories are listed below, and the classification is found in Table 4.

- **Hydrolysis technologies**: These technologies have in common a previous step of hydrolysis to release nutrients used in later fermentations. It involves 11 out of 25 technologies in the portfolio.
- **Partial anaerobic digestion technologies**: Some of the technologies (normally thought for UWWS) have the same approach of AD but stopping in a step previous to biogas

formation. This involves stopping in the formation of VFA or their use as growth media for accumulation of biopolymers.

- **Specific biowaste**: These technologies require the separate collection of a very specific biowaste, namely used cooking oils, spent coffee grounds and animal by-products. This means a smaller amount to treat and, therefore, diverts from the bulk urban biowaste treated with another technology.
- **Thermal treatment**: These technologies require the application of high temperatures to induce changes in the biowaste. Depending on the conditions we might talk about different options, pyrolysis and hydrothermal carbonisation being the ones included in the present document, although there is also the potential to add gasification and other hydrothermal processes.

Table 4. Classification of technologies based on steps/approaches.

Technology	Hydrolysis Technologies	Partial AD Technologies	Specific Biowaste	Thermal Treatment	Nutrient Recovery
Microalgae cultivation	Yes				
Ethanol and other biosolvents from cellulosic rejections of WWTP and OFMSW	Yes				
PLA production from fruits and vegetables *	Yes				
Bioprocess production 2,3-Butanediol from OFMSW, garden and UWWS	Yes				
Biochemical conversion of OFMSW to bioplastics	Yes				
Production of Biopesticides from OFMSW	Yes				
Production of biofertilisers and biostimulants	Yes				
Succinic acid production	Yes				
Production of biosurfactants	Yes				
Bacterial cellulose production	Yes				
Purple photobiotrophic bacteria	Yes				
VFAs production from UWWS anaerobic fermentation		Yes			
Bioconversion of UWWS: production of PHBV and other PHAs		Yes			
Fermentation of used cooking oils into biodegradable polymers			Yes		
Fermentation of SCGs			Yes		
Biochemical production of functional ingredients from animal by-products			Yes		
Slow pyrolysis				Yes	
Hydrothermal carbonization				Yes	
Nutrient recovery (struvite, ammonium sulphate)					Yes
Nitrogen recovery with ion exchange and membrane contactors					Yes

* Although the production of PLA from fruits and vegetables waste might fall within the category "specific biowaste", its flexibility makes more reasonable its classification as hydrolysis technology.

As it can be seen, Table 4 includes many of the technologies identified in this manuscript which can be grouped in, at least, one of the four categories. Those that cannot be grouped in any of the categories are provided individually in Table 5, which features the evaluation of the compatibility of those individual technologies, together with the grouped ones, with AD and composting.

Table 5. Evaluation of the compatibility of technologies with anaerobic digestion and composting.

Family of Technologies	Required AD	Compatibility with AD	Comments	Compatibility with Composting	Comments
Hydrolysis technologies	No	Partial	Solid residue from hydrolysis can go to AD. Lower biogas yield and lower feedstock quality.	Yes	Solid residue from hydrolysis can go to composting. Some technologies might treat composting rejections.
Partial AD technologies	No, but better with AD	Partial	Lower biogas yield and lower feedstock quality.	Partial	Composting of AD digestate.
Thermal treatment	No	Yes	Potential digestate valorisation by pyrolysis or HTC	Yes	Potential pyrolysis of composting rejections.
Methanotrophic bacteria	Yes	Partial	It needs AD. It diverts biogas from energy valorisation.	Partial	Composting of AD digestate.
BES	Yes	Yes	Increases biogas quality.	Partial	Composting of AD digestate.
Insects	Yes, for digestate No, for OFMSW.	Partial	Digestate valorisation. Better yield from OFMSW.	No	Competing
Nutrient recovery	Yes	Yes	Digestate valorisation.	Partial	Composting of AD digestate.
Specific waste	No	Partial	Lower amount of OFMSW to biogas (animal by-products and SCGs). Indifferent for used cooking oils.	No	Competing
Isolation of fibres	No	Yes	It treats waste not treated normally by AD.	Partial	Competing for waste, but rejections of composting might be used for Construction.
Mycelium	No	Yes	It treats waste not treated normally by AD.	Partial	Competing for waste, but rejections of composting might be used for construction.

The compatibility and synergy of the groups of technologies depends on the objectives pursued by each promoter at city/region level. In those places with a well-established system of AD or clear plan for its development, any technology decreasing biogas yield, either by competition for the biowaste or by use of the biogas, will be of little interest. However, the suitability might increase for those technologies treating the digestate in case when the current management system does not yield high value (e.g., as the provided by nutrients recovery). This is also the case for those territories with a well-established composting system, where technologies managing the rejections will have higher probability of success. It can be considered that hydrolysis technologies compete with AD for the most fermentable part of the biowaste. The solid residue from hydrolysis can be treated by AD, but the biogas yield would be lower, and the feedstock would be concentrated in improper material, which usually means a challenge for AD.

In cases in which there is no infrastructure for biowaste treatment, the projects would start from scratch, making this a more suitable technology able to treat all the biowaste separately collected and solve the external dependence for management. The technologies for specific waste are especially suitable for food markets and large producers, where the implementation of separate collection is easier than in households. Food/feed value chain acts as barrier, which means that specific collection of non-animal biowaste might be required for robust technologies.

These are some general trends that can be deduced provided as examples, but it is required a case-by-case study, understanding the potential use of bioproducts and the interest of the cities. Some of them might want to test an alternative to a system not providing enough added value (i.e., composting), while others will try to search for technologies complementing what their well-established systems do not cover. There are cities and regions which might be more interested in technologies able to treat the organic fraction coming from the mechanical sorting of mixed waste to solve the problem of management and divert waste from landfill. This can be the case of cities and regions where the separate collection is snot fully implemented and there is uncertainty about its success in short-term.

5.3. Key Analysis for Cities and Regions

Previous subsections have described the technologies' enabling factors, their performance under real-case conditions and compatibility with well-established treatment options. In order to get an analysis of the key factors for cities and regions to consider for implementation as solutions, it is necessary to combine and analyse this information together, and consider factors others than those specific to technology, this being the objective of this analysis section, which has followed a multi-assessment approach.

The analysis can start from a point of view of **robustness**, which is very important when dealing with (bio) waste subjected to seasonal changes in composition and volume. Among the technologies identified, the most robust technology from a point of view of the theoretical acceptance of low quality of the biowaste is insect breeding. The presence of plastic or glass does not represent a major issue, as the larvae simply do not eat them. Although the technology itself has the potential of a high robustness against poor quality biowaste, it decreases the quality of the frass as fertiliser, and the own nature of the nutrition value-chain acts as a limitation, which means that high quality of the feedstock is required anyway and the presence of animal waste must be avoided, according to in force EU regulations (see specific discussion below on regulatory issues). Fractionation into products out of the nutrition sector becomes an option to increase the applicability of these bioproducts. A similar case is found with thermal treatments, which in principle should cope with improper materials but would affect considerably the quality of the biochar or hydrochar. Feedstock with many impurities has a high potential to affect the performance of technologies involving anaerobic digestion pathways, either completely (methanotrophic bacteria, BES) or partially (production of VFAs). This is closely related to the design of the reactor and the stirring system, which can bring mechanical problems either as a result of plastics or damages by materials such as stones. The same problem can take place with hydrolysis technologies, especially if they are based on a stirred tank reactor. In both cases a pre-treatment is necessary. In the particular case of contaminants, it is important to notice that the presence of some organic compounds or variations in conditions such as pH can affect the metabolism of microorganisms or inhibit the activity of enzymes. Besides, this the fate of contaminant and the uptake into the microorganisms (PGPR, biopesticides, single cell protein) and the solutions of metabolic bioproducts (ethanol, succinic acid, volatile fatty acids) is a point of risk that needs to be assessed with higher or lower relevance depending on the final market sector of the bioproduct. This is applicable to traditional contaminants, such as heavy metals, PAH, or persistent organic pollutants, which are considered in the quality criteria for fertilizing products, such as biochar. Moreover, emergent contaminants such as PFAS and microplastics should not be overseen considering potential changes in legislation.

Regarding the **adaptation to existing AD systems**, which—as discussed—is also very important, the technology of nutrient recovery, also including the recovery through ion exchange and hollow fibre membrane contactors, allows the valorisation of nutrients from the liquid effluent from digestate. This technology is synergistic with anaerobic digestion as valorises by-products and takes benefit from struvite, which causes normally technical problems in commercial facilities due to precipitation. Methanotrophic bacteria can provide an alternative to energetic valorisation of the biogas. This technology depends totally on the presence of an AD facility, and it can only be valuable under circumstances in which nutrition sector has higher strategic priority than energy sector.

As indicated above, it is possible to stop the AD chain in the acidogenic fermentation. This is the case of the technologies going through the production of volatile fatty acids: production of VFA from UWWS and those focused on to biopolymers (fermentation of UWWS: production of PHBV). It might seem that both technologies are the same at different levels of development, but in the first one, the VFA are the bioproduct itself. In this case, the economic feasibility of the process is critical, as it decreases the global yield of biogas. The final market value of the product needs to be high enough to compensate the non-produced energy. Regarding those technologies based on hydrolysis, the competition with AD is clear when OFMSW is the feedstock, but the compatibility increases when the feedstock has high lignocellulosic content (production of ethanol). In the case of pyrolysis, this is even higher, as the lignocellulosic nature is a clear advantage for the production of biochar with high quality. The same applies to mycelium production, but with restrictions depending on the chosen final product. Compatibility is also high for HTC when the issue is the management of digestate.

Some of the technologies identified require the **separate collection of specific biowaste**, which limits its application to household sorting. However, they have important potential for waste coming from markets, where the specific amounts of waste are higher and sorting is easier. This is the case for technologies of valorisation of meat waste, fish waste or fruits and vegetables waste. The case of SCGs and used cooking oils is different, as in this case, the HoReCa sector is the most important producer. Despite the challenges in separation of these waste streams, both can potentially be sorted at household level. Household separation of fruits and vegetables from meat and fish is not likely to be feasible in short term, but it could bring high potential for the valorisation of biowaste into new value chains. Separate collection of specific biowaste requires a strong business model behind to support the extra effort and investment in separate collection. From these specific biowastes, used cooking oils are the ones with higher potential, as the collection is already implemented due to their applicability in biodiesel production. However, the production of alternative bioproducts, such as biopolymers or biosurfactants (in this case combined with other biowaste), from these oils can provide an alternative with higher added value.

Related to **marketability of bioproducts**, the chemical building block approach is a very flexible option, as the molecules obtained are normally simple and considered as commodities in the chemical industry. However, the success of these value-chain relies on the existence of an infrastructure external to the waste management itself that can take advantage of these molecules obtained from waste. This is the case for molecules such as 2,3-Butanediol, ethanol, volatile fatty acids, succinic acid, etc. It is very important to notice that these building blocks from biorefineries need to have a very consistent downstream process. This involves steps of concentration and purification to be separated from the fermentation broth (succinic acid, 2,3-butanediol) or fractionation from blends of metabolic products (as those typical in the production of VFAs or BES). These building blocks need to consider competition with fossil-based (succinic acid) and bio-based materials produced from virgin raw materials (lactic acid, ethanol).

The marketability does not only depend on economy, but also on the existence of enabling regulatory frameworks. This is clearly observed with the sector of fertilisers, making those products for application in agriculture (recovered nutrients, biochar, insect frass, biostimulants from protein hydrolysis, microbial biofertilisers, etc.) closer to market. The opposite is observed with the nutrition sector.

From an **economic point of view**, it is difficult to set a comparison in terms of **investment requirements**, as this depends on the capacity of the facility. In general, those technologies involving a higher number of steps will require a higher investment in equipment, but they normally can provide bioproducts with higher added value. In the case of hydrolysis technologies there are multiple choices, as sometimes the production of biomass is enough (microalgae, PGPR) and in other cases it is essential to apply several steps to get the final product, as for instance the polymerization of lactic acid to obtain PLA. Some of the technologies might take advantage of scale economy. Operation costs depend on factors such as the energy consumption and the use of chemicals and solvents. Enzymes and pure cultures might have an important influence on the operational costs in those technologies making use of them. These factors are very territory-linked, and high differences can be found depending on the location of the facility, including also the costs related to manpower. The costs of treatment are normally highly confidential information, and little information can be extracted from the scientific or technical references. The value of the bioproducts is another important factor for the feasibility of the technology and, in some cases, the increase in operation and investment costs is overcome by the high value of the products from downstream (i.e., biopolymers from used cooking oils, products coming from fractionation of insects, etc.). It is needed to have a certain TRL (at least 7) to give a more accurate estimation of investment and costs. Business models and economical assessment of each particular project is required to set the suitability. Another important issue is the choice in the purification process, which might increase considerably the investment cost and the operational costs. One of the key aspects for the feasibility of a technology is the minimum capacity giving profit. This is important because of the higher capacity of this plant, the higher the investment size, and the risk, which decreases the probability of finding financing. There have been examples on overestimation of the demand (for instance in the bioplastics sector or in the succinic acid) which have led to bankruptcy of companies.

In terms of **employment opportunities**, it must be considered that most of the technologies are industrial processes with a certain level of automatisation, operated normally by SMEs, but with the potential to be adopted by larger waste management companies. Employment related to the logistics of waste collection and transport might arise from those technologies implying extra separate collection, depending on the area covered. The potential of downstream and industrial symbiosis should also be considered as a potential source of employment. This might be applicable in a biorefinery context in which the bioproducts from waste treatment act as raw materials for other types of industry (ethanol, acetate, volatile fatty acids, 2,3-Butanediol, succinic acid). Although the implementation of this kind of technologies needs to consider the applicability of the bioproducts in a local or regional level, the potential of the waste treatment facility as a catalyst for creating new companies transforming the bioproduct into marketable forms should not be overlooked. This step of transformation of the bioproduct does not need to come necessarily by the company in charge of waste management, but it might come from new or existing one. One example of this could be the preparation of products and applications based on PHA or the fractionation of volatile fatty acids.

From a **legal** point of view, the nutrition value chain (food and feed) is the one with the highest restrictions due to food safety, and in the particular case of EU, a connection of separately collected biowaste with animal by-product regulatory framework. This is applicable to insects and the production of single cell protein (microalgae, methanotrophic bacteria), but also to some fertilisers. In the case of biopolymers (PHA, PLA), they need to fulfil the requirements for their corresponding application, the cosmetic sector being less strict than those related to pharmaceutical applications or food packaging. In general, bioproducts which do not go to the nutrition sector do not have legal restrictions besides the corresponding regulations and specifications applicable to products coming from conventional raw materials. The regulatory restrictions also affect other sectors, such as fertilisers or packaging, as far as they are connected to the nutrition sector. Chemistry is the sector with the least restrictions, as in many cases the final product is an intermediate (chemical building block). In the case of bioproducts targeted at construction (mycelium, products from fibres), they need to comply with the technical standards in terms of functionality. In general, there are important regulatory differences in EU when treating biowaste or when treating by-products even though they have similar properties. For this reason, companies developing new technologies tend to treat by-products rather than biowaste to ensure their short-term survival. Moreover, there is also a trend to reach for less stringent market niches for this same reason. One example of this is the trend to fractionation products or to pet food in insects' producers.

Social acceptance of the process is very related to everyday issues, which might affect citizens, such as the noise and odours related to the processes. In most cases, the technologies are implemented in industrial areas far away from populated areas, which is usual for waste treatment facilities (already existing in most cases). As the feedstock is biodegradable, odour will be one of the issues to control in all the cases. In addition, the nature of the bioproduct might have also implications with odour. Therefore, more care must be taken with processes generating volatile fatty acids or treating animal by-products than with processes treating spent coffee grounds.

Social acceptance of the bioproducts is related with issues such as price and suitability, as the bioproducts are competing in the market with other non-biobased products. Besides this, understandable information about the bioproducts, their production process and their benefits are essential for their acceptance, as in many cases the citizen does not even understand which is the bioproduct or their applications. This is the typical case with products from biorefineries. Communication is especially important in the case of agriculture sector with bioproducts such as struvite, ammonium sulphate, biochar, hydrochar, biostimulants, and biopesticides, so the final users can overcome the potential barrier of the use of waste-based bioproducts. A similar case can be found in the nutrition value-chain, both for feed (SCP from methanotrophic bacteria, SCP from microalgae, BSFL meal) and food (bioproducts from SCGs, active peptides, insects, etc.). This acceptance might require communication and dissemination campaigns about the bioproducts and actions such as public surveys (VALUEWASTE [53]) or events like Biowaste Clubs (SCALIBUR [263]). In the value chain of bioplastics, the potential acceptance is higher due to the current awareness about the problem with fossil-based plastics and the need of biodegradable plastics without forgetting the key issues of functionality and price. A similar case is found with visible applications such as urban furniture based on fibres or shoes and purses based on mycelium-based leather. In general, the social acceptance is a parameter very territory-linked and difficult to quantify. Main references use tools such as tailored surveys or social LCA to obtain estimations of the degree of acceptance, but the availability of references is limited.

There is a wide range of value chains and waste streams with multiple connections between feedstocks, technologies and bio-products. Territories, waste management utilities, and project developers can benefit from the possibilities available for treating biowaste, the multiple potential bioproducts, and—in general—the UCBE concept.

As has been discussed, several technologies present certain similarities between each other, and one of the main advantages is the possibility of adapting to the existing waste management systems. The main challenge in the treatment is the identified as a "first step". This has been especially observed with AD, where a good quality of the biowaste is crucial for the chain of microbiological reactions to succeed. As previously discussed, the conventional AD takes place in several steps, the first one being the extremely important hydrolysis of the solid matrix into smaller biomolecules as it is releasing the nutrients.

Hydrolysis may take place by different means (enzymes, thermal or chemical) and on the effectiveness of this step lies the success of the rest of subsequent steps of the whole process: an effective hydrolysis makes biowaste suitable to be used as feedstock of many processes. An advantage of this approach is the theoretical flexibility in the rest of steps. This means that once the nutrients (saccharides and other substances) are released into a liquid hydrolysate, many different bioprocesses, involving different value chains, can be considered. This is observed in the biochemical conversion of OFMSW into biopolymers, in microalgae cultivation, in the production of PGPR, and even in the production of carotenoids from SCGs. However, the main disadvantage of this approach is that it does not represent an integral solution, and the solid residue generated after hydrolysis would need further treatment (i.e., AD).

6. Conclusions

The present manuscript proposes a portfolio of 25 innovative technologies for the treatment of the OFMWS and UWWS from a UCBE perspective. These technologies are conveniently described and the main bioproducts identified, providing a comprehensive compilation of information in order to understand the fundamentals of the technologies and bioproducts. From this point of view, it should be noticed that it is not possible to talk about single technologies, but of processes formed by several steps in most cases, which might have different TRL. As an industrial process, the need to fulfil requirements for smooth operation is one of the key steps in the transition from waste management to circular economy. An advantage from this shift of concept is the flexibility in the use of these steps, as different solutions might provide the same function (i.e., different types of hydrolysis). In addition, the technologies might be applied to a variety of biowaste beyond the originally attributed type. Therefore, these technologies have the potential to give flexible solutions to the broad variety of situations present in the cities and regions in order to tailor them to each specific case.

The technologies identified cover a range of value chains, mainly agriculture, nutrition (food and feed), chemistry, bioplastics, cosmetics, and materials. The technologies present different degrees of development (TRL). Some of them are undergoing tests of pilot scale (some in the framework of H2020 projects) and are being developed in several cases by start-ups. Others, generally developed by established companies, are already on TRL 8–9. It is important to notice that some of the technologies or bioproducts are well consolidated with a determined feedstock or waste, but with lower TRL when applied to a different waste.

The compatibility of the identified technologies with traditional treatment options such as compositing and AD has also been evaluated since, from an adoption point of view, this factor is considered to be an important one. Such assessment allowed the technologies identified to be grouped into four categories: hydrolysis (most of them), partial anaerobic digestion, specific biowaste, and thermal treatment. These groups of technologies and those which could not be grouped in any of the categories (i.e., methanotrophic bacteria, BES, insects, nutrient recovery, isolation of fibres and mycelium) were then evaluated from the point of view of compatibility. The takeaway message that can be extracted is that any technology that competes for the use of biowaste or biogas, thus decreasing biogas yield, will be of little interest under the current scenario. However, technologies that might increase the value of digestate (e.g., as the provided by nutrients recovery) might be promoted. This can be also the case of technologies managing the rejections of composting systems.

From the sake of comparison and selection, a multidisciplinary analysis was carried out, considering technical, environmental, legal and social factors. Some of the technologies yield bioproducts which can be further processed, but downstream bioproducts find themselves many times in a lower degree of development. Therefore, it is crucial to determine the final bioproduct to be able to evaluate the business model, considering also their potential as driving force for local or regional circular economy. Economic factors such as investment requirements and operation costs depend much on the particular characteristics of each project, including the capacity of the plant, the complexity of the process and the local or regional conditions (i.e., electricity). Regulatory barriers are also important, especially those related to animal by-product regulation, pushing in many cases the technologies to use industrial or agrofood by-products. Nutrition value chain is the one finding the most significant legal restrictions. Social acceptance of the processes depends much on factors as noise and odours. The acceptance of bioproducts depends on the final user, and although price and functionality are key aspects, it is important to provide understandable information to the final user to overcome reluctance to the use of waste-based products.

Specificity gives a high potential for added-value products, but it requires the implementation of separate collection which might be of difficult application for households. On the other hand, technologies applied to biowaste from household have a higher impact in waste treatment but need to cope with the heterogeneity of the feedstock. In any case, most of these technologies are less sensitive to biowaste quality than anaerobic digestion from a theoretical point of view.

The degree of interaction with other infrastructures and stakeholders in the area cannot be forgotten. This is the case of technologies using streams from anaerobic digestion or those producing building blocks for the chemical industry. Only with a thorough study of the local or regional economic ecosystem can the feasibility of several of them be determined. The compatibility of the technology with the existing waste treatment systems (mainly AD and composting) needs to be considered, as many technologies might compete or complement the existing facilities. It should be noticed that very few of them provide an integral solution for the management of the chosen biowaste and they need to be combined with other conventional or emerging waste treatment technologies.

The overall aim of this review was to foster the adoption of innovation technologies by empowering, helping and informing project developers from cities and regions on such technologies. The knowledge compiled in the present document provides a general vision of a range of UCBE technologies. However, it is challenging to establish a ranking, as adoption truly depends on each specific city or region, considering factors such as strategic objectives, type/amount/quality of the OFMSW/UWWS, existing infrastructure, etc. Saying so, the present document can be used as guide for the selection of such technologies once those factors are known.

To the best of our knowledge, we found our results to be highly relevant since we have been able to identify a large number of innovative technologies which have already been tested at pilot level. In addition, we propose an approach for the multi-assessment of innovative technologies, including the considerations that, according to our experience, should be taken into account. This document should thus be approached from a point of view of the potential of urban bioeconomy at a territorial level. Such potential, focused on the management of the OFMSW and UWWS for the production of high value products, is considered by the authors to be huge and can decisively contribute to the very much expected change of paradigm towards the consecution of a true UCBE.

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Appendix A. Background on Anaerobic Digestion

Biogas is mainly composed of methane (CH_4), ~60%, and carbon dioxide (CO_2), ~40%, with very small amounts of water vapor and other gases, such as hydrogen (H_2) and hydrogen sulphide (H_2S). Depending on the level of biogas purification, it can be used for a range of applications. **Cleaned biogas** (CH_4 50–75%, H_2S < 1000 ppm) is suitable for cooking, burning in boilers, or generating electricity and heat via combined heat and power units, while upgraded biogas—also known as **biomethane** (CH_4 > 95%)—can be injected into a natural gas grid (H_2S < 4 ppm) or converted into compressed natural gas as transportation fuel (H_2S < 16 ppm). Biogas can also be reformed to produce syngas (mixture of H_2 and CO), which can be converted into methanol or even can be used as a raw material for the petrochemical industry.

Digestate has a high concentration of organic matter, partially stabilised and mostly in the form of suspended matter, in addition to a high concentration of nitrogen and phosphorus, mostly in form of dissolved ammonium and phosphate, and small amounts of calcium and potassium. Digestate can be sold as a stable biofertiliser after post-processes such as composting and drying. Moreover, digestate can be further separated into two phases via a solid–liquid separation mechanical stage (centrifugation, screw-pressing, etc.). Its efficiency depends on good flocculation of the digestate before entering the separation stage. The outputs are as follows:

- A liquor (digestate liquid fraction), which contains dissolved matter with a low concentration of organic compounds and high concentration of nutrients, mainly inorganic nitrogen (N) in the form of ammonium (NH_4^+) and phosphorus (P) in form of phosphates (PO_4^{3-}).
- A sludge stream (digestate solid fraction), which contains the separated biomass with a solid concentration of about 20% *w*/*w*, together with the dissolved compounds which also are contained in the drained stream. This solid fraction is a good raw material for the compost production.

Traditionally, the valorisation of digestate does not go beyond its use as an organic fertiliser or organic soil improver

Anaerobic digestion is a complex process which requires the growth of different types of bacteria at different stages. The main metabolic steps of the AD process come as follows:

1. **Hydrolysis.** The organic matrix of macromolecules is broken into smaller biomolecules by the action of bacteria or temperature. In this way, the complex matrices generate simpler saccharides, lipids, and proteins, serving as later substrates for other bacteria.
2. **Acetogenesis.** Acetogenic bacteria continue the transformation of the organic matter, producing acetate.
3. **Acidogenesis.** The chain of biological processes continues with the action of bacteria generating volatile fatty acids.
4. **Methanogenesis.** Another group of bacteria uses the volatile fatty acids to produce methane.

The multi-step nature of AD allows stopping of the process in intermediate steps to leverage any sub-product of interest and this is a concept used in novel approaches to AD, as well as the sequential optimisation. On the other hand, the complexity of this chain of reactions makes AD very sensitive to the quality of the inputs, which can compromise the yield of the process.

Considering the sensitivity of AD to the quality of the inputs, pre-treatments are an important strategy to both tackle the presence of impurities and improve the efficiency of the process. These pre-treatments are as follows.

- **Mechanical separation**. This pre-treatment phase includes a first grinding followed by a trommel screen. Then, metals are removed through magnetic (ferrous metals) and Eddy current (non-ferrous metals) separators. Other unwanted materials, like residual plastics, are separated by flotation and/or sieving. When unwanted adverse materials are removed, the biomass can enter subsequent phases. **This pre-treatment can be also used before composting** in order to increase the quality both of the input material and the final product.

5. **Pre-hydrolysis**. The first step of the digestion can take place before entering the digestor in order to make easier the biological process. This step aims to depolymerise the polymers that constitute the biomass into monomers like fermentable sugars and peptides. There are two main types:
    - **Thermal Hydrolysis (steam explosion)**. It includes a step of heating and a step of boiling pressure. It is an alternatively sterilisation process in which the substrate becomes pathogen-free, which also enhances biomass break. Actually, the heated liquate exits the pressurised boiling tank through a needle and the flashing damages the cell walls, making the material more accessible to bacteria in the bioreactors. Several commercial technologies based on thermal hydrolysis have been implemented in AD plants (Cambi®, Bio Thelys®, Exelys®, Lysotherm®, among others). They improve digestion capacity, biogas production, and dewatering potential (up to 65% less water content of digestate) and allow the obtention of pathogen-free products [19–22].
    - **Enzymatic Hydrolysis**. This pre-treatment is typically considered for lignocellulosic substrates to improve feedstock biodegradability and biogas production. Hydrolytic enzymes, like hemicellulases and cellulases, are generated by microorganisms (bacteria and fungi) that can be inoculated in the lignocellulosic slurry. This approach is far more cost effective than the direct use of commercial hydrolytic enzymes. Enzymatic hydrolysis improves the efficiency of biogas production through reduction of production time, energy consumption and waste generation, and replacement of chemical or physical treatments [23].

At this point, it is important to highlight that some pre-treatments have demonstrated to improve significantly the efficiency of the process, in terms of digestate concentration or CAPEX and OPEX costs.

Whereas composting has one main output (compost) with a very clear application, AD provides both biogas and digestate. This makes that AD is gaining importance as a profitable and efficient way to recover carbon in the form of renewable biogas. However, although the advantages of biogas as renewable energy are clear, the valorisation of digestate does not go traditionally beyond its use as an organic fertiliser or organic soil improver, but in recent research, new routes have been proposed for solid digestate valorisation [24,25], such as production of bio-fuel for use in domestic furnaces [26], biochar [24,25,27], as well as post treatments for methane recovery [28].

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