Rev Environ Sci Biotechnol (2022) 21:247–267
https://doi.org/10.1007/s11157-021-09605-w

REVIEW PAPER

Organic municipal waste as feedstock for biorefineries: bioconversion technologies integration and challenges

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Received: 30 September 2021 / Accepted: 29 December 2021 / Published online: 11 January 2022

Abstract The need for ensuring resources and energy supplies has stimulated the use of renewable feedstocks for biorefineries. Among organic wastes, the organic fraction of municipal solid waste (OFMSW) outstands because of its increasing amounts and management requirements. Unlike other homogeneous organic waste from food and other industries, OFMSW is characterized by high instability, complexity, and heterogeneity. This review aims to unfold the potential of the OFMSW as feedstock for biorefineries through a discussion on recent valorization alternatives to the commonly employed anaerobic digestion for biogas production. Enzymatic hydrolysis has been identified as a key to unlock the capabilities of OFMSW through the fractioning of structural components into functionalized molecules. In addition, multiple scenarios for the subsequent utilization of such molecules are also presented, together with suitable configurations for processes integration. Lastly, challenges for the OFMSW biorefinery implementation have been identified.

Keywords Biorefinery · Biowaste · OFMSW · Enzymatic hydrolysis · Bioconversion · Valorization

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1 Introduction

The transition from the current linear economy to a circular economy has been attracting widespread interest in recent years. One major driver of this socioeconomic shift paradigm is the expected depletion of material resources (Jowitt et al. 2020). Efficient management of resources becomes, therefore, essential to prevent scarcity. Moreover, resource recovery from the current take-make-waste economic models secures their supply providing a competitive advantage in the future global economy (Ellen MacArthur Foundation 2021; Tonini et al. 2013). Another major driver is the increasing municipal solid waste (MSW) generation, which represents an environmental burden and a high cost to society (Kaza et al. 2018). Comprehensively addressing MSW as a source of resources and not as a residue to be managed opens a door towards a more sustainable society (Sánchez et al. 2015).

The dramatic increase of MSW generation from 1.3 billion tonnes in 2012 to 2.01 billion tonnes in 2018 has been related to population growth rate, rapid urbanization, and overflowed waste streams in high-income countries (Kaza et al. 2018). The global MSW generation is predicted to reach 3.4 billion tonnes by 2050. Nearly half of this amount are biodegradable materials, known as the organic fraction of municipal solid waste (OFMSW) (Al Seadi et al. 2013; Kaza et al. 2018). This fraction comprises two major streams: green waste from parks and gardens, and food waste from households, cafeterias, restaurants, lunch-rooms, and markets (Al Seadi et al. 2013). It is characterized by high moisture and organic matter content, a rather acidic pH, and containing metals and macro/micronutrients (Campuzano and González-Martínez 2016; Barampouti et al. 2019). Therefore, OFMSW is an abundant, carbon-rich, and, so far, free-of-cost resource.

The need for ensuring materials and energy supply as well as minimizing dependency on fossil fuels led to the concept of biorefineries, which is analogous to petroleum-based refineries but uses biomass instead of petroleum as raw material. The major goal of a biorefinery is to maximize the value derived from biomass constituents and intermediates by converting them into a palette of valuable bioproducts and bioenergy (Kamm and Kamm 2004). Several classification systems have been proposed according to different elements of the biorefineries, i.e. platforms, feedstocks, processes, and products (Budzianowski and Postawa 2016). The platform system has been reported as the most significant because it describes intermediates that can be reached via different conversions processes or feedstocks and act as building blocks of different products. Examples of platforms are biogas, C6 sugars, C5 sugars, or H_2 (Venkata Mohan et al. 2016). In terms of feedstock, it has been distinguished between dedicated crops and residues. After raising concerns about food and land-use competition from whole crops, research efforts were shifted towards lignocellulosic biomass-based biorefineries. Recently, different types of waste have been proposed as feedstock as a way of transitioning towards a circular economy, in which waste generation is minimized to a larger extent (Venkata Mohan et al. 2016; Alibardi et al. 2020). To date, the focus of waste biorefineries research has been centered on homogeneous waste streams of specific industries (Mirabella et al. 2014; Carmona-Cabello et al. 2018). However, biorefineries based on OFMSW have been reported to offer larger climate benefits due to the avoidance of conventional management, and of land and fertilizers use for the cultivation of agricultural biomasses (Tonini et al. 2016; Vea et al. 2018). Ongoing advances in OFMSW valorization technologies may unlock its potential as a feedstock for biorefineries.

This review aims to discuss the feasibility of the integration of OFMSW valorization technologies into the biorefinery concept. In this context, enzymatic hydrolysis is presented as a way to obtain functionalized molecules from OFMSW that serve as platforms for bioconversion processes. The current technological status of enzymatic hydrolysis is presented and the most promising valorization routes for the resulting fractions are evaluated. Available examples of OFMSW biorefineries configurations are summarized. The major bottlenecks for ensuring the viability of the OFMSW biorefinery are also discussed.

2 OFMSW valorization state of the art

Resources recovery from waste is not a recent phenomenon (Velis et al. 2009), but it was public health and environmental concerns that brought proper waste management to the political agenda of high-income countries (Wilson 2007). The high biodegradability and moisture content of OFMSW convert this fraction into the major contributor to the environmental impact of landfilled MSW (Wilson 2007). Natural biodegradation of organic waste implies the uncontrolled release of methane and other greenhouse gases, production of leachates that contaminate soil and groundwater, unpleasant odors, and spread of pathogenic microorganisms (Kaza et al. 2018). Consequently, significant national and regional efforts have been done to prevent OFMSW landfilling. For instance, in the European Union, the policy efforts related to waste management are the Landfill Directive 1999/31/EC (DIRECTIVE 2000) and the Waste Framework Directive 2008/98/EC (DIRECTIVE 2008). According to these, waste management should follow a 5-step hierarchy, in which waste prevention becomes the priority followed by waste reuse, recycling, recovery, and disposal. As a result, the landfilling rate dropped from 64% in 1995 to 23% in 2018 according to Eurostat statistics (Eurostat 2021). On top of that, the European Commission launched in 2015 the Circular Economy Action Plan, which aims to reduce landfilled waste to a maximum of 10% (Union 2014). In this context, it is clear that ambitious solutions are needed to ensure that the not-landfilled OFMSW serves a better and more sustainable purpose.

2.1 Current management technologies

To redirect the OFMSW away from landfilling, it was necessary to develop and promote tailored technologies for its treatment. The most implemented technologies were incineration, anaerobic digestion (AD) for biogas production, and composting. Reviews of the benefits and drawbacks from these well-established technologies have already been published (Cerda et al. 2018; Angelidaki et al. 2018; Makarichi et al. 2018), and they will not be discussed here nor thermochemical processes, such as gasification or pyrolysis (Matsakas et al. 2017). Shortly, incineration allows energy recovery from OFMSW, at the expense of high capital and operating costs and the possibility of recovering valuable nutrients (Makarichi et al. 2018). AD for biogas production has been proven to be a robust, efficient, and relatively low-cost process (Scoma et al. 2016; Mayer et al. 2020), but biogas upgrading is necessary for its effective utilization as higher fuel standard (Angelidaki et al. 2018). When applied together, AD and composting treatments allow energy recovery alongside nutrient recycling as a soil amendment. However, AD does not ensure full intrinsic energy exploitation, and high-quality compost is difficult to attain (Cerda et al. 2018).

The shift from landfilling towards more specialized technologies was also fostered by an increase in source-separated collection systems of MSW, which has been described as the first condition for OFMSW valorization (Sisto et al. 2017; Mayer et al. 2020). Source-separated collection facilitates the reuse of waste by reducing pretreatment needs and easing quality verification (Velis et al. 2009; Paes et al. 2019). In contrast to mechanical selection from mixed collection systems, the selection is carried out directly at generating properties or at communal collection points. The OFMSW derived from unsorted or poor source-separated collection systems results in low efficient AD systems and bad quality, non-marketable compost (Cerda et al. 2018; Mayer et al. 2020). For example, Moreno et al. (2021) evaluated the effect of source-separating on the production of bioethanol and biogas. The maximum ethanol concentration achieved for the source-separated OFMSW was double than for the non-separated. However, building robust and high-quality source-separated collection systems involve a significant economic investment (Kaza et al. 2018; Mayer et al. 2020). Therefore, efforts need to be directed to finding more profitable processes to justify the economic investment.

2.2 OFMSW composition

Compared with organic waste streams from the agriculture and food processing industry, which are mostly homogeneous and constant in composition, OFMSW composition is heterogeneous and highly variable (Fava et al. 2015; Barampouti et al. 2019). Hence, its characterization becomes essential in the selection of the appropriate valorization route..The physical and chemical characteristics generally measured are presence of impurities, humidity and solids content, elemental composition (C, H, N, S), pH, and organic matter (biodegradable or not), depending on the objective of the study (Campuzano and González-Martínez 2016). Pleissner and Peinemann (2020) suggested that OFMSW composition should be evaluated in terms of its main constituents, i.e. carbohydrates, proteins, lipids and lignin, and not in further detail. Campuzano and González-Martínez (2016) gathered the characteristics of the OFMSW from 43 cities in 22 countries and obtained an average composition (w/w) of 55.5% carbohydrates, 17.7% protein, 17.5% lipids, and 9.7% lignin. Carbohydrates are the mayor fraction and are composed of free sugars, starch and fibers (cellulose, hemicellulose and pectin). Sugars and starch are more easily-biodegradable than fibers, and therefore highly influenced by the activity of the indigenous microbial consortium during storage and transportation (Campuzano and González-Martínez 2016; Pleissner and Peinemann 2020). While high xylan is associated with more stable composition, it also increases the chemical complexity of the sample hindering its biodegradability and increasing pretreatment requirements (Yang et al. 2015). OFMSW composition has a significant influence on the efficiency of biological processes and their final products as the type of organics and nutrients available influence the kinetics, the efficiency of the process and the bioproducts production potential (Dogan and Demirer 2009; Alibardi and Cossu 2016; Tyagi et al. 2018).

OFMSW characterization is influenced by the continuously changing composition because of seasonal, regional, technological, and socio-economic (Pleissner and Peinemann 2020). Therefore, characterization should be carried out carefully and as site-specific as possible (Tyagi et al. 2018). Straightforward methodologies, such as biodegradability measurement (Ponsá et al. 2010a) and chemical oxygen demand (COD) (Yang et al. 2015), are also relevant for regular quality verifications.

2.3 One waste, multiple names

During the elaboration of this review, an evident confusion with the terminology employed to designate the organic fraction of municipal solid waste was observed. Table 1 compiles different terms that have been employed interchangeably throughout literature, some of them not accurately enough. The term “biomass”, i.e. mass of living organisms (Houghton 2008), has been employed to designate all natural carbonaceous resources that can be used to generate fuels (Pang 2016). Thus, it is an unspecific and widely overused term. In Table 1 it can be seen how only 10% of the published works related to the term “biomass”, are also related to the term “waste”. Terms such as “organic waste”, “biowaste” or “food waste” fail to describe the origin of the residue, i.e. industrial, agricultural, or municipal. For them, less than 30% of the published works are related to municipal (or urban) wastes (Table 1). Contrary, the terms “municipal waste” or “household waste” fail to describe the type of residue, i.e. plastic, metal, electronic, or organic, and again, less than 30% of the published works actually discuss organic wastes. The most accurate term “organic fraction of municipal solid waste”, or its acronym “OFMSW”, is the less used one with only 925 papers published in the Web of Science (Table 1). It was also observed that the term “OFMSW” is used indiscriminately to refer to fresh food used to simulate real waste or food waste from university cafeterias. However, these types of waste may not be representative of the complexity of the OFMSW coming from municipal treatment facilities (Zhou et al. 2013; Alibardi and Cossu 2015). The authors of this review would like to emphasize that the term used to designate the organic fraction of the waste separately collected from municipalities should be standardized to not increase its inherent variability and to facilitate the comparison of results reported in the literature.

Table 1 Number of published works for the keyword search in the Web of Science (June 2021)

Word search	Article	Review	Total Papers	% Total
“Biomass”	313,014	14,451	327,465	
AND “Waste”	32,133	2633	34,766	10.6%
AND “Municipal” OR “Urban”	10,328	732	11,060	3.4%
“Organic waste”	4418	410	4828	
AND “Municipal” OR “Urban”	1145	133	1278	26.5%
“Biowaste”	1658	100	1758	
AND “Municipal” OR “Urban”	404	27	431	24.5%
“Food waste”	7647	807	8545	
AND “Municipal” OR “Urban”	1612	229	1841	21.8%
“Municipal waste”	5455	430	5885	
AND “Organic”	1460	146	1606	27.3%
“Household waste”	1597	64	1661	
AND “Organic”	430	23	453	27.3%
“Organic fraction municipal solid waste” OR “OFMSW”	862	63	925	

3 The OFMSW biorefinery

Biorefineries design is not a straightforward task and it should be tailored to the specifics and quantity of the feedstock, the location constraints, and regional policies (Kamm and Kamm 2004; Moncada et al. 2016). A common principle when designing a biorefinery is that the decomposition of the feedstock should be conducted hierarchically following a flexible and logical sequence, this is known as the cascading principle (Fava et al. 2015; Moncada et al. 2016; Alibardi et al. 2020). The logic of the sequence might be adapted to the goal of each biorefinery but commonly, selling price and purity restrictions establish the first steps (Moncada et al. 2016). Another common principle is the integration of feedstocks, technologies, and products to maximize the use of resources and optimize the overall performance within the biorefinery (Moncada et al. 2016; Alibardi et al. 2020). For such a heterogeneous substrate as the OFMSW, i.e. with unpredictable quality, the integration of different conversion processes also reduces the inherent risk of failure (de Sousa et al. 2021).

This intrinsic complexity of municipal organic wastes entails a wide spectrum of potentially marketable products in a waste biorefinery (Moretto et al. 2019; Pleissner and Peinemann 2020). So far, most of the proposed OFMSW biorefinery-like configurations have been centered around AD technology for biogas production (Dogan and Demirer 2009; Escamilla-Alvarado et al. 2017b; Tyagi et al. 2018; Khoshnevisan et al. 2018b). However, authors in the literature do not seem to agree whether an OFMSW biorefinery should employ AD technology for biogas production as the main platform (Sisto et al. 2017; Elyasi et al. 2021) or as a complementary platform to handle intermediates (Mahmoodi et al. 2018a; Valentino et al. 2018). For a biorefinery to be economically robust and minimize financial risks it has to be able to decide among different bioproducts thus pushing towards multi-platform designs that would also enhance the recovery of resources (Moncada B et al. 2016; Alibardi et al. 2020; Tonini et al. 2013) Furthermore, Barampouti et al. (2019) and Mahmoodi et al. (2018a) highlighted that biogas might be outcompeted by other liquid biofuels, i.e. bioethanol or biodiesel. Finally, to reach environmental sustainability, the substitution of complex chemical routes and petroleum-based precursors in the production of commodities or high-value products would tip the balance in favor of bioproducts (Laurent et al. 2014; Venkata Mohan et al. 2016; Escamilla-Alvarado et al. 2017b). Therefore, future efforts should be focused on integrating other valorization technologies alongside energy production.

As of traditional refineries, the configuration of biorefineries involves several conversion pathways or platforms with their corresponding upstream and downstream operations. To summarize the latest advancements in the valorization processes of OFMSW, technologies have been classified according to the step of the conversion process they belong to: upstream, midstream, and downstream. A summary of all the discussed technologies can be seen in Fig. 1.

3.1 Upstream

Upstream steps comprise all activities that occur before the bioconversion, ranging from the generation and collection of OFMSW to the pretreatments required to prepare the material for the subsequent steps. The control of waste generation is beyond the reach of biorefineries and it is associated with seasonality, population dietary patterns, and income levels (Kaza et al. 2018).

As for many other organic wastes, pretreatment technologies have been evaluated for OFMSW. Generally, pretreatment aims to remove unsorted materials, reduce particle size, increase stability or enhance accessibility to simpler components and its configuration depends on the objective of the subsequent bioconversion process (Yang et al. 2015; Liu et al. 2021). Pretreatment methods for biowaste have been extensively reviewed and traditionally classified in different categories: physical or mechanical, chemical, and biological (Romero-Cedillo et al. 2017; Mahmoodi et al. 2018a; Barampouti et al. 2019; Cesaro et al. 2020), which are non-exclusive but rather complementary. The final choice of pretreatment layout highly influences the efficiency of subsequent bioconversion and downstream processes, the cost and benefit, the energy demand, and the environmental impact (Yang et al. 2015; Alibardi et al. 2020).

Physical pretreatments are applied for size reduction through milling, chipping, or grinding (Barampouti et al. 2019) to enhance the surface area accessible to enzymes or microorganisms (Romero-Cedillo et al. 2017). Physical pretreatments are also

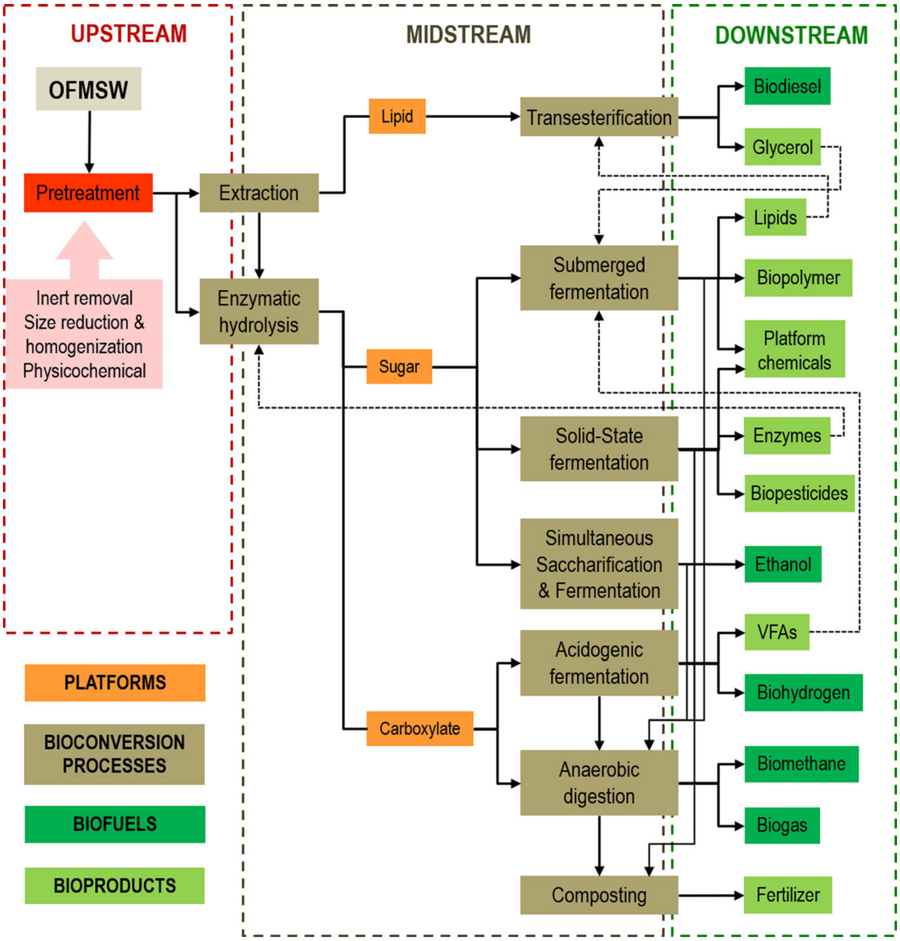

Fig. 1 Possible configuration options and products for a multi-platform OFMSW biorefinery

applied to reduce the degree of polymerization of the insoluble fraction through exposure to high temperatures (Barampouti et al. 2019). The application of high temperature for a certain period also acts as a pasteurization step reducing the activity of the inherent microbial consortium of the OFMSW (Barampouti et al. 2019).

Chemical pretreatments employ chemical agents, alkaline or acid, to modify the structure of the substrate, typically with the combination of temperature (physicochemical) (Romero-Cedillo et al. 2017). Dilute acid pretreatments have been widely applied because they also act as a hydrolysis step (Barampouti et al. 2019). Favorable results in terms of sugar solubilization have been reported in the literature when employing acids on kitchen waste (Vavouraki et al. 2013).

3.2 Midstream: the role of enzymatic hydrolysis

The integration of two or more platforms can counteract the fact that biorefineries are highly capital intensive (Escamilla-Alvarado et al. 2017a). As proposed by Alibardi et al. (2020), to construct different platforms, it is crucial to first fractionate, separate, or isolate individual components that act as intermediates for specific conversion processes. These authors proposed four different technologies for this purpose, washing, solid–liquid extraction, enzyme, or membrane technologies (Alibardi et al. 2020). A summary of the main advantages and disadvantages of these processes can be seen in Table 2. Washing, solid–liquid, and membrane separation processes have gained more relevance for homogeneous food waste streams to separate abundant components with high market prices, such as antioxidants, pigments, or

Table 2 Advantages and disadvantages of the main technologies for initial separation of OFMSW components

Technology	Objective	Advantages	Disadvantages	References
Washing	Solubilization of organic matter	Cost-effective; eco-friendly (water)	Inefficient; limited accessibility to the substrate	(Ao et al. 2020)
Solid–liquid extraction	Targeted group of compounds (i.e. lipids)	Simple; wide adaptability	Environmental and economic cost of organic solvents; chemical transformation of the matrix; long processing time; limited efficiency; temperature requirement	(Alvira et al. 2009, Naviglio et al. 2019)
Membrane separation	Separation of specific compounds	Highly selective; energy efficient; eco-friendly	Cost; fouling; not efficient for complex streams	(Arbige et al. 2019; Matharu et al 2016)
Enzymatic hydrolysis	Fractioning of structural components	Possibility to integrate with bioprocesses; no inhibitory compounds; energy efficient; eco-friendly	Long processing time; high cost; limited by accessibility to the substrate	(Escamilla-Alvarado et al. 2017a)

polyphenols (Ng et al. 2020; Sharma et al. 2021). When working with OFMSW, extraction techniques are mainly used for oil extraction in the production of biodiesel (Barampouti et al. 2019; Liu et al. 2021; Ischia et al. 2021). Conversely, filtration techniques using membranes are used for the separation of high-value products obtained at further steps of the processing cascade (Huang and Ramaswamy 2013; López-Gómez et al. 2020). Of special interest are the enzyme-based separation technologies, the only ones that allow a fractioning of the complex OFMSW structures into functionalized molecules. These molecules become building blocks for the subsequent steps of the processing cascade (Escamilla-Alvarado et al. 2017a; Pleissner and Peinemann 2020).

Enzymes are proteins that catalyze chemical reactions of the metabolism of all living organisms with great specificity and efficacy. They withhold a great potential as biocatalysts in many industrial sectors, including biorefineries (Chaplin and Bucke 1990; Escamilla-Alvarado et al. 2017a). Indeed, the industrial market of enzyme technologies has increased from US $600 million to US $7 billion in revenues in the last 20 years (Arbige et al. 2019). They have been essential for the development of 2nd generation biorefineries that convert lignocellulosic biomass, such as agricultural feedstock, to bioethanol and other bioproducts (Alvira et al. 2010). So, it can be expected that they also hold the key to unlock the potential of OFMSW despite the challenge of continuous adaptation to its variable composition (Pleissner and Peinemann 2020). The pathway for the use of enzymes on renewable feedstocks is being facilitated by developments in enzyme formulations through protein engineering, i.e. greater stability and substrate specificity or lower operating temperatures (Chapman et al. 2018), alongside dropping enzyme prices, which are a limiting factor for its application (Arbige et al. 2019).

The main goal of enzymatic hydrolysis is the breakdown of macromolecules into their functional units. Considering that carbohydrates and fibers represent up to 85% of the OFMSW composition (Campuzano and González-Martínez 2016), a great number of fermentable sugars could be obtained upon the fractioning of this waste (Yang et al. 2015). The rate of this conversion process is influenced by several factors, such as lignin content and distribution, cellulose crystallinity and degree of polymerization, accessible surface area and particle size of the substrate, or chemical and structural changes during the conversion (Alvira et al. 2010; Liu et al. 2021). Additionally, the types of enzymes employed and their synergistic effects also impact the outcome (Escamilla-Alvarado et al. 2017a; Hu et al. 2018). Escamilla-Alvarado et al. (Escamilla-Alvarado et al. 2017a) reviewed the most common enzymes applied in biorefineries and their applications.

Enzymatic hydrolysis of OFMSW has been applied successfully as pretreatment to increase the biogas yield during AD processes, as it facilitates the hydrolysis step of complex components, which is the first and rate limiting step followed by acidogenesis, acetogenesis and methanogenesis (Romero-Güiza et al. 2016; Mlaik et al. 2019). However, its application for releasing and recovering sugars from waste is scarce in literature. Table 3 summarizes the retrieved publications dealing with enzymatic hydrolysis as a sugar releasing step for further valorization processes. All publications dealt with "real" OFMSW collected from different treatment facilities (Spain, Iran, and Germany), therefore, besides the inherent variability of this waste, variabilities related to the specifics of each region should be expected. The selection of enzymes varies among authors with cellulases as a shared type. Cellulases are a family of enzymes including endoglucanase, exoglucanase, and β-glucosidase activities that depolymerize cellulose into cellobiose and ultimately glucose (Lynd et al. 2002; Escamilla-Alvarado et al. 2017a). Amylases are the second employed enzymes and degrade starch into oligosaccharides and ultimately glucose or maltose (Escamilla-Alvarado et al. 2017a). Remarkably, all authors employed enzymatic cocktails, therefore benefiting from synergistic effects of enzymatic activities. It has been shown how cellulases benefit from the removal of xylan by xylanases, which leads to enhanced fiber swelling and accessibility (de la Torre et al. 2017; Hu et al. 2018). Despite the variety of enzymatic activities, the conditions employed for the enzymatic hydrolysis are very similar and characterized by high temperatures and a rather acidic pH. Molina-Peñate et al. (2022) explored the use of milder conditions, in terms of lower temperature and higher pH, achieving a 93% of the hydrolysis performance at high temperature. Enzyme dosage is the most inconsistent condition, sometimes not even addressed (López-Gómez et al. 2019; Stylianou et al. 2020), because of the lack of standardized units for enzymatic cocktails that contain several enzymatic activities. All authors performed mechanical pretreatments of the waste, mainly for inert materials removal and particle size reduction, whereas some also performed a dilute acid pretreatment previous to the enzymatic hydrolysis of the OFMSW (Ghanavati et al. 2015; Mahmoodi et al. 2018a; Izaguirre et al. 2019; Ebrahimian et al. 2020). The improvement in the released sugars after the dilute acid pretreatment calculated based on the data provided by the authors was 28% for Izaguirre et al.(2019), 49% for Mahmoodi et al. (2018a), and 17% for Ebrahimian et al. (2020). Ghanavati et al. (2015) did not provide the data of the enzymatic hydrolysis of untreated OFMSW. However, when comparing the total sugars concentration attained, these improvements do not excel the enzymatic hydrolysis performed without a preliminary chemical pretreatment (Table 3). In fact, the highest sugar concentration declared was achieved by Stylianou et al. (2020) without chemical pretreatment using a tailor-made enzymatic cocktail and was of 107.3 g/L, equivalent to 75% glucan and 12.5% xylan conversion. It should be highlighted that in all cases glucose was the major sugar representing more than 80% of the final composition of the hydrolysates. López-Gómez et al. (2019) made a comparison between separately and non-separately collected OFMSW obtaining 18% more sugars in the separately collected (80 g/L). It seems that tailor-made enzyme cocktails could overcome the need for physicochemical pretreatments that might have negative impacts in later processing steps because of the release of inhibitors of fermentative processes (Ghanavati et al. 2015). Mahmoodi et al. (2018a) were the only researchers assessing the influence of the pretreatment on the resulting solid fraction after the enzymatic hydrolysis. These authors declared a complete removal of xylan and a significant removal of starch after treatment with 1% acid at 160 °C for 60 min, hence proving a reduction in the degree of depolymerization beneficial for the enzymatic hydrolysis (Alvira et al. 2010). These sugars concentrations are generally lower than those recently obtained in enzymatic hydrolysis of food waste (164–204 g/L), which are homogeneous streams with lesser inert content (Kwan et al. 2018).

After the enzymatic hydrolysis two fractions can be differentiated, a liquid fraction containing solubilized compounds and a solid fraction containing partially digested and undigested components, which are substrates for subsequent steps. An overview of the main advantages and disadvantages of the bioconversion processes shown in Fig. 1 can be seen in Table 4.

3.2.1 *Valorization of sugar concentrated hydrolysate*

The liquid hydrolysates obtained after enzymatic hydrolysis processes are not only high-concentrated

Table 3 Summarized valorization routes based on enzymatic hydrolysis of real OFMSW

Enzymes[a]	Enzymatic hydrolysis conditions	Pretreatment	Total sugars concentration	Valorization liquid hydrolysate		Valorization solid hydrolysate	References
				Microorganism used	Bioproduct obtained		
Tailor-made cocktail (cellulases and amylases)	50 °C; pH 5; 150 rpm; 72 h; 20% (w/v)	Remove impurities, milling, autoclaving	80 g/L from ssOFMSW 66 g/L from mcOFMSW	*Bacillus coagulans*	Lactic acid 230 g/kg dry OFMSW	–	(López-Gómez et al. 2019)
Tailor-made cocktail	50 °C; pH 5; 150 rpm; 72 h; 20% (w/v)	Remove impurities, milling, autoclaving	31.2–107.3 g/L	*Actinobacillus succinogenes*	Succinic acid 300.4 g/kg dry OFMSW[b]	–	(Stylianou et al. 2020)
Cellulase (Celluclast 1.5 L) β-Glucosidase (Novozym188)	50 °C; pH 7; 150 rpm; 72 h; 10% (w/v)	Remove impurities, milling, dilute-acid	96.1 g/L in total: 65.6 g/L (acid hydrolysis) 30.5 g/L (enzymatic hydrolysis)	*Cryptococcus aerius*:	Lipids 39.6 g/kg dry OFMSW	–	(Ghanavati et al. 2015)
Xilanase (Pentopan 500 BG) Cellulase (Celluclast BG) Glucoamylase (NS 22,035)	50 °C; pH 4.8; 170 rpm; 48 h; 13.5% (w/v)	Remove impurities, lyophilize, milling, dilute-acid	25.3 g/L	*Burkholderia sacchari*:	Poly(3-hydroxybutyrate) 20.6 g/kg dry OFMSW[b]	–	(Izaguirre et al. 2019)
Cellulases (Cellic CTec2) Hemicelluloses (Cellic HTec2)	45 °C; pH 4.8; 120 rpm; 72 h; 5% (w/v)	Remove impurities, milling, autoclave, dilute-acid	70.8 g/L in total: 46.7 g/L (acid hydrolysis) 24.1 g/L (enzymatic hydrolysis)	*Mucor indicus*	Ethanol 194 g/kg dry OFMSW	Biomethane 145 L/kg dry OFMSW	(Mahmoodi et al. 2018b)

Table 3 continued

Enzymes[a]	Enzymatic hydrolysis conditions	Pretreatment	Total sugars concentration	Valorization liquid hydrolysate		Valorization solid hydrolysate	References
				Microorganism used	Bioproduct obtained		
Cellulases (Cellic CTec2) α-amylase Glucoamylase	45 °C; pH 4.8;120 rpm; 72 h; 5% (w/v) Followed by: 90 °C; pH 6; 2 h Followed by: 65 °C; pH 4.5;24 h	Remove impurities, drying, milling, autoclave, organosolv (ethanol and acetic acid)	40.9 g/L	*Enterobacter aerogenes*	Hydrogen 71.4 L/kg dry OFMSW 2,3-butanediol 139.1 g/kg dry OFMSW Ethanol 98.3 g/kg	Biomethane 23 L /kg dry OFMSW	(Ebrahimian et al. 2020)
Viscozyme L	55 °C; pH 3.5; 24 h; 10% (w/v) 25 °C; pH 4.5; 24 h; 10% (w/v)	Remove impurities, milling, autoclaving	47 g/L (50 °C) 42 g/L (25 °C)	–	–	*Bacillus thuringiensis* spores 1.3×10^8 spores/ g dry OFMSW	(Molina-Peñate et al. 2022)

ssOFMSW: source-separated OFMSW; mcOFMSW: mixed collected OFMSW

[a] In all the references enzymes were provided by Novozymes A/S

[b] Calculated based on the data provided by the paper

Table 4 Advantages and disadvantages of the main technologies of bioconversion processes in an OFMSW biorefinery

Technology	Objective	Advantages	Disadvantages	References
Transesterification	Bioconversion of lipids to biodiesel	Energy-efficient, simplified downstream	Time consuming, cost of biocatalyst	(Escamilla-Alvarado et al. 2017a)
Submerged fermentation	Bioconversion of liquids to bioproducts	High process control and versatility, facilitated downstream	Large wastewater, limited soluble oxygen	(Sala et al. 2019)
Solid-state fermentation	Bioconversion of solids to bioproducts	Reduced wastewater, increased yield, low-energy	Mass-heat transfer problems, difficult process control and scale-up, complex downstream	(Sala et al. 2019)
Simultaneous fermentation and saccharification	Bioconversion of liquids and solids to bioproducts	Process simplification in time and cost, reduced substrate inhibition	Reduced yields by compromised optimum conditions	(Chacón et al. 2021)
Acidogenic fermentation	Bioconversion of liquids and solids to VFAs	Complex and variable substrates	Difficult process control	(Agler et al. 2011)
Anaerobic digestion	Bioconversion of liquid and solid wastes to biogas	Robust, energy-efficient, relatively low-cost	Need of further processing of solids, high cost of biogas upgrade	(Mayer et al. 2020)
Composting	Bioconversion of solid organic wastes to compost	Simple; robust	Quality requirements, low value of compost, odors	(Cerda et al. 2018)

VFAs, volatile fatty acids

in sugars (carbon source) but also contain other functionalized molecules, i.e. proteins, amino acids, organic acids, and minerals. Therefore, these liquors are a suitable substrate for fermentative processes to produce bioproducts with higher market value (Pleissner and Peinemann 2020). In Table 3, the valorization routes proposed include commodities, such as acetic acid, succinic acid, and 2,3-butanediol, homopolymer for bioplastic applications, and biofuels, such as ethanol, hydrogen, and lipids for biodiesel. Thus, a wide range of bioproducts and applications can be obtained from OFMSW. Processes simplification is an important goal for biorefineries. From Table 3 only López-Gómez et al. (2019) employed the hydrolysate without the need of supplementation of other carbon sources or nutrients nor an additional autoclave step. These authors selected a low nutritional requirement and thermophilic strain, which provided competitive advantages to unavoidable contaminants originally present in the waste. Furthermore, they achieved the highest production per kg of OFMSW (230 g lactic acid/ kg of dry OFMSW). However, in some instances, the addition of supplements can be justified by the increase in product yield. For instance, Izaguirre et al. (2019) showed the inability of *Burkholderia sacchari* to produce Poly(3-hydroxybutyrate) in the hydrolysate related to a lower C/N ratio than the metabolically required and they recommended further studies on limiting nutrient selection. The use of physicochemical pretreatments is decisive for the performance of fermentative processes because of the release of inhibitory compounds. Ghanavati et al. (2015) required a detoxification step before the use of the hydrolysate from the dilute acid pretreatment because of the high content in inhibitors, such as furfural or phenolic compounds. A cost–benefit evaluation should be performed when designing a biorefinery as a higher sugar yield might not compensate for the cost derived from additional detoxification steps after harsh pretreatments. A better selection of the enzyme cocktail or a proper valorization of the remaining solid fraction, which only 2 authors in Table 3 considered, can lead to greater overall performance.

3.2.2 *Valorization of solids remaining after enzymatic hydrolysis*

There are two valorization routes for the solid fraction remaining after the enzymatic hydrolysis of OFMSW presented in Table 3, the anaerobic digestion to biogas, or ultimately biomethane, and solid fermentation with a specific microorganism. The biomethane amount per gram of dry matter is 6-times higher for Mahmoodi et al. (2018a) than for Ebrahimian et al. (2020). This might be explained by the different configurations proposed. Mahmoodi et al. (2018a) achieved a better integration of processes by reducing residues. These authors used both liquid fractions, from the acid pretreatment and enzymatic hydrolysis, for the production of bioethanol and both solid fractions, from the enzymatic hydrolysis and the ethanolic fermentation (suspension remaining after evaporation of ethanol), for biogas production. In this sense, Ebrahimian et al. (2020) did not use the liquid fraction from the ethanol pretreatment nor the solids after the anaerobic fermentation of *Enterobacter aerogenes*. However, the latter obtained a wider spectrum of bioproducts from a more versatile fermentative process. Despite the clear benefits of AD to biogas, other technologies might bring new opportunities in a biorefinery scenario.

Solid-state fermentation (SSF), described as the fermentation of solids in the absence or near absence of free water (Pandey 2003), is a technology that has gained relevance for the valorization of organic wastes (Yazid et al. 2017; Sadh et al. 2018; Martínez-Avila et al. 2021). In contrast to submerged fermentation, SSF is a simpler process that has lower energy requirements and operational cost but also reduced options for process control and monitorization, hindering the scale-up (Sala et al. 2019). Molina-Peñate et al. (2022) performed a preliminary evaluation of the resulting solid fraction after enzymatic hydrolysis as a substrate for a SSF process producing spores of the widespread bacterial biopesticide *Bacillus thuringiensis*. Ballardo et al. (2017) also evaluated the growth of this microorganism on untreated OFMSW, even though they showed a promising valorization pathway to a compost-like material with enriched biopesticide properties, the use of enzymatic hydrolysis opens a multi-platform scenario. OFMSW has been also evaluated as a substrate for SSF processes after other pretreatments. Estrada-Martinez et al. (2019) evaluated on a pilot scale (18 kg) the use of the fruit and vegetable fraction of the OFMSW after a mild thermal pretreatment as the substrate for a mixed yeast culture SSF. These authors reached an ethanol production of 186.4–193.5 g/g dry OFMSW at pilot scale. SSF can also be complementary to the AD process, for instance, digestate has been evaluated as the substrate of SSF (Rodríguez et al. 2019; Mejias et al. 2020). One of the most relevant applications of SSF from a biorefinery perspective is for the production of enzymes. The integration of enzyme production from OFMSW within the biorefinery will increase cost-efficiency and reduce dependency on third parties (Vea et al. 2018; Marín et al. 2019). For this purpose, fungi outstand as the preferred microorganism because of their inherent enzymatic battery for biomass degradation (Payne et al. 2015). Crude enzymes have been produced using OFMSW as substrate in SSF for *Trichoderma reseei* growth and evaluated for enzymatic hydrolysis showing a similar efficiency to that of a commercial enzyme preparation. (J. Abdullah and Greetham 2016). The use of homogeneous streams, richer in lignocellulosic materials and porosity can lead to higher enzyme yields production (Bansal et al. 2012).

Simultaneous saccharification and fermentation (SSCF) consist in the integration of enzymatic hydrolysis and fermentation processes (Barampouti et al. 2019). The main advantages of SSCF are the simplification of production steps, which results in time and costs reduction, and the attenuation of product inhibition in enzymatic hydrolysis. However, it is hampered by the incompatibility of optimum pH and temperature for the different processes (Chacón et al. 2021). Chacón et al. (2021) recently reported a production of 255 g of lactic acid per kg of OFMSW (not clear if on a dry or wet basis) using mechanically separated OFMSW and a thermophilic strain. This value is slightly higher than that reported for the fermentation of the liquid hydrolysate (Table 3).

All the mentioned processes are based on sugars conversion (sugar platform), yet another bioconversion platform has been proposed, the carboxylate platform (Agler et al. 2011). It comprises the conversion of organic feedstocks to short-chain carboxylates, such as volatile fatty acids (VFAs). Carboxylate platform is generally based on anaerobic fermentation with mixed culture, which can effectively cope with the variability of municipal substrates because of the interaction among the metabolism of the microbial community (Agler et al. 2011). Basically, it consists in promoting the first stages of AD, hydrolysis, and acidogenesis (Demirel and Yenigün 2002). VFAs levels that can be achieved from OFMSW can reach 770 g COD_{VFA}/ g volatile solids (VS). It has been shown that this process benefits from microaerobic conditions, which can enhance productivity and VFAs chain length (den Boer et al. 2016). The VFAs are building blocks of many chemical and biological processes. For instance, polyhydroxyalkanoate (PHA) production within the same reactor can be attained by applying a feast-famine regime (Korkakaki et al. 2016).

3.3 Downstream technologies

Few studies have focused on the downstream of OFMSW valorization processes. In part, because the substantial efforts required to develop them and advancements are rather slow, except for AD-related ones, but also because of the arduousness of the task. The repeatedly mentioned complexity and heterogeneity of the OFMSW difficult the purification of desired products as undesired by-products complicate the downstream processes (Bonk et al. 2015). Theoretical approximations with models and techno-economic analysis have been made to provide better insights into the critical requirements and milestones (Demichelis et al. 2020; Elyasi et al. 2021). It is undoubtedly that more technical and economical efforts in the downstream sections are required for the manufacturing of the bioproducts and implementation of an OFMSW biorefinery (Liu et al. 2021).

The majority of advancements are related to biogas upgrade (Sun et al. 2015) and bioethanol production (Demichelis et al. 2020), as they have been the most studied and implemented technologies. However, tentative steps are also being taken for the separation of chemical building blocks. López-Gómez et al. (2020) attempted a downstream configuration for the proposed lactic acid production in Table 3. These authors performed a purification of a pilot-scale fermentation of OFMSW, highlighting the importance of large volumes of fermented broth for separation processes to succeed technically and economically. The lactic acid recovery involved several membrane steps based on electrodialysis and implied a reduction by half of the yield, from 220 to 110 g/kg of dry OFMSW.

3.4 Configuration options for the integration of OFMSW valorization technologies

This section reviews a collection of OFMSW biorefineries proposed in the literature that explore valorization routes beyond biogas and compost production. A comparison of the bioconversion technologies used and of the state of development, in terms of product recovery consideration, economical assessment, and energy balance for each biorefinery is summarized in Table 5. These proposals are initial implementation stages mostly based on technologies already developed at pilot-scale, yet lacking a complete implementation assessment.

The presented approaches of OFMSW biorefineries (Table 5) include two at pilot scale (200–380 L) located within the facility of a municipal full-scale waste water treatment plant (WWTP) in northeast Italy. Another approach combines pilot and laboratory facilities located in an experimental biorefinery of organic solid wastes within a Brazilian university campus. These pilot approaches take advantage of already existing waste management facilities, which offer logistical advantages, i.e. no mechanical pretreatments or transportation requirements. The last two are a laboratory-scale proposal, the only one not working with source-separated OFMSW, and a theoretic approach based on literature.

In terms of conversion technologies applied, all the proposals have in common the use of AD for waste minimization and energy production. Moretto et al. (2020) and Valentino et al. (2018) employed a similar configuration scheme, first, they performed an acidogenic fermentation to obtain a fermented stream rich in VFAs that was sent to a solid–liquid separation unit. The filtered stream was sent to an aerobic line composed of a sequencing batch reactor (SBR) for biomass selection and a batch reactor for PHA production. The solid stream was converted to biogas via AD. Following this scheme with an AD conducted at thermophilic conditions (55 °C), Valentino et al. (2018) obtained a yield of 37 g of PHA/kg VS and 0.42 m^3 of biogas/kg VS. In a later study using biological sludge from the municipal WWTP as co-substrate, Moretto et al. (2020) evaluated the application of a thermal pretreatment (72 °C, 48 h) on the

Table 5 Reviewed biorefinery configurations for OFMSW

Feedstock	Scale	Conversion technologies	Product recovery	Economic evaluation	Mass balance Products (Yields[a])	Energy balance			References
						Produced	Consumed	Net	
ssOFMSW + Biological sludge from WWTP	Pilot	Acidogenic fermentation; Aerobic SmF for PHA production; co-AD	No	Preliminary	Yes PHA (76 g/kg VS); Biogas (0.42 m^3/kg VS)	6.8 MJ/kg VS	6.1 MJ/kg VS	0.7 MJ/kg VS	(Moretto et al. 2020)
ssOFMSW	Pilot	Acidogenic fermentation; Aerobic SmF to PHA; AD	No	Yes	Yes PHA (37 g/kg VS); Biogas (0.68 m^3/kg VS)	7.8 MJ/kg VS; 93.4 MWh/d	6.4 MJ/kg VS; 7.7 MWh/d	1.4 MJ/kg VS; 85.7 MWh/d	(Valentino et al. 2018)
ssOFMSW + cooking oil	Pilot & Bench	Transesterification; Glycerol SmF to 1,3-Propanediol; AD; Composting	Yes, for biodiesel	Preliminary	No Biodiesel; 1,3-Propanediol; Biogas (0.58 m^3/kg VS); Compost	NM	NM	NM	(de Sousa et al. 2021)
mcOFMSW	Bench	Enzymatic hydrolysis; Ethanolic SmF; AD	Yes, for bioethanol	No	Yes Bioethanol (199 g/kg VS); Biogas (0.16 m^3/kg VS)	11.2 MJ/kg VS	NM	NM	(Mahmoodi et al. 2018a)
ssOFMSW	Theory	Oil extraction; Transesterification; Enzymatic hydrolysis; Fermentation; AD	Yes	No	Yes Biodiesel (0.1 L/kg VS); Glycerol (0.01 L/kg VS); Bioethanol (078 g/kg VS); Biomethane (0.08 m^3/kg VS); Biofertilizer (100 g/kg DM)	8.6 MJ/kg VS	NM	NM	(Barampouti et al. 2019)

ssOFMSW: source-separated OFMSW; mcOFMSW: mixed collected OFMSW; WWTP: wastewater treatment plant; SmF: submerged fermentation; PHA: polyhydroxyalkanoates; AD: anaerobic digestion; VS: volatile solids

[a] Yields are expressed per kg of initial substrate; NM: Not mentioned

performance of the acidogenic fermentation. The enhancement in organic matter solubilization led to a yield improvement from 0.37 to 0.65 g COD_{VFA}/g VS so the authors decided that the implementation of the thermal pretreatment was crucial for the process. These authors also evaluated the addition of an ultrafiltration membrane to the centrifuge for the solid–liquid separation step and two temperatures (37 °C and 55 °C) for the anaerobic co-digestion (co-AD) step. The thermophilic operation of the co-AD led to higher yields in terms of specific gas production, 0.51 m^3 of biogas/kg VS compared with 0.44 m^3 of biogas/kg VS for the mesophilic. However, the energy balance showed the mesophilic operation as more beneficial because of lower thermal energy consumption that allowed the anaerobic line to be self-sustainable. This fact highlights the importance of performing mass and energy balances when designing potential biorefineries (Moncada B et al. 2016). Comparing the two described proposals in terms of mass balance and energy, it can be seen how for similar energy consumptions, the net profit was half for the biorefinery proposed by Moretto et al. (2020). Yet, the PHA production was doubled, which leads to higher economic benefits from the sale of this product. Both papers performed a preliminary economic assessment on top of the energy and mass balances, which is essential to evaluate the dichotomy between energy and bioproducts for each specific case scenario.

The approach presented by Sousa et al. (2021) was an experimental biorefinery to treat the wastes generated in a university campus (40 L/d cooking oil, 2500 kg/d pruning waste, and 750 kg/d food waste) and provide a model for municipal managers of small towns. The configuration consisted of a pilot transesterification reactor (40 L) for the conversion of oil waste into biodiesel and glycerol with a 93% conversion yield. Then, the produced glycerol was evaluated at a lab-scale fermentation to produce 1,3-Propanediol. Additionally, a traditional biogas-composting configuration was set to process the food and pruning wastes, it included a 9.6 m^3 low-cost biodigester with a 4 m^3 gasometer and a 450 m^2 compost yard. Since mass and energy balances are not presented it is difficult to evaluate the performance of the biorefinery. The declared biogas yield (0.58 m^3 of biogas/kg VS) was relatively low considering that the other pilot-scale biorefineries partition the carbon line into PHA and achieved similar values. However, this proposal offers a small-scale and low-cost point of view that might ease the implementation pathway of OFMSW biorefineries.

Finally, the last two proposals from Table 5 are configured to produce bioethanol and biogas. On a lab scale, Mahmoodi et al. (2018a) proposed a hydrothermal pretreatment to solubilize starch and increase surface area followed by a separation step, amylase hydrolysis of the liquid fraction, cellulose hydrolysis of the solid fraction to release the remaining sugars, an ethanolic fermentation for the resulting liquid fractions and an AD process for the solid fractions. The final yields attained were 199 g ethanol/kg VS and 0.16 m^3 of biogas/kg VS. Biogas yield is considerably smaller than the presented at pilot scales, which might be related to more exhaustive operations upstream AD. In the publication of Mahmoodi presented in Table 3 (Mahmoodi et al. 2018b), this same author proposed a different configuration using acid hydrolysis to substitute the need for amylase hydrolysis. The results from both configurations were similar but slightly lower for the acid pretreatment with 194 g ethanol/kg VS and 0.15 m^3 of biogas/kg VS. Before the scale-up of these processes, an economic evaluation to study the impact of the cost of enzymes and an environmental evaluation to study the impact of the acid pretreatment are necessary to ensure the best possible configuration is selected.

4 Implementation challenges of OFMSW biorefineries

The implementation of biorefinery frameworks for the management, treatment, and valorization of organic municipal wastes has to overcome several challenges besides the previously highlighted technical aspects, i.e. handling the impact of waste composition, energy and chemicals demand of pretreatments, the efficacy of enzymatic cocktails, technological readiness at larger scales, and difficulties to recover bioproducts. Close collaboration among research actors, municipalities, and industries is necessary to achieve a fruitful implementation with its associated environmental benefits.

4.1 Composition

As repeatedly mentioned in this review, OFMSW is a variable and heterogeneous stream. The main factors affecting the composition of OFMSW are seasonality, weather, urban density, and regional nutritional habits, economic activities, and sorting instructions (Puig-Ventosa et al. 2013; Campuzano and González-Martínez 2016; Cerda et al. 2018). On top of that the citizen engagement in waste sorting, the disposal bags employed, and the collection system highly influence the quality of the waste in terms of non-organic, or inert, components (Al Seadi et al. 2013; Sisto et al. 2017). These factors can also influence the purity of final bioproducts as for compost (Cerda et al. 2018). Campuzano et al. (2016) observed that the characteristic of OFMSW with higher variability were nutrients such as phosphorous, sulfur, free sugars, or raw fiber. To mitigate the effect of such variations in subsequent microbial processes, mechanical pretreatments for the removal of non-organic materials are practically mandatory (Alibardi and Cossu 2016; Cerda et al. 2018). For instance, the VFA production from organic wastes has been reported to be more influenced by the feedstock characteristics than by the fermentation conditions (Moretto et al. 2019).

Another compositional challenge is the low calorific value and high moisture content of OFMSW. This results in higher volume and weight, hampering transportation, and microbial activity, which leads to biodegradation and lactic acid production (Matsakas et al. 2017; Alibardi et al. 2020; Stylianou et al. 2020). The establishment of an organized and efficient value chain is required to reduce collection, transportation, and storage period to a minimum.

4.2 Economic investment

Biorefineries are associated with high costs of construction, maintenance, and operation of the conversion plants (Lee et al. 2019). To justify such an investment biorefineries need to be economically profitable and, ideally, rely on multiple income sources. An additional income source to the revenues from the sale of the obtained bioproducts or energy is a gate fee for waste acceptance and treatment (Sadhukhan and Martinez-Hernandez 2017). Gate fees are particularly interesting at initial implementation stages as they represent an incentive for waste managers to deviate from landfills and implement waste valorization technologies and also provide a stable income until the complete establishment of the biorefinery (Alibardi et al. 2020). Budzianowski and Postawa (2016) recently stated that for a biorefinery to be truly economically viable, a total chain integration is required to ensure the optimization of energy and resources and reduce capital and operating costs. Economical sustainability is also benefited from flexibility towards diverse feedstocks and products (Kamm and Kamm 2004). The ability to shift between energy and commodity chemicals production endows the biorefinery to assimilate fluctuations in value-added products prices and market demands (Duan et al. 2020). Finally, size is another relevant factor influencing the economy of biorefineries. Larger sizes benefit from the economy of scale (Ragauskas et al. 2006), yet smaller sizes can lead to more specialized systems. Reduction of size by decentralization also reduces the cost associated with long-distance transportation and approaches valorization technologies to low-volume generation points (Matsakas et al. 2017).

4.3 Stakeholders interest

The implication of actors throughout the value chain of the OFMSW conversion process is necessary to develop long-term strategies and move forward from the current waste management model towards a more sustainable scenario. These stakeholders range from political figures to local citizens (Sisto et al. 2017). Local governments and decision-makers shape the policies required to favor bio-based products over chemical-based. Khoshnevisan et al. (2018a) define future policies as a source of uncertainty when assessing the environmental profile of source selected OFMSW. This lack of guarantees on long-term political interest might discourage investors from accepting bioconversion technologies and resonate with technological advances. The main producers of OFMSW are households, therefore citizens' engagement in waste sorting and acceptance of waste-derived bioproducts is also essential. A recent survey evaluates the marketability of bio-based products showing a general consumer acceptance in specific markets and a willingness to pay related to ideology (Moretto et al. 2020).

5 Conclusions

The need for new municipal solid waste management scenarios that ensure the continuity of materials within production cycles calls upon holistic and sustainable solutions. OFMSW has shown remarkable potential for its management in a biorefinery-like environment, where it can be initially fractionated to attain multi-platform configurations. Research studies in enzymatic hydrolysis have displayed promising perspectives for it to be used as an initial separation step of OFMSW's components. Meanwhile, the traditional waste management technologies, i.e. AD for biogas production and composting, will remain as powerful tools for the integration of secondary waste streams, already depleted of high-interest components. However, before the implementation of the OFMSW biorefineries, valorization technologies need to step from laboratory scale to industrial scale and final products formulations need to be addressed in cost-effective downstream processes. Ultimately government regulations promoting bioeconomy strategies and cooperation among the different parties involved have the ability to increase industrial interest and foster technological advances.

Acknowledgements Esther Molina thanks Generalitat de Catalunya for her pre-doctoral grant (DI 7, 2019). Financial support was provided by the Spanish Ministerio de Ciencia e Innovación (Ref. PID2020-114087RB-I00).

Author contributions All authors contributed to the article conception and design. Literature search, data analysis and first draft were performed by Esther Molina-Peñate. Adriana Artola and Antoni Sánchez critically revised the work. All authors read and approved the final manuscript.

Funding Ministerio de Ciencia, Innovación y Universidades (Grant No: PID2020-114087RB-I00), Agència de Gestió d'Ajuts Universitaris i de Recerca (Grant No: DI 7 2019).

Availability of data and material Not applicable.

Code availability Not applicable.

Declarations

Conflicts of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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