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Review

The valorization of the anaerobic digestate from the organic fractions of municipal solid waste: Challenges and perspectives

Alessandra Cesaro

Department of Civil, Architectural and Environmental Engineering, University of Napoli Federico II, via Claudio 21, 80125, Napoli, Italy

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ABSTRACT

The anaerobic digestion is a well-established process for the treatment of organic solid waste, pursuing its conversion into a methane rich gas destined to energy generation. Research has largely dealt with the enhancement of the overall bioconversion yields, providing several strategies to maximize the production of biomethane from the anaerobic processing of a wide variety of substrates. Nevertheless, the valorization of the process effluents should be pursued as well, especially if the anaerobic digestion is regarded in the light of the circular economy principles. Aim of this work is in identifying the state of the art of the strategies to manage the digestate from the anaerobic processing of the organic fractions of municipal solid waste. Conventional approaches are described and novel solutions are figured out in order to highlight their potential scale up as well as to address future research perspectives.

1. Introduction

In the last decades, anaerobic digestion has raised as a key technology for the sustainable management of organic waste. The energy and climate policies entered into force over time, together with the supporting schemes to promote renewable energy production, have been among the major drivers for its industrial application (Edwards et al., 2015). The generation of a methane-rich gas from a large variety of organic substrates has attracted great attention, especially when considering the possible processing of residual streams. These could be diverted from landfills and conveniently used to fulfil the global increasing energy demand while reducing the environmental burdens of both conventional fuels and waste disposal.

The success of this technology is witnessed by the increasing number of plants and installed treatment capacity. In European countries like Germany, Italy, Denmark, Czech Republic and Austria, anaerobic digestion accounts for the major contribution to the production of biogas. In 2015 there were approximately 17400 biogas plants in Europe, differing for type and size. Nevertheless, more than 16600 plants had a total electricity installed capacity higher than 10000 MW (Scarlat et al., 2018). The European Biogas Association estimated that the number of plants further increased at 18202 in 2018 (European Biogas Association, 2019). The kinds of substrate fed to these digesters stand as an additional difference among the European plants, although in the last years the predominant use of energy crops, industrial and municipal waste can be recognized (Scarlat et al., 2018).

In this dynamic context, pursuing the competitiveness of the anaerobic digestion among the processes for the production of energy from renewable sources, great efforts have been devoted to the study of the strategies to maximize the anaerobic bioconversion of organic substrates into biogas.

The critical factors affecting the generation of biogas have been extensively reviewed (Mao et al., 2015; Rasapoor et al., 2020) and several approaches have been proposed to enhance the content of methane in the biogas. Some of them focus on the substrate, pursuing the adjustment of its characteristics via either adequate pretreatments (Atelge et al., 2020; Cesaro and Belgiorno, 2014) or the co-digestion (Mata-Alvarez et al., 2014; Siddique and Wahid, 2018). Other strategies are mainly devoted to the optimization of the complex biochemical reactions involved in the anaerobic process. It is well known that the anaerobic digestion develops through four stages, namely: the hydrolysis of the high molecular weight components, the acidogenesis of simpler organic molecules into volatile fatty acids (VFA), which are then further converted into acetic acid, hydrogen and carbon dioxide during the acetogenesis; the final step is the methanogenesis, ending in the generation of the methane-rich biogas. The microbial groups are dissimilar among these stages and their growth requires different operating conditions. Low hydraulic retention time (HRT) and acidic pH are generally preferred in the acidification step, whereas methanogenesis is promoted at higher HRT and pH values (Pramanik et al., 2019). In this

E-mail address: alessandra.cesaro@unina.it.

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view, the separation of both the hydrolytic and the fermentative steps from the methanogenic one has been proposed and successfully applied at industrial scale. Two-stage anaerobic digestion systems result in higher process stability and better performances than single stage reactors, especially for the treatment of highly biodegradable substrates (Srisowmeya et al., 2020). Three-stage systems have also been proposed to overcome the shortcomings of the two-stage digesters, mainly related to the pH control. Three distinct chambers are continuously operated to perform hydrolysis, acidogenesis/acetogenesis and methanogenesis, so that the ideal scenario for optimal pH maintenance is ensured (Chatterjee and Mazumder, 2019). Further strategies to improve the process stability and enhance methane generation include the addition of nanoparticles, trace elements as well as activated carbon (Zhang et al., 2019).

Plenty of studies have been devoted to the enhancement of methane production from the anaerobic digestion. Conversely, the treatment of the anaerobic effluent, namely the digestate, has been considered a side aspect for a long. However, the identification of sustainable management strategies to handle the digestate represents a key issue.

Anaerobic digestion is a well-established process for the recovery of organic waste, but its successful implementation turn to be consistent with the circular economy principles only if the digestate potential can be fully displayed. In this regard, the conventional management strategy has been directed towards its use as fertilizer, but innovative concepts and techniques have been proposed in scientific literature as possible alternatives.

Aim of this work is in identifying the state of the art of the strategies to manage the digestate originating from the anaerobic processing of the organic fraction of municipal solid waste (OFMSW) and its main components, namely food leftovers and yard residues. Conventional approaches are described and novel solutions are figured out in order to highlight their potential scale up as well as to address future research perspectives.

2. Characteristics of the anaerobic digestate from the organic fractions of municipal solid waste

The digestate is a mixture of partially degraded organic matter, microbial biomass and inorganic compounds (Alburquerque et al., 2012). Its characteristics depend on the feedstock composition and quality, the anaerobic technology adopted as well as the operating parameters.

The OFMSW is variously defined in different countries, but it mainly refers to a mixture of food waste, leaf and yard waste. Nevertheless, its composition varies among regions, seasons as well as in dependence of the cultural and socio-economic conditions. This, in turn, affects the OFMSW characteristics, as detailed by Campuzano and González-Martínez (2016). These authors observed the highest variability for total phosphorus, sulphur, hemicellulose, Kjeldahl nitrogen, free sugars, lignin and raw fibre. Therefore, the characterization of the substrate destined to anaerobic digestion is extremely important to predict - under the same conditions - the properties of the resulting digestate.

Source-sorted organic residues are usually a high-quality feedstock. However, depending on the collection methods and yields, they can contain non-digestible materials, such as pieces of plastic, rubber, glass, which end up in the digestate if not properly removed during the feedstock pretreatment stage (Al Saedi et al., 2013).

The relative presence of carbohydrate, lipids and proteins further accounts for the digestate composition and biological stability. During anaerobic digestion, labile organic constituents are degraded at an extent that depends on the residence time of the material in the digester. This is usually limited to meet efficiency criteria for energy production at industrial scale, so that the digestate is not completely exhausted in terms of easily-degradable organic compounds (Alburquerque et al., 2012).

Trzcinski and Stuckey (2011) studied the operating parameters affecting the stability of the OFMSW digestate taken from a continuous anaerobic two-stage system. This consisted of a hydrolytic reactor (HR) with a 10 L working volume, intermittently mixed and with a concentric stainless steel mesh that was used to separate the coarse solids from the leachate. The former were retained in the reactor; the leachate was fed to a submerged anaerobic membrane bioreactor (SAMBR), consisting of a 3 L reactor with a submerged Kubota polyethylene flat sheet membrane, working under mesophilic conditions. The authors highlighted how higher temperature and solid retention time resulted in higher methane yield and volatile solid removal in the HR. They further compared the stability of the solids withdrawn from both the HR and SAMBR, which contained anaerobic bacteria as well as recalcitrant lignocellulosic fibers. The results showed that the solids taken from the SAMBR were more degraded than in the HR, despite their greater recalcitrance to biological degradation.

Both the feedstock composition and the process operating conditions also influence the nutrient content of the digestate. The adopted technology, in terms of total solids fed to the digester, is mainly responsible for its moisture content. The latter, in turn, accounts for the rheological behavior of the digestate, as Peng et al. (2020) recently discussed with reference to high solid anaerobic digestate.

Table 1 outlines the most commonly reported characteristics of digestate samples originating from the anaerobic treatment of either OFMSW or its components, processed as sole substrates or in co-digestion with other organic residues.

The analysis of the only data referring to digestate samples withdrawn from larger scale digesters (full and demo) highlights pH values ranging between 7.7 and 8.7 and a dry matter (DM) content ranging between 1.7 and 12.7. The latter aspect is of course depending on the anaerobic technology, which includes both wet and dry systems.

If it does not originate from high solid processes, the digestate is usually a liquid to thick slurry. Dewatering is thus applied, most commonly via screw press, screening drum press (vibrating screen) and centrifuge (Al Seadi et al., 2013). These technologies split the digestate into a liquid and a solid fraction, as schematically represented in Fig. 1. Either the whole digestate or the fractions obtained from its solid/liquid separation can be differently valorized. Some options (i.e. use as fertilizer, generation of value added chemicals) can be applied regardless of the solid content of the digestate; other can involve only specifically characterized substrates (i.e. culture media for microalgae), as discussed in the following paragraphs. It is worth highlighting that, depending on the valorization process, either the digestate or its solid/liquid portions could require additional pretreatments to better fit the specific process.

Among the chemical parameters of the digestate reviewed in literature, the greater variability can be recognized in the content of total nitrogen (TN) as well as ammonia nitrogen ($N{-}NH_4^+$), as plotted in Fig. 2. This evidence is consistent with the findings of Guilayn et al. (2019), analysing a large dataset of chemical-physical parameters of different kinds of digestate. The authors mainly attributed the digestate composition variability to the overall nitrogen content and DM. They identified the digestates from OFMSW or its components as characterized by particularly high TN contents (71.8 ± 38.4 g/kg_{DM}), while being rich in Total Potassium (TK) (56.0 ± 16.8 g/kg_{DM}) and with a low range of Total Phosphorous (TP) content (14.2 ± 6.8 g/kg_{DM}). The same study further pointed out that the nitrogen variability drives that of the C/N ratio, the typical indicator of the organic stability for soil application (Guilayn et al., 2019). Considering the data reported in Table 1 about digestate samples originating from the larger scale facilities, the C/N ratio ranges between 1.5 and 12.1 (Fig. 3a), with the lowest value observed for the digestate characterized by the highest nitrogen content. Fig. 3b shows the limited variability of the digestate organic content, expressed as volatile solids (VS). The maximum value was observed for the digestate withdrawn from the hydrolytic reactor of a two-stage anaerobic system. The final effluent of the same process had a VS content corresponding to the median value of the analyzed dataset. This value, expressing the organic content of the digestate, is relatively high. Nevertheless, it could

Table 1
Characterization of the anaerobic digestate from OFMSW or its components.

Digestate characteristics										Anaerobic digestion process						Reference
pH	DM	VS	Total C	Total N	N–NH$_4$	N$_{org}$	Total P	Total K	C/N	Substrate	HRT [d]	OLR [kg$_{VS}$/m^3 d]	AD stages	Temperature	Digester	
[-]	[%]	[% TS]	[g/kg$_{DM}$]	[g/kg$_{DM}$]	[g/kg$_{DM}$]	[% TKN]	[g/kg$_{DM}$]	[g/kg$_{DM}$]	[-]							
7.9	6.1		311	129	86.8	33	14.7	26.2	7.1	Slaughterhouse waste, SS-organic household waste[a]	40–50		not specified	Mesophilic	Full scale	Abubaker et al., 2011
8.0	1.7		411	153	118	23	11.8	64.7	11.0		40–50		not specified	Thermophilic	Full scale	
8.7	5.9		406	89.8	55.9	37.7	6.8	62.7	12.1	Silage, SS-organic household waste[a]	20		not specified	Mesophilic	Full scale	
8.5	37	48	245	16	6.2		1.5	10.5		OFMSW, horse manure	30		One stage		Pilot scale	Arab et al. (2017)
7.69	8.8	65.0	383	110	81.9		7.2	36		OFMSW	Statistical analysis of data regarding digestate from OFMSW anaerobic digestion under different conditions					Beggio et al., 2016
7.61						55.4			2.7	Sludge, fruit and vegetable waste	14	1.46	One stage	Mesophilic	Pilot scale	Di Maria et al. (2014)
7.41						47.0			7.0		14	1.70	One stage	Mesophilic	Pilot scale	
7.31						58.4			7.4		14	2.08	One stage	Mesophilic	Pilot scale	
7.29						69.0			10.0		14	2.46	One stage	Mesophilic	Pilot scale	
7.05						75.0			13.3		14	2.80	One stage	Mesophilic	Pilot scale	
8.9	34	50.1	302		0.25	26	5.1	5.3	18.9	Food waste, green waste (90/10 w/w)	28		not specified	Mesophilic	Pilot scale	Grigatti et al. (2020)
6.4	44.9	66.8		15.7	1.2	92.4	12.7	15.0	8.3	OFMSW			One stage	Mesophilic	Pilot scale	Massaccesi et al. (2013)
8.4	43.7	73.6		15.4	1.1	92.7	31.4	2.9	29.8	OFMSW			One stage	Mesophilic	Pilot scale	
8.9	50.2	75.5		10.3	1.2	88.3	54.0	13.4	37.5	OFMSW			One stage	Mesophilic	Pilot scale	
8.7	37.3	76.7		17.6	2.4	86.4	45.2	9.2	28	OFMSW			One stage	Mesophilic	Pilot scale	
6.5	7.4				94.6				30.5	Food waste (12 kg), human excreta (3 kg)	60		One stage	Mesophilic	Pilot scale	Owamah et al. (2014)
	2.4	55		100	0.8		10	40		OFMSW	40	1.96	One stage	Mesophilic		Stoknes et al. (2016)
	5.9	75.1	404	65	33.3				6.7	Energetic crops (1.9 FM), cow slurry (21.8 FM), agro-industrial waste (17.9 FM), OFMSW (58.4 FM)	30–40		First stage	Thermophilic	Full scale	Tambone et al. (2009)
	3.6	68.4	377	110	68.4				3.4		50		Second stage	Thermophilic	Full scale	
	3.8	69.1	38.6	143.7	94.0	34.6			7.7	OFMSW (80%), pig slurry (20%)	50		Two stages	Thermophilic	Full scale	Tambone et al., 2010
8.0	6.74	67.6	386.1	116	60.0		19.9	44.1	3.3	Food waste	94–117	2–6	One stage	Mesophilic	Lab scale	Tampio et al. (2015)
8.0	6.81	73.7	395.0	127.8	66.1				3.1	Food waste	58	4	One stage	Mesophilic	Lab scale	Tampio et al. (2016)
7.6	7.88	80.8	328.7	99.0	21.6				3.3	Food waste	47	4	One stage	Mesophilic	Lab scale	
8.3	1.99	61.8	341.7	236.2	196.0				1.5	Food waste	26	3.3	One stage	Mesophilic	Demo-scale	
8.3	3.22	58.7	319.9	139.8	99.4				2.3	OFMSW	24	3.7[b]	Two stages	Thermophilic	Full scale	
7.6	3.42	69.9	394.7	64.3	49.7				6.1	Vegetable waste, activated sludge	16	3.8[b]	One stage	Thermophilic	Pilot scale	

[a] Source separated organic household waste.
[b] Expressed as kg$_{COD}$/m^3 day.

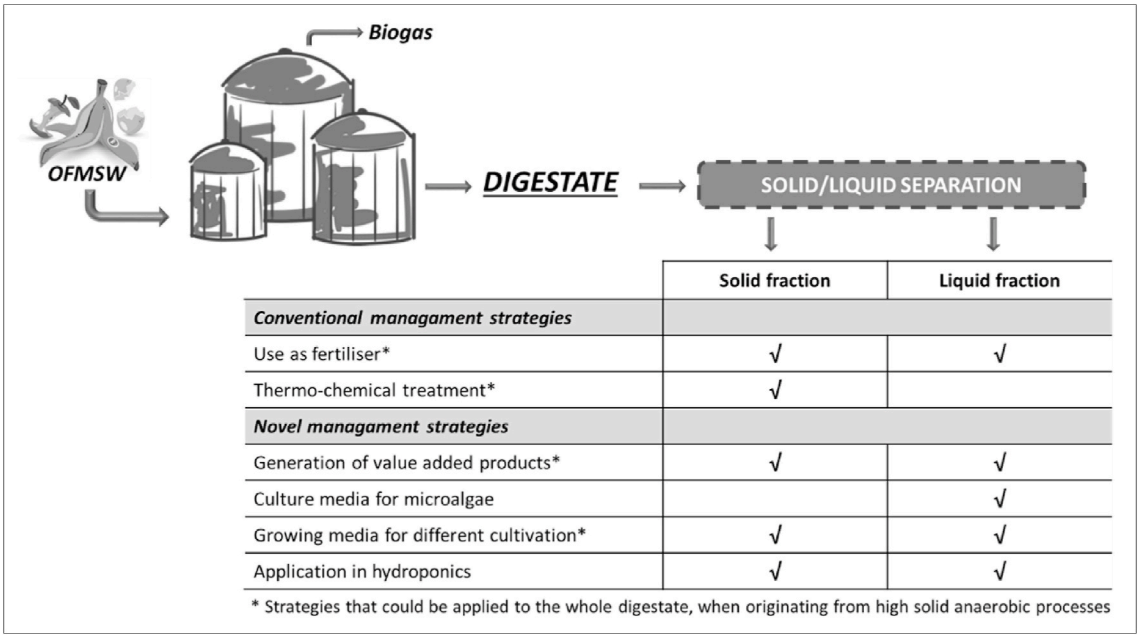

Fig. 1. Possible management strategies for OFMSW digestate.

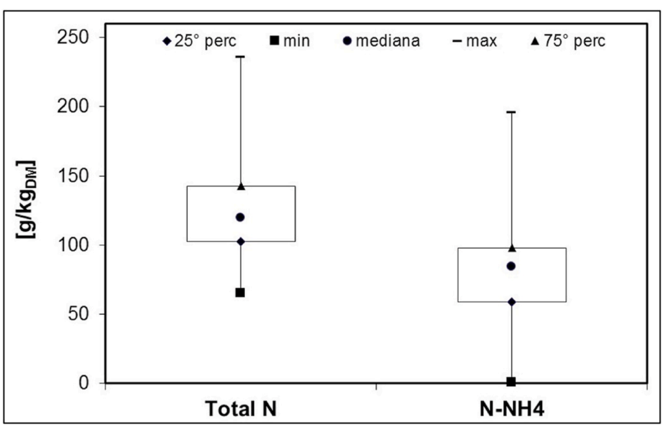

Fig. 2. Variation of the contents of both total and ammonia nitrogen in digestate, as reported in literature.

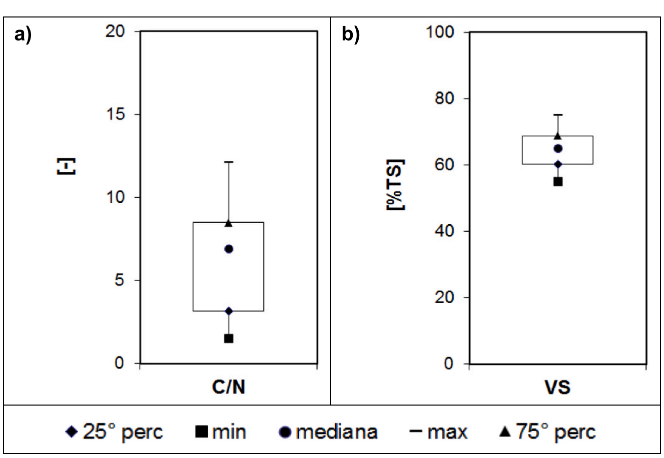

Fig. 3. Variation of the a) C/N ratio and b) volatile solid content of digestate, as reported in literature.

be attributed to the presence of co-feedstocks other than OFMSW, with high fibrous content (Guilayn et al., 2019). The anaerobic processing of the sole OFMSW can, indeed, produce a digestate with a VS content as low as 55%TS.

3. Conventional management strategies

The characterization of the digestate is fundamental to address its valorization.

Due to the content of nutrients, the traditional management of the digestate has been directed towards its application on soil and this is the reason for the huge availability of data referred to the characterization of the agronomic properties, as reported in Table 1.

3.1. The use as a fertiliser

Anaerobic digestion proceeds by the degradation of the more labile organic fractions and the concentration of the more recalcitrant molecules. This accounts for the biological stability level of the digestate (Tambone et al., 2009) and depends on the characteristics of the substrate fed to the digester, which often is used to define the legal status of the digestate (Beggio et al., 2019).

Both food waste and OFMSW can generate digestates with high agronomic values (Abubaker et al., 2012; Cheong et al., 2020; Tampio et al., 2016), but the pretreatments can influence this potential. Tampio et al. (2015) characterized the agronomic value of digestates obtained from the lab-scale anaerobic digestion of both untreated and autoclaved food waste. The authors found that the thermal pretreatment of food waste determined the formation of Maillard compounds, which affected the nitrogen containing molecules. As a result, the autoclaved food waste digestate was evaluated to be more suitable as soil amendment than fertilizer.

The agronomic value, which is somehow related to the biological stability, is only one of the characteristics considered to qualify the digestate as a fertiliser. Specific requirements on the phytotoxicity as well as on the hygienic quality have to be met in order to ensure the safe use of the digestate on soil. In this view, the European Union has recently enforced the Fertiliser Regulation to characterise different kinds of digestates, including the one originating from source sorted OFMSW. This Regulation represents a milestone to promote the trade of waste-based fertiliser and it is an important step in the European circular economy (Stürmer et al., 2020). It establishes 11 Component Material Categories (CMCs) to produce different EU fertilising products: the OFMSW digestate falls within CMC 5 - Digestate other than fresh crop digestate. Different CMCs can contribute to a range of the so called Product Function Categories (PFCs), as detailed in the Annex I to the EU Regulation. Table 2 sums up the main requirements for CMC 5 as well as those established for the PFCs that can be obtained using the OFMSW digestate. The presence of metals and pathogens is regulated in order to ensure the safe use of waste-based materials on soil.

It is worth highlighting that, when dewatering is applied to OFMSW digestate, the liquid fraction tends to concentrate most of the initial nitrogen content (Tambone et al., 2017).

The liquid fraction of the digestates from industrial-scale anaerobic plants was fully characterized by Akhiar et al. (2017), who compared different dewatering devices. They pointed out that centrifugation may provide a greater separation efficiency than screw press and vibrating screen. The authors further highlighted the impact of the separation device on the Total Kjeldahl Nitrogen (TKN) concentration. The ratio of TKN in suspended particles out of the total TKN ranged between 46 and 65% in the liquid fractions of the digestate after screw press or vibrating screen and it dropped to 11% after centrifugation. In a pot trial on sandy soil, Haraldsen et al. (2011) showed that the use of the liquid fraction of the anaerobic digestate as fertilizer gave a much lower total loss of N in comparison with the use of its nitrified forms. Nevertheless, ammonia loss to the atmosphere may occur when this liquid fraction is not rapidly mixed in the soil after application.

The dynamics of nitrogen in digestate-soil systems have raised great attention, with respect to both the environmental impacts and the optimization of the fertilizer value. In this view, Rigby and Smith (2013) compared the performances of four different digestates to find that the overall nitrogen release depended on the intrinsic properties of the digestate. The kind of soil accounts for the nitrogen processing capacity and, in turn, for its production rate, but only under specific circumstances it can influence nitrogen availability and loss.

The emission of ammonia is one of the drawbacks associated with the

Table 2
Main requirements for Component Material Category (CMC) 5 as well as for the Product Function Categories (PFCs) of fertilising products that can include OFMSW digestate under the Regulation (EU) 2019/1009 of the European Parliament and of the Council of June 5, 2019.

Requirements for Component Material Category (CMC) 5 - Digestate other than fresh crop digestate	
Non admitted feedstock	the organic fraction of mixed municipal household waste separated through mechanical, physicochemical, biological and/or manual treatment
	sewage sludge, industrial sludge or dredging sludge
	animal by-products or derived products falling within the scope of Regulation (EC) No 1069/2009 […]
Temperature-time profile	thermophilic anaerobic digestion at 55 °C for at least 24 h followed by a hydraulic retention time of at least 20 days
	thermophilic anaerobic digestion at 55 °C with a treatment process including pasteurization
	thermophilic anaerobic digestion at 55 °C followed by composting in:
	70 °C or more for at least 3 days
	65 °C or more for at least 5 days
	60 °C or more for at least 7 days, or
	55 °C or more for at least 14 days
	mesophilic anaerobic digestion at 37–40 °C with a treatment process including pasteurization
	thermophilic anaerobic digestion at 55 °C followed by composting in:
	70 °C or more for at least 3 days
	65 °C or more for at least 5 days
	60 °C or more for at least 7 days, or
	55 °C or more for at least 14 days
Digestate characteristics	PAH in either the solid or the liquid fraction of the digestate $\leq$ 6 g/kg_{DM}
	Macroscopic impurities (glass, metal or plastics) above 2 mm $\leq$ 3 g/kg_{DM}
	Sum of the same macroscopic impurities $\leq$ 5 g/kg_{DM}
	Oxygen uptake rate $\leq$ 25 mmol $O2/kg_{organic\ matter}$ h, or Residual biogas potential $\leq$ 0.25 L $biogas/g_{VS}$

Requirements for Product Function Categories (PFCs)

Parameter	**Measure unit**	**PFC1(A) Organic fertilizer**		**PFC1(B) Organo-mineral fertilizer**		**PFC (3) Soil improver**	**PFC (4)**	**PFC (6) Plant biostimulant**[b]
		Solid	**Liquid**	**Solid**	**Liquid**	**(A) Organic**	**Growing medium**	**(B) non-microbial**
Dry matter	% (w/w)	–	–	–	–	20	–	–
N	% (w/w)	≥2.5	≥2.0	≥2.5, of which 1% N_{org}	≥2.0, of which 0.5% N_{org}	–	–	–
P_2O_5	% (w/w)	≥2.0 or	≥1.0 or	≥2.0 or	≥2.0 or	–	–	–
K_2O	% (w/w)	≥2.0	≥2.0	≥2.0	≥2.0	–	–	–
Sum of nutrients	% (w/w)	≥4.0	≥3.0	≥8.0	≥6.0	–	–	–
C organic	% (w/w)	≥15.0	≥5.0	≥7.5	≥3.0	≥7.5	–	–
Cd	mg/kg_{SS}	≤1.5		≤3.0 or 60 mg/kg_{P2O5}		≤2.0	≤1.5	≤1.5
Cr VI	mg/kg_{SS}	≤2.0		≤2.0		≤2.0	≤2.0	≤2.0
Hg	mg/kg_{SS}	≤1.0		≤1.0		≤1.0	≤1.0	≤1.0
Ni	mg/kg_{SS}	≤50		≤50		≤50	≤50	≤50
Pb	mg/kg_{SS}	≤120		≤120		≤120	≤120	≤120
As	mg/kg_{SS}	≤40		≤40		≤40	≤40	≤40
Cu	mg/kg_{SS}	≤300		≤600[a]		≤300	≤200	≤600
Zn	mg/kg_{SS}	≤800		≤500[a]		≤800	≤500	≤500
Biuret	mg/kg_{SS}	Absent		≤12		–	–	–
Salmonella	in 25 g or 25 ml	Absent		Absent		Absent	Absent	Absent
E. Coli/ Enterococcaceae	in 1 g or 1 ml	≤1000		≤1000		≤1000	≤1000	≤1000/1000 UFC/g

[a] If not added to the fertilizer.
[b] Additional requirements on pathogens applied.

direct soil distribution of anaerobic digestates, along with the release of carbon dioxide (CO_2) and nitrous oxide (N_2O) (Pezzolla et al., 2012). Therefore, the aerobic stabilization of the digestate or its solid fraction is used to complete the biostabilization reactions started during the anaerobic process (Arab et al., 2017; Arab and McCartney, 2017; Maynaud et al., 2017) and obtain a more stable product to be applied on soil. The impact of the aerobic stabilization of food waste digestates on the potential CO_2 emissions was recently studied by Grigatti et al. (2020), together with the nitrogen and phosphorous nutritional capacity for plant. Both wet and dry-batch anaerobic digestates were tested and, due to their C/N ratio, different amounts of products were used to ensure the same amount of nitrogen potentially available for crops during the experiments. This condition affected the whole CO_2 emissions, which for the dry-batch digestate doubled those of the wet one. In both cases, composting strongly reduced these emissions, without seriously affecting the potential fertilising capacity.

3.2. The thermo-chemical treatment

The treatment of the digestate for its valorization has been extensively carried out via thermochemical processes, namely gasification, pyrolysis and hydrothermal carbonization (Pecchi and Baratieri, 2019).

The gasification occurs in a temperature range between 600 and 1200 °C and under oxygen sub-stoichiometric conditions. It has been mainly applied to promote the conversion of the digestate into a syngas, containing hydrogen and methane, in order to improve the overall energy gain. The integration of high-solid anaerobic digestion and air gasification was studied for the treatment of the digestates originating from grass and manure. It was shown that syngas yields were affected by operating temperatures as well as by the digestate characteristics, which also influenced the syngas composition significantly (Li et al., 2018).

More recently, Singlitico et al. (2020) compared six waste-to-energy routes for the digestate produced from the organic fraction of municipal solid waste, in order to assess the impact of the energy recovery on the economics of the biomethane production. The authors found that the anaerobic digestion coupled with the steam gasification of the dried digestate can maximize the amount of renewable gas produced. This resulted in the lowest costs as well as in the highest net present value. Additionally, the greatest CO_2 emission saving was obtained, due to the considerable amount of natural gas that could be replaced by the one produced via the coupled process.

However, an effective gasification requires the digestate drying in order to lower the TS content below 30%. Similar consideration raises for the pyrolysis, although it can be run at lower operating temperatures and without gasifying agents. Among the pyrolysis products, the biochar is the most frequently targeted when the process is applied to the organic waste digestate. OFMSW digestate-based biochars may be either applied as fertilizer (Opatokun et al, 2016, 2017) or used to obtain sorbent materials (Chen et al., 2019; Huang et al., 2020; Liu et al., 2020; Sun et al., 2013; Wongrod et al., 2018). Both phosphorous and potassium contents are higher in the biochar than in the original digestate (Monlau et al., 2016) and the water holding capacity is higher as well, accounting for better performances as soil amendment.

Li et al. (2020) studied a hydrothermal pretreatment to optimize the dewatering of food waste digestate and generate biochar and biogas from the resulting solid and liquid fractions, respectively. Mass and energy balances performed at pilot scale showed that in the whole process, including the hydrothermal pretreatment, the pyrolysis and the anaerobic digestion, additional 3.59 tons of wood pellet would be needed to supply the energy to treat 100 tons of digestate. Although such external input could be further reduced by using the wasted heat in the thermal processes, the overall mass balance rate was approximately 94%.

An integrated approach was also proposed considering the pyrolysis of the digestate for the production of syngas, to be injected in the anaerobic digester for enhanced biofuel recovery (Yang et al., 2020). The comparison between the theoretical and the experimental methane production proved that the improvement was not only due to the stoichiometric conversion of the syngas to methane, but also due to the positive effect on the anaerobic conversion of food waste.

Among thermo-chemical processes, hydrothermal carbonization (HTC) has also raised interest as possible digestate valorization technique. This process does not require the drying of the digestate like gasification and pyrolysis, so that it can be used to treat the digestate from wet anaerobic processes without extensive pretreatments (Sharma et al., 2020b). The hydrothermal carbonization occurs, indeed, in water environment, at temperatures as high as 300 °C and at pressures up to 10 MPa. It results in: i) a gaseous product, mainly consisting of carbon dioxide; ii) a liquid fraction containing water soluble organic compounds, and iii) a hydrochar with potential fertiliser properties.

Akarsu et al. (2019) evaluated the effects of HTC conditions on the yields and properties of the hydrochar obtained by both food waste and its digestate. Experimental results indicated a higher mass yield of hydrochar for the food waste digestate. This enhanced when the operating temperature and the treatment time increased from 175 °C to 200 °C and from 15 to 30 min, respectively. The hydrochar was successfully investigated for its combustion reactivity and hydrogen yield via steam gasification, suggesting additional integrated digestate valorization concepts.

The hydrochar from OFMSW digestate has been also used to obtain porous carbons. To this end, Bernardo et al. (2020) performed a HTC using the native pH conditions of the digestate (8.3) as well as lowering its pH to 3.0 by adding sulphuric acid (H_2SO_4). The resulting hydrochars were then activated with potassium hydroxide (KOH). The pH adjustment did not affect hydrochar characteristics and resulted in porous carbons with higher ash content and lower surface area. Notwithstanding, the preliminary evaluation of their sorption capacity against phosphate showed comparable performances. This was likely due to the higher mineral content of the hydrochar obtained from the acidified samples, which promoted the formation of complex with the phosphate ions. The HTC has been successfully investigated also for the digestate obtained from mechanically sorted MSW, showing the improvement of both carbon content and ignition (Pawlak-Kruczek et al., 2020).

Another interesting integrated approach was proposed by Sharma et al. (2020a), studying the production of hydrochar from the HTC of the digestate originating from microwave-pretreated yard waste. The pretreatment was found to positively influence the production of hydrochar, which showed enhanced physico-chemical, structural and combustion properties with regard to that obtained from the untreated substrate. The thermo-chemical process of the pretreated waste digestate resulted in 21% increase in carbon content. This condition, along with the reduction in volatile matter content, determined a greater thermal stability as compared to that of the untreated waste digestate.

The use of microwave has also been reported to assist the liquefaction of the solid digestate originating from the anaerobic treatment of pig slurry, olive pomace, maize silage, sorghum silage and onion scraps, with the aim of bio-oil production (Barbanera et al., 2018). In the study, the optimum operating conditions for the microwave-assisted liquefaction were identified with reference to both the yield and the higher heating value of the bio-oil. Additional considerations on the energy used for the microwave treatment provided a theoretical basis for the process scale-up.

4. Novel solutions

The conventional use of the OFMSW digestate as fertilizer may imply some difficulties. Its quality must meet more and more stringent standards to reduce the risk of soil contamination (Stürmer et al., 2020), while the increasing urbanization is reducing the availability of lands destined to agriculture (Burgin, 2018). The application of thermo-chemical processes, when not limited by the moisture content of the digestate, has the main constraints of the technological complexity and the energy consumption.

Further solutions are thus required to provide alternative valorization paths, closing the loop of the material cycle.

4.1. Generation of value-added products

The circular perspective underlying waste management has promoted the development of the biorefinery concept. The International Energy Agency (2014) defined the biorefinery as "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)". Since the anaerobic process perfectly fits this framework by converting organic residues into energy carriers and value added chemicals, the valorization of the digestate should be better addressed towards products with a market value. This depends on the production costs as well as on the market conditions, including the existence of the demand and the competition with fossil fuel derived products.

Budzianowski (2017) reported values and volumes of several bioproducts and bioenergies that may be obtained from biomass in biorefineries. The author pointed out that some biopharmaceuticals, biocosmetics and bionutrients can be produced only in relatively lower volumes than biofertilizer; nevertheless, they may achieve higher values. Bionutrients, such as proteins, play a pivotal role in the life of both humans and animals as a source of nitrogen and essential amino acids. A recent study proposed the generation of microbial proteins, also known as single cell proteins (SCPs), using OFMSW-based digestate as nitrogen source (Khoshnevisan et al., 2019). In this study, the OFMSW digestate was centrifuged and the resulting supernatant was filtered and pasteurized at 70 °C for 1 h. Then, it was diluted to test different ammonium concentration for SCP cultivation by a mixed culture of methanotrophs, whose growth was promoted by the methane produced from the OFMSW anaerobic digestion. Experimental results showed that the original content of both trace elements and nutrients in the OFMSW digestate was not sufficient to methanotrophs for a full uptake of the ammonium from the medium and its assimilation in the form of proteins. Moreover, the typical total ammonia nitrogen concentration in the OFMSW digestate seems not realistic for the current scale-up of the SCP production process, claiming the need for further research.

Among high-value bioproducts, biochemicals constitute the largest class of high-value.

Biochemicals include volatile fatty acids (VFAs), which are commonly generated from the fermentation of biomass, including the OFMSW (Vea et al., 2018). Nevertheless, the anaerobic digestate contains poorly degradable organic fraction that can be properly pretreated and used as substrate for VFA generation, as suggested by Fang et al. (2018). These authors proposed a fungal pretreatment by *P. sajor-caju* and *T. versicolor* to promote the solid state fermentation of the solid digestate obtained from the anaerobic processing of wasted fruits and vegetables residues. The maximum VFA yield obtained after the pretreatment of the solid digestate using *P. sajor-caju* was 240 $mg_{COD}/g_{VS\ added}$ and it was more than double the one gained from the raw substrate. The results were also found to be comparable with the maximum VFA generation from other organic matrices, such as waste activated sludge and wheat straw. This indicates the potential of the digestate in VFA production, despite it has already undergone an anaerobic process.

Another recent study assessed the potential of the digestate to be converted in a range of value added products via solid state fermentation (Cerda et al., 2019). The digestate originated from the wet, mesophilic anaerobic treatment of source sorted biowaste, followed by a solid/-liquid separation. The solid fraction, characterized by an average moisture content of 75.6%, was sanitized for 1 h into a previously heated oven at 70 °C. After being cooled down, this was used for the different fermentation experiments, aiming at the production of hydrolytic enzymes, biosurfactants and biopesticides. Experimental results were promising for the biopesticide production, but showed low generation yields for both enzymes and surfactants. In the former case, the reason was likely the poor biodegradability of the digestate; the high pH as well as the inadequate nutrient conditions were recognized as the main limits in the production of surfactants.

The scale up of the solid state fermentation of the biowaste-based digestate for the production of biopesticides was tackled by Rodríguez et al. (2019). The greater mass in the pilot scale reactor resulted in a substantial increase in the spore content when compared to the bench-scale reactors, and the overall results indicated the technical feasibility of the process.

4.2. The use as culture media for microalgae

The integration of anaerobic digestion and microalgae cultivation has raised as an interesting approach to improve the competitiveness of the biogas upgrading. The biogas generated from the anaerobic conversion of organic substrates mainly consists, indeed, of methane (CH_4) and carbon dioxide (CO_2), whose removal is fundamental to obtain a gaseous product suitable for energy purposes. As many microalgal strains are able to convert biogas CO_2 to organic biomass via photosynthetic reactions, the biogas upgrading via microalgae cultivation seems a suitable alternative to conventional CO_2 adsorption processes (Nagarajan et al., 2019). Most microalgae are tolerant to CH_4 and its presence in the biogas was found to enhance the fixation of CO_2. Microalgal strains resistant to high methane concentrations have been developed as well (Nagarajan et al., 2019), pushing microalgae-based biogas upgrading.

Such approach is even more interesting when considering that the digestate, obtained together with the biogas from the anaerobic digestion, can be provided to microalgae as a nutrient source for their growth (Xia and Murphy, 2016). The overall integrated process may generate electricity from the upgraded biogas as well as microalgal biomass having multiple industrial applications (Bhattacharya and Goswami, 2020). It can be used, indeed, for the generation of either energy or value - added products (Koutra et al., 2018).

Massa et al. (2017) compared three different kinds of digestates as growth media for three microalgae strains and found that the digestate originating from municipal solid waste was the poorest one. Conversely, the vegetable biomass digestate allowed the same growth performance than the one achieved on the respective standard media for the target strains, with ammonia-nitrogen removal efficiencies ranging between 79 and 99.5%, depending on the strain. A further insight in the use of the digestate as growing medium for microalgae was provided by McDowell et al. (2020), who compared anaerobic effluents originating from cow manure, pig manure and food waste. These authors highlighted that, as the food waste digestate contained the highest level of total inorganic nitrogen, the microalgae grown on this medium accumulated the higher protein concentration, making them suitable as livestock. Similar results were reported by Mayers et al. (2017), studying the use of food waste anaerobic digestion effluent as source of nitrogen and phosphorus for the production of the marine microalge *Nannochloropsis sp*. These authors found that the anaerobic digestion effluent, at 50% dilution, could replace up to 100% of the algae nitrogen demand, without relevant impacts on both biomass growth and volatile fatty acid productivity.

These evidences pointed out the influence of the anaerobic digestion feedstock on the quality of the digestate for its use as cultivation medium. Nevertheless, the same kind of digestate may differently affect the growth of diverse microalgae strains. In this view, diluted kitchen waste digestate was assessed as growing medium of ten different microalgae species (Yu et al., 2017). Only four of them could survive in the presence of the digestate, with two of these highlighting the best tolerance level. For these species, namely *Scenedesmus* SDEC-8 and *Chlorella* SDEC-18, the cultivation in the digestate accounted for an overall increase in the lipid content that was almost 70% higher than the one observed in the control medium. This condition, which came along with a sharp increase in the lipid productivity, made these strains most preferable for biodiesel production (Yu et al., 2017).

The production of biodiesel from microalgae grown in food waste digestate was also studied by Shin et al. (2015), using *Scenedesmus bijuga* as target strain. To this end, the digestate was diluted with wastewater municipal effluent. Experimental results showed that 1/20 dilution ratio resulted in the highest biomass and lipid productivity and proved to be the best condition for the production of the fatty acid methyl esters to generate high quality biodiesel. Under semi-continuous operations, a food waste digestate treated by electrocoagulation and diluted twice provided higher algal productivity than the same medium diluted by five times. Nevertheless, both conditions were equally effective in terms of nitrogen and phosphorous reduction (Chen et al., 2016).

The dilution of the digestate is necessary not only to prevent inhibition phenomena due to the high ammonia content (Uggetti et al., 2014), but also to reduce the limits posed by the turbidity to the photosynthesis. However, the dilution may complicate both the process engineering and scale up. For this reason, undiluted anaerobic digestate was ozonated and studied as *Chlorella* growth medium (Cheng et al., 2016). Ozone concentrations up to 2 mg/mg_C enhanced biomass growth by increasing the amount of compounds that could be easily assimilated by microalgae.

The reduction of the turbidity effects can be also obtained by optimizing the cultivation systems, in order to promote a more efficient light utilization. This can be obtained by either temporal or spatial light distribution systems. The former relies on the rapid movement of the algae cells between light and dark zones of the culture vessel, providing a so called "flashing light effect". This system has proved to increase the efficiency of light utilization, but to any significant degree due to the random turbulence provided. Spatial distribution systems collect the light and distribute it over large surface areas, in order to deliver it to microalgae at saturation light intensities. These may be differently applied to both open and closed cultivation systems, but they are generally more expensive than temporal light distribution systems, which represent the preferred solution when the digestate is used as cultivation medium (Chuka-ogwude et al., 2020).

It is worth highlighting that the cultivation system itself influences the productivity of microalgae as well as their possible use. In this regard, Moreno-Garcia et al. (2017) stated that if microalgae are intended to be used for biofuel generation, they can be cultivated in either open or closed systems. Conversely, the utilization for pharmaceutics requires less contamination and microalgae should be better cultivated in closed systems. As for the productivity, the comparison between open ponds and bioreactors has been reported in recent studies dealing with the use of agro-waste digestate as growing medium (Pizzera et al., 2019; Simonazzi et al., 2019) and it was found to be dependent on the algal species.

Pizzera et al. (2019) used a suspension mainly containing microalgae of the families *Chlorellaceae* and *Scenedesmaceae*. These authors found that the raceway pond system provided a higher specific removal rate and slightly higher biomass productivity than the column photobioreactor. Conversely, when using *Phaeodactylum tricornutum* as source of eicosapentaenoic acid, both the algal and the acid productivity were almost two-fold higher in photobioreactors than in open ponds (Simonazzi et al., 2019).

A novel two-step bubble column-photobioreactor has been recently proposed as photosynthetic biogas upgrading technology, in order to implement a Cascading Algal Biomethane-Biorefinery System (Bose et al., 2020). A decision-making strategy was also developed, in order to facilitate the maximization of the financial sustainability of the proposed cascading system layout. The authors concluded that coupling waste anaerobic digestion with microalgae cultivation may entail significant economic benefits, but such opportunities are yet to be explored in detail (Bose et al., 2020).

4.3. The use as growing media for fungal, insect and invertebrate cultivation

The OFMSW digestate can represent a suitable substrate for different kinds of cultivations.

The high content in nitrogen makes the liquid fraction of the digestate a suitable fertilizer solution for the cultivation of mushrooms (Pérez-Chávez et al., 2019), but the solid portion as well as a solid state digestate may be used as growing media for insects and invertebrates. Some experiences have already been carried out by using either the liquid or the solid portion of the digestate as obtained from conventionally applied separation techniques.

O'Brien et al. (2019) successfully tested solid digestates derived from dairy manure and food waste in the cultivation of the fungal specie *Pleurotus ostreatus*. At 35% concentration, the solid digestate provided the highest productivity of 1147 $g_{FW\ mushroom}/kg_{dry\ substance}$. However, the use of the same digestate at a concentration of 70% dry weight inhibited the growth of the target mushroom, possibly due to the high salt content of the food waste fed to the digesters.

In the view of a biorefinery approach, the study of Schimpf et al. (2019) considered the use of the solid digestate from the acidification reactors of a two stage anaerobic process in *Lentinula edodes* cultivation. These authors found that the optimal concentration of solid digestate in the growing medium was 40%, which provided the highest degradation degrees for cellulose, hemicellulose and lignin. The same condition determined the highest utilization degree of carbon, nitrogen, sulphur, phosphorous, nickel and cobalt as well as the best mushroom yield. The results are comparable with those achieved in the study of O'Brien et al. (2019), despite the different origin of the digestate as well as the different target mushrooms. Such approach is particularly interesting for those two-stage anaerobic digestion systems adopting biofilm-based reactors to run the methanogenic step. In these cases, the solid/liquid separation of the effluent from the acidification reactor is necessary to feed the methanogenic one with the liquid fraction, in order to avoid clogging issues in the biofilm-based reactor (Yeshanew et al., 2016). Nevertheless, this poses the need to identify sustainable options to handle the solid digestate fraction and its use as growing medium can be a smart solution.

Similarly, applications considering the OFMSW digestate as feed for insects and invertebrates may prove to be a sustainable management option. The use of worms and invertebrates is a well-established practice for the treatment of putrescible waste: vermicomposting is the emblem of the role of worms and insects in waste management. The implementation of this process for the OFMSW treatment was proved to benefit from the addition of the OFMSW digestate, which enhanced the mix nutritional value (Manyuchi et al., 2017).

The wider integration of the invertebrate growth processes with the organic waste treatment has been recently reviewed by Girotto and Cossu (2019). These authors discussed the possible biorefinery platforms based on the creation of a chain including putrescible waste, invertebrates and biofuel/proteins. However, the putrescible organic could be replaced by its digested form, obtaining comparable outcomes. In this view, Spranghers et al. (2017) compared four different substrates, namely chicken feed, restaurant waste, vegetable waste and its solid digestate, for the growth of the black soldier fly *Hermetia Illucens* larvae. Experimental results showed that the prepupae reared on the digestate were low in crude fat and high in ash compared to those reared on the unfermented vegetable waste; conversely, the chitin content was comparable. Appreciable amounts of branched chain fatty acids, which are mainly synthesized by bacteria and fungi, were also found in the prepupae reared on the digestate, indicating that they originated from the anaerobic bacteria.

4.4. Applications in hydroponic cultivation

Following the evolution of the modern horticulture systems, that has recently moved from soil-grown systems to soilless ones (Barrett et al., 2016), the potential of the anaerobic digestate has been also explored as growing medium in hydroponic systems (Magwaza et al., 2020). These can be considered as an engineered plant cultivation method, which uses soil-less growing medium and a nutrient solution (Savvas, 2003).

Waste based composts have been extensively studied as growing media in hydroponic cultivation, while the use of the digestate is more recent. Although Krishnasamy et al. (2012) proposed the treatment of food and vegetable waste digestate for the hydroponic cultivation of silverbeet, most attempts refer to agro-waste based anaerobic effluents. Ronga et al. (2019) evaluated the cultivation of baby leaf lettuce in hydroponic systems, using both the liquid and the solid digestate as alternative growth medium and nutrient solution, respectively. The digestate used in this study originated from an industrial biogas plant operated in Reggio Emilia (Italy), treating maize, silage, triticale, cow slurry and grape stalks. For the experimental purpose, five types of solid substrates, including solid digestate (SD), were combined with two nutrient solutions, namely the liquid digestate (LD) and a standard solution. Results showed that none of the growing media, nutrient solutions and their combination was phytotoxic and the best performances in terms of shoot dry weight were obtained when the SD and the LD were used with the standard nutrient solution and the agriperlite growing medium, respectively (Ronga et al., 2019). Nevertheless, the microbiological analysis of the baby leaf lettuce showed a Coliform charge higher than the selling threshold when the SD was used together with the standard solution. However, the authors stated that the washing operations to make the baby leaf lettuce ready-to-eat are able to reduce the microbiological charges recorded in their study, pointing out the possible use of the digestate for the hydroponic cultivation of this vegetable.

The successful hydroponic cultivation of the lettuce (*Lactuca sativa*) has been experienced also by using humic-like substances (HLS) extracted from the digestate. The average increase in aerial biomass was observed to range between 7 and 30%, depending on the applied HLS dose. The best performances were obtained when the manure digestate extract was applied at the higher fulvic-like acids dose, although this was likely related also to the amount of nutrients provided by the extract itself (Guilayn et al., 2019).

Different considerations raised for tomatoes. Mupambwa et al. (2019) used 40% diluted digestate as nutrient solution for the hydroponic cultivation of this crop. The digestate originated from the mesophilic anaerobic treatment of cow manure and its macro-nutrient levels were observed to be not sufficient. Moreover, the possible phytotoxicity required ammonia conversion prior to the utilization of the digestate in the hydroponic system.

Based on the knowledge from existing hydroponic/aquaponic cultivation and organic fertigation, Stoknes et al. (2016) proposed a full cycle of organic material, in which the digestate from food and garden waste anaerobic treatment was differently used in a novel bubble insulated greenhouse, supplied with the energy and the CO_2 obtained from the biogas. The authors developed a novel, recirculating system that maximized waste microbial oxidation as an aquaponic one, using media-based beds for plant cultivation and the digestate as the ammonia-rich solution in place of the aquaculture effluents.

Fuldauer et al. (2018) further explored the feasibility of using the food waste digestate in hydroponic cultivation systems and found that coupling a dewatering sifter with a hydroponic system could be an economically competitive option to handle the digestate by recycling its nutrient content.

5. Technical considerations

The valorization of the OFMSW digestate is a key condition to implement anaerobic processing technologies in agreement with the circular economy principles underlying waste management.

The traditional use of the fertilizer potential of the anaerobic digestion effluents seems an option no longer sustainable, nor economically competitive, unless it pursues bioremediation purposes. Recent advances has demonstrated the successful application of composted OFMSW digestate on a diesel contaminated soil, where it acted as source of nutrients and inoculum (Gielnik et al., 2019).

Conversely, when the soil application is intended for agricultural aims, the processing costs of the digestate are not always counterbalanced by the revenues from the product sale. The need to improve the biological stabilization of the digestate via aerobic post-treatments requires, indeed, additional operating costs, while the poor confidence of the stakeholders towards waste-based soil amendments and fertilizers does not promote their market. Therefore, the practice of giving the digestate for free is widespread among anaerobic digestion plant operators. In this way, they do not bear the costs of digestate disposal, nor they benefit from its possible marketing. These issues, along with the current depletion of arable lands as well as the environmental concern about nitrogen leaching represent the main conditions driving the search for alternative, sustainable solutions.

Considering its residual methane potential, digestate recirculation in the anaerobic system may be a potential approach. In this view, the proper pretreatment of the digestate can both enhance the availability of its organic pools (Brémond et al., 2020; Somers et al., 2018) and reduce the possible presence of persistent organic pollutants (Cesaro et al., 2019). Nevertheless, digestate recirculation can promote the accumulation of ammonium in the anaerobic reactor, especially at critical organic loading rate (Wu et al., 2018) and would not definitely close the loop of material cycle.

The identification of down-stream strategies is necessary and this is not possible without considering the different moisture content of the digestates originating from either wet or dry anaerobic digestion technologies. In the former case, solid/liquid separation is usually applied to the digestate, so that the management of both the liquid and the solid fractions has to be defined. Bearing these aspects in mind, the valorization of the OFMSW digestate should be pursued in a wider biorefinery framework, integrating anaerobic digestion with systems providing novel solutions or approaches. Table 3 summarizes the main strengths and weaknesses of the strategies discussed in this work, pointing out the current technology readiness with reference to OFMSW digestate applications.

High-solid OFMSW digestates can be adequately converted into valuable products or energy carriers via thermo-chemical processes, which rely on well-established technologies but are usually high-energy demanding. This may hinder their economic competitiveness, providing the overall improvement of the energy and material balance of a possible integrated plant only over a threshold treatment capacity, to be determined case by case.

The generation of value added compounds from the digestate stands as the objective of several processes other than the thermochemical ones. A wide variety of products can be generated and relevant market segments could be interested in this kind of strategy, pursuing the shift from a fossil-based economy to a bio-economy. As the availability of the feedstock would not be a concern, due to the large and continuous generation of OFMSW worldwide, the process selection should consider the market value of the bioproducts, which depends on the costs required for the OFMSW conversion process as well as on the specific market conditions.

Budzianowski (2017) stated that the market share of biochemicals and biomaterials may achieve between 17% and 38% of the total market by 2050, with selling prices of the basic bioproducts ranging between 0.5 and 2 €/kg. The use of residual biomasses, like OFMSW digestate, would greatly support the development of biorefineries, lowering production costs and promoting a cascading approach to valorize under-exploited substrates.

It is worth highlighting that in May 2014 the European Council adopted the Regulation setting up the Bio-based Industries Joint Undertaking in order to contribute to the development of a resource

Table 3
Possible solutions for OFMSW digestate valorization: advantages, drawbacks and technology readiness.

Valorization option	Applicability	Advantages	Drawbacks	Technology readiness
Use as fertilizer	Solid/Liquid digestate	Well-established practice Clearly regulated Poor technological complexity for its production and use	- Ammonia and odour emissions - Application limited by the reduction of arable lands - Scarce confidence of stakeholders towards waste-based products	Full scale
Thermo-chemical processes	Solid digestate	Well-known processes Possible conversion into value added energy carriers	- Significant technological complexity - High energy demand	Pilot/Full scale
Source of value-added products	Solid/Liquid digestate	Suitable approach for digestate cascading use Possibility to reduce production costs with regard to the use of non-waste materials	- Need to optimize the operating conditions - Feasibility depending on the market value of targeted products	Demo scale
Use for microalgae cultivation	Liquid digestate	High integration level with anaerobic digestion processes as both digestate treatment and biogas upgrade	- Ammonia inhibition problems - Light penetration issues - Possible adverse effects of digestate quality and biogas trace elements	Pilot/Demo scale
Use as fungal/invertebrate growing media	Solid digestate	Exploitation of digestate nutrient value Easy-to-implement and established practices	- Unclear and fragmented regulatory framework for the use of the obtained products	Lab/Bench scale
Hydroponic cultivation	Solid/Liquid digestate	Low-cost practice Possible spatial-wide applications	- Need for the identification of operating conditions	Lab/Bench scale

efficient and low carbon economy based on advanced biorefineries. In this context, interesting projects are currently ongoing at demonstrative or semi-industrial scale, pointing out the high readiness level of most technologies. Some of them, focusing on solid organic waste anaerobic digestion, pursue the integration of this process with microalgae cultivation. The possibility of upgrading biogas through the cultivation of microalgae in the digestate accounts for the interest towards the combined process, which stands as a perfect example of the circular economy concept. Nevertheless, monitoring the microalgae growth rates, limiting inhibitory effects as well as technology costs are recognized as the main constraints for full-scale applications (Wall et al., 2017). The photosynthetic efficiency is, indeed, the parameter most affecting the microalgae production costs, estimated in the range 3.1–11.0 €/kg, and this makes the choice of the cultivation location important as well (Ruiz et al., 2016). If microalgae cultivation stands as a process in a biorefinery, the industrial profitability will depend on the market value of the final target product. Considering the sole biorefinery cost (excluding biomass production and harvesting costs) varying between 0.4 and 4.3 €/kg on the basis of both the location and the target products, the commercialization of bulk commodities from microalgae seems not appealing yet (Ruiz et al., 2016).

Moreover, as already pointed out for the generation of bioproducts, when the OFMSW digestate is involved, a more comprehensive understanding of the potential market opportunities is required (Stiles et al., 2018) and precise legislative framework needs to be figured out. The latter aspects is particularly important when the microalgae cultivated in the OFMSW digestate are intended for the production of either feed or food. In this case, the producer is responsible for the safety of the product, which has to comply specific regulations. Nevertheless, the overall legislative framework is particularly complex and it is not always clear which Regulation and maximum levels for contaminants apply (Spiegel et al., 2013).

In this regard, the impacts of both OFMSW digestate quality and trace elements in the biogas on microalgae cultivated in combination with anaerobic systems has not been fully explored yet and represents an urgent need to promote this kind of biorefinery.

Although promising, it is important to highlight that the digestate intended for microalgae cultivation needs to be a liquid effluent and it has to be further diluted to avoid ammonia inhibition as well as light penetration issues. This may open a room for integration of microalgae growth with fungal or insect cultivation that, conversely, have been successfully experienced on solid digestate. Nevertheless, the need to define adequate legislation for the safe use of OFMSW digestate based products as well as market conditions to ensure the economic profitability stands as the main constraints of these easy-to-implement processes.

Among the more recent valorization options, the use of the digestate in hydroponic cultivation seems more versatile. It is quite close to the traditional use as fertilizer, but framed in a novel cultivation approach, better fitting urban areas requirements. As such, the potential risks for the transmission of contaminants from the digestate to the crops still need to be comprehensively investigated. This may either reduce the applicability of hydroponic systems to selected species or entail the definition of appropriate process operating conditions. In this regard, the wider legislative framework to ensure the safe implementation of these systems for the valorization of the OFMSW digestate can be recognized as the main condition hindering the scale up. Moreover, the comprehension of both mass and energy flows plays a pivotal role in identifying the sustainability and the circularity of a system integrating waste valorization and growing practices, as shown for two model European cities in the study of Weidner and Yang (2020).

Nevertheless, as food production within urban environments has attracted considerable interests, the scale up of such a promising valorization alternative is worth both technical and scientific efforts.

6. Conclusive remarks

This work discussed the state of the art of the strategies for the valorization of the digestate originating from the anaerobic treatment of the organic fraction of municipal solid waste. The possible generation of methane from the anaerobic conversion of one of the most abundant organic residues has greatly pushed the widespread application of this process. This was mainly due to the funding schemes that supported the production of renewable energy while ensuring the economic profitability of these treatments.

The evolution of the regulatory framework around anaerobic digestion plants as well as the need to fit the circular economy principles underlying waste management require the definition of new strategies to ensure the sustainable treatment of the digestate, providing an alternative to its use as fertilizer. Novel approaches pursue either the conversion into value added products or the use as growing medium or nutrient solution. As most processes have already been experienced using raw materials, the technology readiness is generally high. Nevertheless, the specific operating conditions need to be identified and tested in a relevant environment before proposing an engineered solution. In this contest, the role of research is fundamental and it should investigate:

- the yields of the OFMSW digestate conversion into value added products. These studies should address the production of high-value

compounds, while being flexible enough to adapt to the changeable market conditions. The latter can affect, indeed, the economic feasibility of this kind of valorization strategies. As most studies generally refer to the effluents of anaerobic digestion processes, future efforts could be interestingly directed towards the identification of any relation between the biostabilization level of the digestate - that is related, in turn, to the retention time in the digester - and the quality and quantity of the target products;
- the exploitation of raw OFMSW digestate as either growing medium or nutrient solution within novel cultivation schemes. Research should focus on the technological solutions to overcome the current limits as well as on the possible risks posed by the use of a waste-based material for the production of food and feed. This may, in turn, result in the need to provide specific operational steps to ensure minimum qualitative standard for these applications;
- the mass and energy balance together with the overall impact assessment of the integrated processes, so as to address the scale up of innovative biorefineries centered around OFMSW anaerobic digestion. In this view, general approaches should be properly dropped in site-specific frameworks, in order to consider all the particular conditions influencing the feasibility of the proposed solutions.

The future technical and scientific efforts would hold even a greater potential to boost the large-scale implementation of novel solutions if carried out in interdisciplinary frameworks. This would provide deep and highly specific insights for a more comprehensive appreciation of the proposed strategies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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