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Integrating anaerobic digestion and composting to boost energy and material recovery from organic wastes in the Circular Economy framework in Europe: A review

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ABSTRACT

In the global context of raw materials and energetic crisis, recovering energy and materials from organic wastes becomes mandatory in Europe to meet the principles of Circular Economy. This manuscript reviewed the state of the art and highlighted research gaps of integrated anaerobic digestion and composting (IADC) to treat organic wastes. Biogas produced through anaerobic digestion and high-quality compost produced through composting can lessen the environmental effect of organic waste management while also sustaining it economically. In addition, the IADC allows for removing most of the common organic contaminants with high efficiency. Main research gaps and future challenges that still need to be addressed are represented by the need (i) for more full-scale studies providing environmental and economic sustainability assessment, (ii) to boost organic waste degradation during the anaerobic step, (iii) to evaluate the degradation pathways of contaminants during the treatment, and (iv) to spread the technology through policy actions.

1. Introduction and aim of the review

The COVID-19 pandemic and ongoing geopolitical conflicts have brought attention to how important it is to guarantee the security and resilience of raw material and energy supplies. For instance, natural gas and fertilizers were within the goods most affected by the critical scenario in the last years. According to Eurostat, the price of natural gas in the European Union increased up to the 40 % and 100 % in the first half of 2022 compared to the same period in 2021, for household and non-household consumers, respectively (Fig. 1) (Eurostat, 2023a). The increase was particularly significant in some countries, hardly affecting economies that were strongly depending on Russian natural gas. The prices of fertilizers can vary significantly depending on various factors such as global demand and supply dynamics, changes in production and transportation costs, currency fluctuations, weather conditions, and government policies, among others. However, COVID-19 pandemic and ongoing conflicts have also impacted the fertilizer market by causing supply chain disruptions and increasing production costs, among other challenges, resulting in increased fertilizers prices (Fig. 2) (IndexMundi, 2023). For instance, urea, diammonium phosphate and potash prices increased of about four, two and three times in one year (spring 2021–spring 2022), posing serious threats to agricultural productions. In addition, both natural gas and synthetic fertilizers supplies relies on fossil and non-renewable resources, posing a serious challenge for future supplying. Furthermore, the environmental issues related to the extraction, transformation and use of natural gas and synthetic fertilizers (i.e., greenhouse gas emissions, eutrophication) rise challenges towards the transition to sustainable production systems (Cherkasov et al., 2015; Günther et al., 2018; Khan and Mohammad, 2014).

Anaerobic digestion (AD) and composting have emerged in the last decades as suitable biological processes to recover energy and biofertilizers from organic wastes (OW) (Awasthi et al., 2019; Singh et al., 2022). OW might play a crucial role in enhancing Circular Economy (CE) in Europe by serving as a renewable resource for energy production, materials manufacturing, and other applications. These products can serve as alternatives to fossil-based products and fuels and can help reduce GHGs and other environmental impacts associated with traditional fossil-based production processes (Casau et al., 2022; Sherwood, 2020; Yang et al., 2021). Several studies have shown that the use of OW for energy production and material manufacturing can also contribute to the development of more sustainable and resilient economies. For instance, a study by the European Commission estimates that the use of biomass for energy production could contribute to the creation of up to 800,000 jobs by 2030 and reduce European GHGs emissions by up to 3.8

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% annually (European Commission, 2018).

The integration AD and composting (IADC) have emerged recently as a sustainable biorefinery to effectively valorise OW and overcome the drawbacks of these biological processes.

In this context, this review aims to describe the state of the art and research gaps of the IADC systems to boost energy and material recovery from OW under the CE framework in Europe. After an OW overview highlighting their favourable and negative characteristics for biological treatment (Section 2), a literature review of IADC is presented, with a particular focus on process sustainability, fate of pollutants during the process and agronomic quality of biofertilizers recovered (Sections 3 and 4). Finally, research gaps and future challenges to further

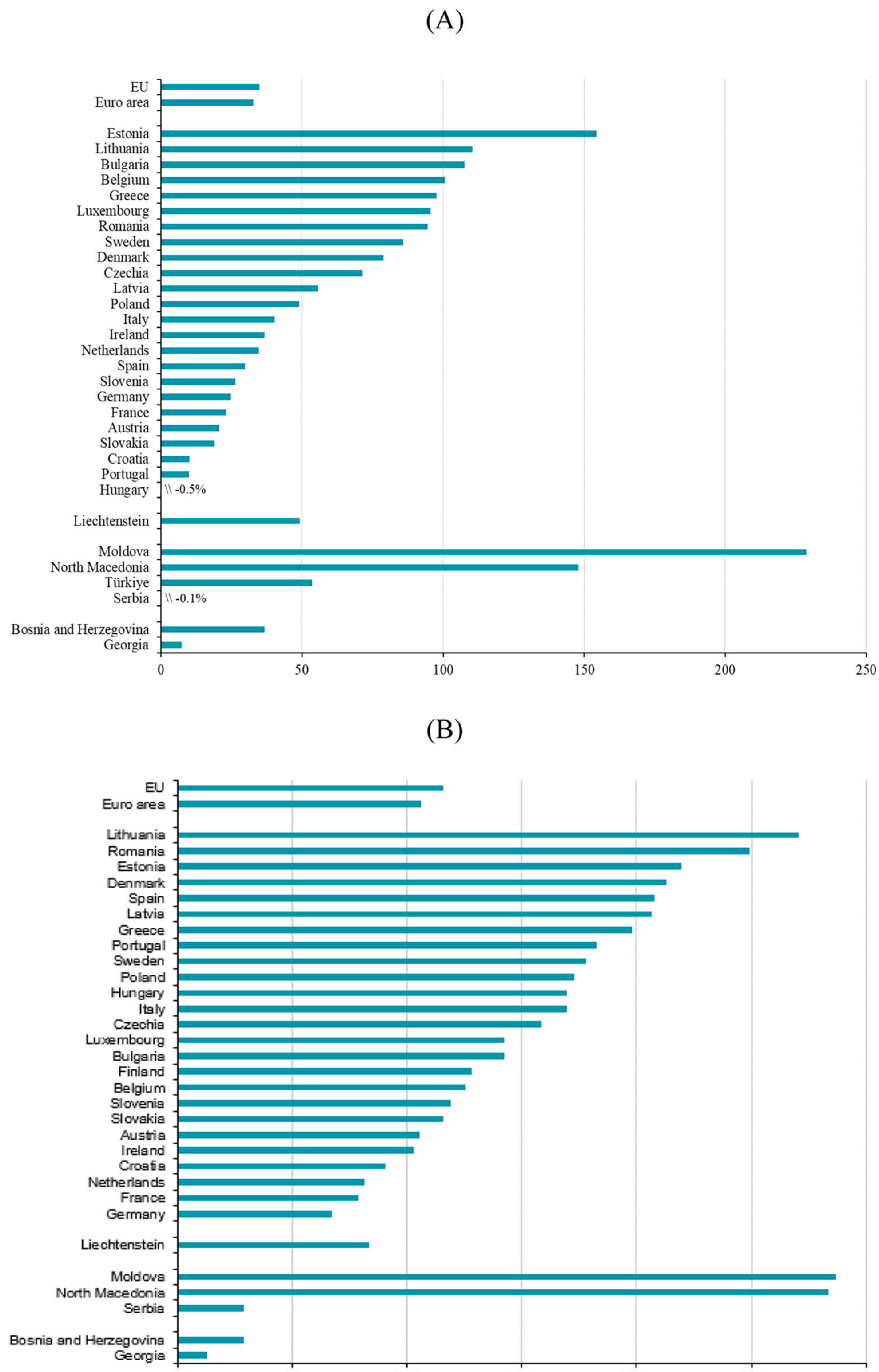

Fig. 1. Change in natural gas prices (%) for household (A) and non-household (B) consumers compared with previous year, same semester, first half 2022. (Adapted from Eurostat (2023a).)

implement this technology are reported and discussed in Section 5, whereas Section 6 provides some insights on policy aspects related to IADC and organic waste management in Europe.

2. Organic wastes overview

OW refer to any waste material that originates from living organisms, such as municipal organic wastes (MOW), green municipal wastes (GMW), animal manures (AM), agro-industrial residues (AIR) and sewage sludge (SS) (Table 1). OW can have variable physical, chemical, and biological characteristics depending on the source and composition of the waste, being their fermentability the most important common characteristic (Campuzano and González-Martínez, 2016; Dadrasnia et al., 2021; Fermoso et al., 2018; Kacprzak et al., 2017; Reyes-Torres et al., 2018). Generally, OW are rich in carbon and nitrogen, which makes them an ideal source of nutrients for microorganisms. Chemically, organic waste can have a high moisture content and a low pH, which can affect the rate of decomposition and the types of microorganisms that can thrive in the waste. Some types of OW can also contain contaminants such as heavy metals, pathogens, and organic pollutants (Campuzano and González-Martínez, 2016; Dadrasnia et al., 2021; Fermoso et al., 2018; Kacprzak et al., 2017; Reyes-Torres et al., 2018). Due to the inner variability of OW, they were separately described in the following Sections (Table 1).

2.1. Municipal organic wastes

The organic fraction of municipal solid waste (MOW) is the portion of municipal solid waste that is composed of biodegradable organic materials such as food waste. A sizeable portion of the municipal waste produced in Europe is MOW. Approximately 34 %, or 86 million tonnes, of the 249 million tonnes of municipal solid waste produced by the EU-28 (the 28 EU Member States) in 2017 were MOW, including both separate collected and mixed collected MOW (Eurostat, 2021). Therefore, the EU's shared waste management goals cannot be achieved without addressing the bio-waste stream.

The physical, chemical, and biological characteristics of MOW can vary depending on the source and composition of the waste (Campuzano

Table 1
Organic wastes classification and main favourable and negative features for biological treatments.

Organic waste	Favourable features	Negative features
MOW[a]	Highly putrescible High content of nutrients High content of organic matter	High seasonal variability High content of water Presence of inerts/non biodegradable materials[f]
GMW[b]	High content of organic matter High total solids content Low presence of inerts/non biodegradable materials	Scarcely putrescible Low content of nutrients Unbalanced nutrients ratios
SS[c]	Highly putrescible High content of nutrients High content of organic matter Low seasonal variability	High content of water Presence of emerging contaminants Unbalanced nutrients ratios
AIR[d]	High content of organic matter Low presence of inerts/non biodegradable materials	Seasonal production variability Scarcely putrescible Low content of nutrients Unbalanced nutrients ratios
AM[e]	Highly putrescible High content of nutrients High content of organic matter	High seasonal variability High content of water Presence of emerging contaminants Presence of pathogens Unbalanced nutrients ratios

[a] Municipal organic wastes.
[b] Green municipal wastes.
[c] Sewage sludge.
[d] Agro-Industrial residues.
[e] Animal manures.
[f] Depending on collection (manually sorted or mechanically sorted).

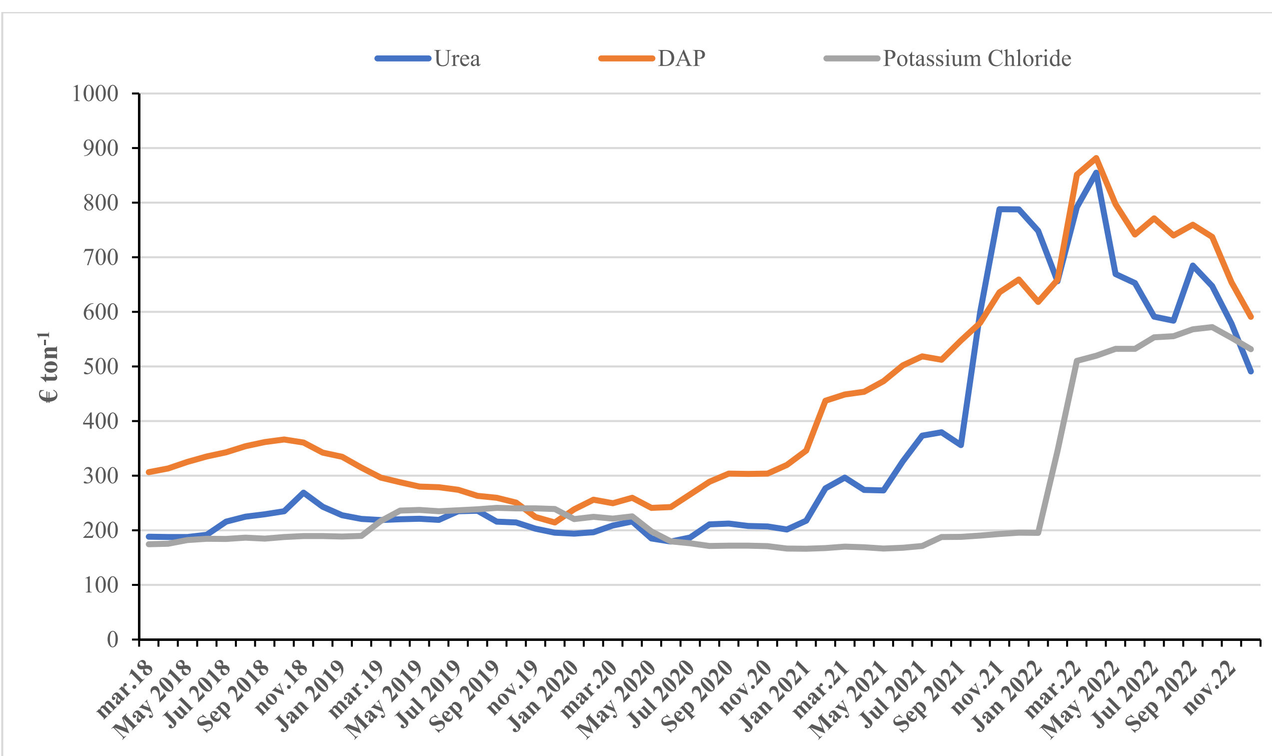

Fig. 2. Change in global prices (€ ton^{-1}) for urea, diammonium phosphate (DAP) and potassium chloride over the last 5 years (2018–2022). (Adapted from IndexMundi (2023).)

and González-Martínez, 2016; Wei et al., 2017; Zhu et al., 2021). Also seasonality can affect MOW characteristics, even if some authors reported no significant differences in the physico-chemical composition of MOW in different seasons, i.e. Papa et al. (2022) observed no difference between summer and winter for pH, total solids, volatile solids, total organic C, lipids and fibres composition in different MOW. Physical characteristics of MOW include their moisture content, density, and particle size distribution, among others. MOW typically have a high moisture content (i.e., 65–85 % weight bases), which can affect its suitability for composting or AD. The high density of MOW can also affect its handling and transportation, with denser materials requiring more energy to be transported (Campuzano and González-Martínez, 2016). The particle size distribution of MOW can impact its susceptibility to degradation by microorganisms, with smaller particles having a higher surface area-to-volume ratio and thus being more readily biodegradable. Main chemical characteristics of MOW include their organic matter content, nutrients content, and pH. MOW is typically rich of easy degradable organic matter (i.e., sugars, fats, proteins), making them an easy fermentable substrate in composting and AD. MOW usually contain high concentrations of nutrients (i.e., 2–5 %, 0.5–2 %, and 1–3 % on dry weight bases of N, P and K, respectively), which can be recovered in the biofertilizers. The pH of MOW can vary depending on the source and composition of the waste, with acidic materials such as fruit and vegetable waste having an acidic pH (Campuzano and González-Martínez, 2016; Zhu et al., 2021).

MOW may contain a variety of contaminants, which can negatively affect its quality and suitability for composting or AD (Fisgativa et al., 2016; Wainaina et al., 2020). Some of the common contaminants found in MOW include, among others: (i) inert/non biodegradable materials (i.e., glass, metals, and plastics), that can interfere with biological processes and contaminate the biofertilizers, (ii) hazardous materials (i.e., batteries, electronics, and chemicals) that can pose a health and safety risk to workers and the environment if not properly handled, and (iii) pathogens (i.e., bacteria, viruses, and parasites). While inert/non biodegradable materials and hazardous materials occurrence in MOW is mainly due to accidental contamination, pathogens are naturally present in MOW, and they develop spontaneously on putrescible biomasses. Among bacteria, the most important pathogens are *Salmonella* spp.; others, like *Listeria* or *Clostridia*, may also be present in the material, but they are also present in the soil and therefore are of secondary importance if the waste is used as a soil conditioner (Böhm, 2007). Several viruses of plant origin may be present in the MOW, as well as gut-related viruses of animal and human origin (i.e., hepatitis A virus, rotaviruses, and caliciviruses, SARS Covid-19) (Anand et al., 2022). From the species pathogenic to warm-blooded animals and humans in Europe, mainly *Candida albicans* and *Aspergillus fumigatus* have to be mentioned as pathogens that may contaminate MOW. Some of the most important parasites of epidemiological relevance that may occur in MOW are protozoal ones (i.e., *Cryptosporidium parvum*) and metazoic parasites (i.e., eggs of Ascaris species) (Böhm, 2007).

To ensure the quality of MOW, proper collection, sorting, and handling practices are essential. This includes separating MOW from other waste streams, minimising exposure to the elements, and implementing measures to control odour and prevent contamination (Fisgativa et al., 2016).

2.2. Green municipal wastes

Green municipal wastes (GMW) refer to the organic material that is produced from the maintenance of landscapes and gardens, such as grass clippings, leaves, and twigs. Providing an exact figure on the amount of GMW produced in Europe is challenging since it varies depending on the country, region, and even the type of waste considered. However, some estimates are available. The European Compost Network estimates that around 55 million tonnes of GMW (grass, leaves, twigs, and prunings) are produced annually in Europe.

Characterizing GMW is also challenging since this waste stream has typically a high degree of compositional variability due to various factors like the geographic and climatic characteristics of the collection sites. For instance, pruning wastes are more abundant in spring, whereas grass clippings and leaves are more representative in summer and winter, respectively (Vandecasteele et al., 2016). This affects for instance the pH of GMW, with acidic materials such as pine needles having a lower pH. Despite the reported heterogeneity, some general characteristics of GMW can be summarised. First, GMW are characterized by a high content of total solids (i.e., 40–60 % weight bases), which reduces their transportation costs and density, making them an ideal bulking material in composting or solid-state AD. GWM also show high content of organic matter (up to 90–95 % weight bases), being the recalcitrant fractions of cellulose and lignin predominant. This fact slows down their biodegradation and makes co-treatments with more biodegradable wastes or pre-treatments mandatory to obtain a significant biodegradation, in particular under anaerobic conditions (Cucina et al., 2021a). Biodegradation of GMW is also slowed down by the low concentration of nutrients of GMW (i.e., C/N ratio is usually over 40) (Reyes-Torres et al., 2018). The unbalanced C and nutrients ratios make the co-treatment of GMW mandatory in composting and AD (Reyes-Torres et al., 2018). Despite these negative characteristics, GMW usually show low concentration of contaminant, in particular heavy metals, which is positive to avoid biological processes' inhibition and ensure the quality of the recovered biofertilizers.

2.3. Sewage sludge

Sewage sludge (SS) are defined as the solid or semi-solid residues obtained from the treatment of wastewaters (Fijalkowski et al., 2017) and have been spread in agricultural soil to reclaim organic matter and nutrients for decades following the European Directive 86/278/EEC (Pellegrini et al., 2016). In the last years, SS utilization in agriculture was limited in many European countries due to the evidence that most SS are highly polluted by pathogens, microplastics, heavy metals and organic micropollutants (i.e., in particular those derived from the treatment of urban wastewaters) (Cucina et al., 2021b). Considering that European yearly production of SS accounts for about 10 million tonnes of dry matter (taking into account only urban wastewaters) (Eurostat, 2022), it is evident that biological processes may represent a suitable solution to allow a safe valorisation of SS, recovering high amounts of energy and nutrients.

SS characteristics vary according to several factors (i.e., origin of the wastewater, stabilization processes conditions), but they are usually characterized by a high content of water (i.e., ranging from 75 % to 90 % weight bases) and an alkaline pH. SS usually contain on average 50–70 % of organic matter, and 30–50 % of mineral components, including 3–6 % of N, 0.5–5 % of P, and 1–5 % of K, as well as significant amounts of micronutrients (Samolada and Zabaniotou, 2014; Tyagi and Lo, 2013). SS organic matter usually shows high biodegradability and mineralizes fast due to relatively small content of lignin or cellulose, making them suitable for AD and composting processes (Astals et al., 2013). Nevertheless, it should be highlighted that SS often show unbalanced C/N ratio (i.e., lower than 10), that result in slow microbial growth and N-losses during biological treatments or when applied to soils (Astals et al., 2013; Cucina et al., 2021b; Pellegrini et al., 2016). When C/N ratio is low, microorganisms are not able to fix N in organic forms and thus, N can be lost following different pathways depending on SS characteristic, soil characteristics and environmental conditions, i.e., temperature. In alkaline soils, NH_4^+-N is rapidly lost as NH_3 into the atmosphere, whereas in anaerobic or waterlogged soils, denitrification can occur, converting nitrate into nitrogen gas (N_2) or nitrous oxide (N_2O), which are lost as well into the atmosphere. Finally, NO_3^- produced from SS mineralization in soil can be vulnerable to leaching, especially in sandy soils or soils with poor water-holding capacity (Cameron et al., 2013; Zilio et al., 2023).

One of the main drawbacks of SS for biological valorisation is certainly the presence of different contaminants, both inorganic (i.e., heavy metals) and organic (i.e., polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), adsorbable organo-halogens (AOX), pesticides, surfactants, hormones, pharmaceuticals, nano-particles and many others) (Cucina et al., 2021b; Fijalkowski et al., 2017). These contaminants can affect negatively the development of AD and composting, as well as biofertilizers quality. Moreover, the presence of several pathogenic species of living organisms (i.e., bacteria, viruses, and protozoa along with other parasitic helminths) can create potential hazards to the health of humans, animals and plants. Nevertheless, it should be noted that contamination of SS is common in SS produced from urban wastewater treatment, whereas it is rarely reported for SS coming from other sectors (i.e., treatment of process wastewater in food and pharmaceutical industry) (Cucina et al., 2021b). These latter SS may represent a suitable source of biodegradable residues for AD and composting, also taking in consideration their stable composition (i.e., SS coming from wastewaters resulting from standardized manufacturing processes have scarce seasonal variability) (Cucina et al., 2021b).

2.4. Agro-industrial residues

Agro-industrial residues (AIR) refers to residual biomasses obtained as wastes from the agricultural field and agriculture-related industries from various process such as the production of agricultural outcomes (i.e., fruits, vegetables, olive oil, and wine) (Freitas et al., 2021; Yaashikaa et al., 2022). The availability and composition of AIR depend on the type of operation involved, the various steps involved in processing, the characteristics of raw materials used, the season, and the type and nature of products obtained. This makes the estimation of the amount of AIR yearly produced in Europe challenging. For instance, about 300 million tonnes of crop residues derived from cereal cultivation can be estimated in Europe, considering that cereal production in 2020 was about 300 million tonnes and that a residue-to-crop production ratio of 1 can be assumed for most of the common crops in Europe (Eurostat, 2023b; Scarlat et al., 2010). Other relevant agricultural industries in Europe are olive oil and wine manufacturing, which account for about 20 and 10 million tonnes of AIR produced yearly, respectively (Donner et al., 2022; Kovalcik et al., 2020).

Also providing general composition and characteristics (i.e., moisture content and pH) of AIR is challenging since this category groups different materials coming from different raw materials and processes. For instance, some AIRs are characterized by high water content (i.e., olive mill wastes), whereas others have a high content of total solids (i.e., straws, husks). AIR main composition includes carbohydrate polymers (i.e., starch, cellulose, and hemicellulose), proteins, lipids, fibres, and other organic compounds that have a variable biodegradability (Nair et al., 2022). Fibres- or cellulose-rich AIR (i.e., corn stalks, wheat straw, fruits' hulls) are characterized by scarce biodegradability, as already discussed for GMW, whereas proteins-, starch- and lipids-rich AIR (i.e., coffee husks, olive mill waste, soybean extraction panels) are more biodegradable. Concerning nutrients, generally AIRs are characterized by low concentrations of N (Yaashikaa et al., 2022), resulting in high C/N ratio and in the need to co-treat these residues in AD and composting. A positive feature of AIRs is the low occurrence of contaminants, pathogens, inerts, and non-biodegradable materials. Conversely, it should be noted that some AIR can contain high concentrations of inhibitory molecules for biological processes, such as phenols (i.e., olive mill wastes) and alkaloids (i.e., coffee husks) (Freitas et al., 2021).

2.5. Animal manures

Animal manures (AM) are referred to the complex mixture of organic and inorganic materials originated from livestock activities as the results of animal metabolism (Dadrasnia et al., 2021). The rapid growth of the human population has pushed the production of livestock, leading to an increased intensive animal production, which produces large amounts of AM. Therefore, in the European Union (EU-27) and UK, animal farming generated yearly >1.4 billion tonnes of AM during the period 2016–2019 (Köninger et al., 2021).

The high degree of variability in nutrient concentration makes it challenging to determine the chemical composition of AM. Several elements, including the environment, season, animal species and classes, feeding habits, developmental stages of animals (nutrient intake, digestion, and absorption), as well as the length of time the manure is stored, may influence the chemical and nutrient composition of AM (Dadrasnia et al., 2021). As example, some AMs are liquid product (i.e., pig slurry), whereas others are semi-solid or solid (i.e., dairy manure and chicken manure, respectively). Generally, AM are valuable sources of organic matter and nutrients and are thus used as fertilizers to improve crop yield by direct application to the soils. Nevertheless, environmental threats following agricultural application of AM to the soil push towards new sustainable recycling technologies (i.e., AD and composting). Organic matter in AM is usually characterized by high biodegradability, which is often limited because of the low C/N ratio of AM. Indeed, AM contain high concentrations of nutrients, especially N, P and K. For instance, chicken manure can contain up to 3–5 % (fresh weight bases) of N (Dadrasnia et al., 2021).

The main negative feature of AM for biological valorisation through AD and composting is the occurrence of contaminants (i.e., antibiotics) and pathogens, that need to be evaluated in order to avoid processes inhibition and biofertilizers contamination. In a recent review, high concentrations of different antibiotics were detected in pig manure (i.e., 1.6 μg kg^{-1} of macrolides, 0.048–354 μg kg^{-1} of tetracyclines, and 0.015–20 μg kg^{-1} of sulfonamides) (Congilosi and Aga, 2021). The same review also reported high concentration of different antibiotic classes in poultry and cattle manures.

3. Biological treatments of organic wastes

OW disposal can lead to several environmental problems if not managed properly. Some of the issues include among others: (i) methane emissions, (ii) soil and water contamination, (iii) air pollution, and (iv) land consumption. On the other hand, proper disposal and management of OW through AD and composting can contribute to achieve CE and SDGs objectives. Indeed, organic wastes can be transformed into valuable resources such as biogas and biofertilizers, achieving SDGs 2 (no hunger), 6 (clean water and sanitation), 7 (affordable and clean energy), 12 (responsible consumption and production), and 13 (climate action). In Table 2, a rough estimation of the potential yearly reclamation of energy (in the form of biogas), organic matter (OM) and plant nutrients (N, P, and K) from OW in Europe is shown. The estimation was carried out taking in consideration the data reported in previous Section 2 (availability, Mtonnes year^{-1}; total solids, organic matter, N, P and K concentrations, % dry weight bases) and considering the biogas potential of the different OW (Garcia et al., 2019; Meyer et al., 2018). Dealing with OM and nutrients, the estimation was carried out to evaluate the total reclaimable amounts (tonnes year^{-1}), without considering processes efficiencies and recovery.

Overall, about 217,500 Mm^3 year^{-1} of biogas might be recovered through AD from OW. Assuming an average methane concentration in biogas of about 60 % v/v, it is possible to estimate the reclamation of >130,000 Mm^3 year^{-1} of methane from OW, which could be used in co-generation engines to produce electricity and heat or be purified and injected into natural gas grid (Meyer et al., 2018). This may help reducing European dependence on Russian gas and climate impact of energy production in Europe. Regarding materials potentially reclaimable in the form of biofertilizers (i.e., digestate and compost), OW may provide about 400 Mtonnes year^{-1} of OM, contributing to soil fertility and GHGs emissions mitigation through C sequestration in soil (Liu et al., 2023). Considerable amounts of N, P and K could also be

Table 2
Potential reclamation of biogas, organic matter, and nutrients from organic wastes in Europe.

Organic waste	Availability[a] (fw[c])	Availability (dw[d])	Biogas potential[b]	Reclaimable biogas	TS[e]	OM[f]	Reclaimable OM	N[g]	Reclaimable N	P[g]	Reclaimable P	K[g]	Reclaimable K
	$Mtonnes_{fw}\ year^{-1}$	$Mtonnes_{dw}\ year^{-1}$	$Mm^3\ Mtonne_{dw}^{-1}$	$Mm^3\ year^{-1}$	$\%_{fw}$	$\%_{dw}$	$Mtonnes\ year^{-1}$	$\%_{dw}$	$tonnes\ year^{-1}$	$\%_{dw}$	$tonnes\ year^{-1}$	$\%_{dw}$	$tonnes\ year^{-1}$
MOW[h]	90	36	600	21,600	40	80	29	3	1080	1	360	2	720
GMW[i]	55	33	300	9900	60	90	30	0.5	165	0.2	66	0.5	165
SS[j]	100	20	400	8000	20	75	15	5	1000	3	600	3	600
AIR[k,m]	330	132	500	66,000	40	90	119	1	1320	0.5	660	1	1320
AM[l]	1400	280	400	112,000	20	75	210	3	8400	2	5600	3	8400
			Sum	**217,500**		Sum	**403**	Sum	**11,965**	Sum	**7286**	Sum	**11,250**

[a] Sources: Eurostat (2023b); Eurostat (2022); Eurostat (2021); Meyer et al. (2018); Scarlat et al. (2010).
[b] Sources: Garcia et al. (2019); Meyer et al. (2018).
[c] Fresh weight.
[d] Dry weight.
[e] Total solids.
[f] Organic matter.
[g] Sources: Yaashikaa et al. (2022); Nair et al. (2022); Cucina et al. (2021a, 2021b); Dadrasnia et al. (2021) Zhu et al. (2021); Reyes-Torres et al. (2018); Campuzano and González-Martínez (2016); Astals et al. (2013).
[h] Municipal organic wastes.
[i] Green municipal wastes.
[j] Sewage sludges.
[k] Agro-industrial residues.
[l] Animal manures.
[m] Taking into account crop residues and residues from olive oil and wine manufacturing.

potentially reclaimed from OW (about 12, 7 and 11 Mtonnes year^{-1}, respectively), with a remarkable impact on economy (i.e., reduced cost and dependence on external supply) and environment (i.e., reduced emissions from synthetic fertilizers extraction and production). Within the OW, AM may contribute more than the others (MOW, GMW, SS, and AIR) in energy and materials reclamation mainly due to their larger availability (Table 2).

Nowadays, different technologies are available to treat and dispose OW. Landfilling and incineration have been the most used disposal strategy for OW for centuries, but once the drawbacks of OW landfilling/incineration have emerged (i.e., high environmental impact, low capability of waste reduction, hazard removal and value recovery) (Siddiqua et al., 2022; Munir et al., 2018), other sustainable technologies have been explored and are now available to treat OW. For instance, pyrolysis and gasification of OW producing energy carries (i.e., syngas, oils) and organic amendments (i.e., biochar) are now being used to treat OW due to their high capabilities of reduce waste volumes and remove hazardous contaminants. Nevertheless, their moderate to high levels of environmental impact, as well as their moderate capacity to recover value from the OW, are still limiting their application (Munir et al., 2018). Hydrothermal processing is another promising OW treatment, which allows to effectively recover value from OW, reduce waste volumes and environmental impacts, and remove hazardous contaminants. The low technology readiness level of hydrothermal treatments is the main drawback of this technology that still find poor application in industrial contexts (Munir et al., 2018).

Biological processes such as anaerobic digestion (AD) and composting are other options available to treat OW. As previously mentioned in Section 1, AD and composting are established biological processes used to treat OW and recover energy and biofertilizers due to some advantages. Nevertheless, both processes show some drawbacks that need to be considered for their application and that can be solved by integrating AD and composting. In the next Sections 3.1 and 3.2, and in Table 3, AD and composting are briefly described focusing on their main positive and negative features. Following that, benefits of AD and composting integration are described in Section 3.3.

3.1. Anaerobic digestion

AD anaerobically degrades OW to biogas and digestate through four

Table 3
Advantages and drawbacks of anaerobic digestion and composting of organic wastes.

Biological treatment	Advantages	Drawbacks
Anaerobic digestion	Energy production Reduced odour emissions Reduced environmental impacts Preservation of nutrients in the digestate Small area requirements	Production of large volume of digestate[a] Low stabilization of organic matter[a] Potential presence of pathogens in the digestate[a] Low degradation of emerging contaminants[a] Needs to post-treat the digestate[a] High investments Complex operations Needs of specialized workers
Composting	High stabilization of organic matter High degradation of emerging contaminants Sanitation of the product Reduction of volumes Low investments Simple operations	Energy consumption Potential odour emissions Leachate production Potential environmental impacts Loss of nutrients (mainly N) Large area requirements

[a] Depending on the performance and operative conditions (i.e., mesophilic/thermophilic temperature) of anaerobic digestion.

successive phases, i.e., hydrolysis, acidogenesis, acetogenesis and methanogenesis (Wang et al., 2018). AD can be operated under psychrophilic, mesophilic, and thermophilic temperature regimes (15–20 °C, 35–40 °C, 55–60 °C, respectively), with the last two conditions being the more effective for organic matter degradation and biogas production. AD processes can also be classified in wet, semi-dry and dry AD based on total solids content in the reactor, as well as in mono- and multi-stage AD when the process phases are carried out in one digester or separated in two or more reactors. Biogas is a gas mixture mainly composed by methane and carbon dioxide (55–65 % and 35–45 %, v/v) that can be used as an alternative energy source through its combustion in boilers or combined heat and power units (Lin et al., 2018). In addition, biogas conversion to high-value products (i.e., upgrade to biomethane) have being increasingly evaluated recently (Patel et al., 2020). Digestate have been considered a by-product of AD for decades, but its potential reuse in agriculture to reclaim nutrients and organic matter have gained interest to substitute mineral fertilizers that depend on fossil energies and non-renewable resources. Indeed, digestate is widely considered as an organic fertilizer, being rich in organic matter and plant macronutrients (N, P and K) (Peng et al., 2020; Tambone et al., 2010). Being AD a process that can be operated in different conditions and with different schemes, providing general advantages and drawbacks of this process might be challenging (Table 3). Overall, energy production is considered the main advantage of AD, making the process theoretically self-sufficient from the energetic point of view. Potentially, the biogas exceeding the requirements of AD could be used for producing and supplying energy to other stakeholders, improving the sustainability and circularity of AD (Lin et al., 2018). In addition, being operated in closed reactors, AD requires small areas and reduces odour emissions, leaching, and nutrients depletion. When it comes to AD drawbacks, literature considers the following as the main limits of AD: (i) high initial investments, (ii) complex procedures that require specialized workers, (iii) process instability and, (iv) production of large volumes of digestate that need post-treatment to remove pathogens, stabilize organic matter and degrade organic contaminants. With concern to the last point, it should be highlighted that high-performing AD processes (i.e., operating under thermophilic conditions and with an adequate retention time/organic loading rate) produce high-quality digestate that can be directly used in agriculture to reclaim organic matter and plant nutrients (Pigoli et al., 2021; Zilio et al., 2021). However, AD of OW is commonly carried out using mesophilic and wet conditions and applying short retention time to increase treatment capacity. This leads to producing large volumes of poorly stabilized digestate that cannot be directly applied to the soils due to the presence of large amounts of unstable organic matter, pathogens and organic contaminants (Congilosi and Aga, 2021; Juanpera et al., 2022; Peng et al., 2020).

3.2. Composting

Composting is a self-heating process largely used to treat OW, which proceeds through three phases, i.e., mesophilic, thermophilic and maturation (Cerda et al., 2018). Composting exploits aerobic metabolism (not <6 % v/v of oxygen) of different microorganisms that are able to use OW as carbon and energy source. As a result of their metabolisms, they convert OW mainly into CO_2, water, compost, and heat (Wang and Zeng, 2018). During the active phase it is necessary to reach thermophilic conditions (temperature > 55 °C) to inactivate pathogens and weed seeds (Cerda et al., 2018). Compost is an organic-rich material mainly composed by stabilized and recalcitrant organic compounds, thus being a valuable soil amendment (Cucina et al., 2018). Composting usually lasts 90 days and requires controlled conditions, such as moisture (50–60 % weight bases), oxygen concentration (higher than 5–6 % v/v), C/N ratio (between 20:1 and 40:1), and temperature (Cerda et al., 2018; Cucina et al., 2018; Wang and Zeng, 2018). Composting have been used extensively to treat OW since decades due to several advantages: (i) recovery of plant nutrients and stabilized organic matter in agriculture, (ii) sanitation of the product, (iii) reduction of volumes due to large loss of moisture during the active phase, (iv) low initial investments, and (v) simple operations that do not require specialized workers (Table 3). Furthermore, since the attention on emerging contaminants (i.e., antibiotics, toxins, ARG-genes) has become greater, a high capacity of composting to degrade them has been highlighted (Congilosi and Aga, 2021). This is mainly due to physical (i.e., high temperatures), chemical (i.e., presence of ammonia, oxidizing environment) and biological factors (aerobic bacteria generally have excellent degradation capabilities of organic contaminants) (Congilosi and Aga, 2021; Policastro and Cesaro, 2023; Tacconi et al., 2019). Nevertheless, some drawbacks of composting have emerged, posing serious questions about sustainability and circularity of this process. Energy requirements to maintain operative conditions have been recognized as the main limitation of composting, reducing its economic and environmental sustainability (Blengini, 2008; Serafini et al., 2023). In addition, large area requirements, potential environmental concerns (i.e., odour emissions, GHGs emissions, leachate production), and resource depletion (i.e., N losses during the process) pointed out that composting does not fulfil the principles of CE (Saer et al., 2013; Serafini et al., 2023; Wang and Zeng, 2018).

3.3. Integration of anaerobic digestion and composting: techno-economic aspects

Both AD and composting have advantages and disadvantages for OW treatment that can be overcome through various strategies, with the integration of the two processes being one of the most promising. Technically, IADC can be carried out by composting the digestate coming from AD, with or without addition of bulking agents (i.e., tree pruning, wood chips) depending on the moisture content of the digestate. Digestate storage is not usually foreseen in a IADC plant, thus limiting the area requirements (Le Pera et al., 2022). Composting time may be shortened taking into account that part of the fermentable organic matter present in the OW has been degraded during AD, for a total duration of the integrated process that is usually around 90 days (about 30 days of AD and 60 days of digestate composting). This may lead to a reduction of the area requirements for the composting operations of about 30 % with respect to a composting plant. Furthermore, if a IADC and a composting plant with the same areas are compared, the IADC plant allows to treat a larger amount of OW using the same area. Considering that the treatment of OW is one of the main components of the incomes of a treatment plant (Bottausci et al., 2023), the economic advantage is evident.

Temperature evolution during digestate composting follows the typical behaviour of composting, proceeding through a mesophilic, a thermophilic and again a mesophilic (curing) phase. Usually, during digestate composting the thermophilic phase is reduced in intensity (i.e., lower peak temperature, lower degree hours accumulated) since part of the organic matter have already been mineralized during AD.

The main benefits of integrating the two biological processes might be summarised as follow:

- High potential of resource recovery: AD removes most of easy degradable organic compounds and converts them in biogas, whereas composting allow a high stabilization of the residual organic matter, allowing to apply stabilized organic C to the soil, favouring C sequestration and reducing GHGs emissions into the atmosphere. Nutrients loss are limited during AD and organic N in the digestate is less prone to volatilization during composting, increasing the fertilizing potential of compost and reducing the dependence from mineral fertilizers.
- Energetic sustainability: AD produces biogas which can be used to sustain the energetic requirements from composting (i.e., energy for ventilation, turning operations); moreover, in the case that energy

recovery exceed the requirements from the OW treatment, the biogas surplus may be used to produce energy for surrounding stakeholders and/or it can be upgraded to biomethane and entered to the grid of natural gas. Biogas upgrading to biomethane allows for simple distribution, storage and selling through the existing natural gas grid, and this is of crucial importance in the growing biogas market in Europe (Bumharter et al., 2023).

- Environmental sustainability: AD has the capacity to reduce the fermentability of OW in controlled environments, allowing for odours and GHGs emissions control. Furthermore, N in compost is usually found in organic form, reducing the risk of ammonia emissions into the atmosphere or nitrate leaching into the groundwaters from compost application (Chalhoub et al., 2013).
- Economic sustainability: composting is an energy requiring process and it has high costs in terms of human resources. Nevertheless, when coupling composting with AD, the overall economic balance turned to be positive due to the large amount of energy and incomes potentially available from biogas production, also in a context where compost has practically no market value (Le Pera et al., 2022; Hamedani et al., 2020).
- High removal efficiency of organic contaminants.

Summarising, integrating AD and composting may represent a suitable strategy for OW valorisation and recycling, meeting the CE principles and several SDGs goal (Fig. 3). Since the four criteria established by the Waste Framework Directive are met by recycling OW through IADC (i.e., *the substance is used for specific purposes, there is an existing market for the substance, the use is lawful, the use will not lead to adverse environmental or human health impacts*), it urges that European legislative bodies develop EoW criteria also for OW, as already done for other waste streams (e.g., iron, steel and aluminium scrap, glass cullet, copper scrap, plastics) (European Parliament, 2008). This could help promoting OW recycling in a CE perspective and achieving SDGs (Fig. 3). Indeed, AD allows safe disposal of OW and wastewaters and produce clean energy, reducing GHGs emissions and climate change (SDGs 6, 7 and 13). Composting of digestate, allowing sustainable biomass production, helps achieving the objectives of zero hunger, as well as protecting life below water and on land (SDGs 2, 14 and 15).

Having presented the potential benefits and the main techno-economic aspects of AD and composting integration, the following Section 4 is devoted to present a literature review dealing with significant studies on the field describing technical aspects including sustainability assessment (Section 4.1), the fate of contaminants during the process (Section 4.2), and the agronomic quality of the recovered biofertilizers (Section 4.3).

4. Integration of anaerobic digestion and composting

4.1. Literature review of integration of anaerobic digestion and composting

Table 4 shows the results of the literature review carried out to describe the state-of-the-art of AD and composting integration. Among the OW, AIR co-treatment with AM using IADC have been widely described both at pilot- and full-scale (Cucina et al., 2022a; Hamedani et al., 2020; Li et al., 2018; Michalopoulos et al., 2019). Although reporting some interesting results concerning suitability of digestate for composting, pilot-scale studies are usually affected by the lack of sustainability assessment (Cucina et al., 2022a; Michalopoulos et al., 2019). Conversely, the works from Li et al. (2018) and Hamedani et al. (2020) reported the results from full-scale studies of integrated treatment of AIR and AM, including a detailed sustainability assessment. When studying different disposal strategies for dairy manure, corn stover and tomato residue (i.e., AD, composting and AD+composting), Li et al. (2018) showed that turned windrow co-composting in piles of the digestate coming from dry batch mesophilic co-AD resulted in the best environmental performances, mainly due to the production of biogas (379 m^3 $tVSf_{eed}^{-1}$) used in combined heat and power engines. Overall, they also pointed out that placing the AD and composting facilities on farm was advantageous for all life cycle impact categories. Similar results were reported by Hamedani et al. (2020) who described the benefits of integrating AD and composting to treat a mixture of manure, cheese whey and green crop residues. Results demonstrated the economic and environmental profitability of this treatment (i.e., outstanding environmental benefits were represented by means of the −167.52 $kgCO_2$ global warming potential), which was mainly due to bioelectricity production. Interestingly, sustainable economic performance was demonstrated independently from the presence of incentives regarding the electric production.

Also MOW treatment through IADC has been evaluated (Cucina et al., 2021c; Le Pera et al., 2022; Leow et al., 2020). A pilot-scale study showed a reduced biogas production from mesophilic batch AD of MOW and GMW, and it was attributed to the scarce biodegradability of the GMW fraction. Nevertheless, digestate composting produced a high-quality amendment characterized by high content of organic matter and plant nutrients (N, P and K) (Cucina et al., 2021c). In a LCA study of

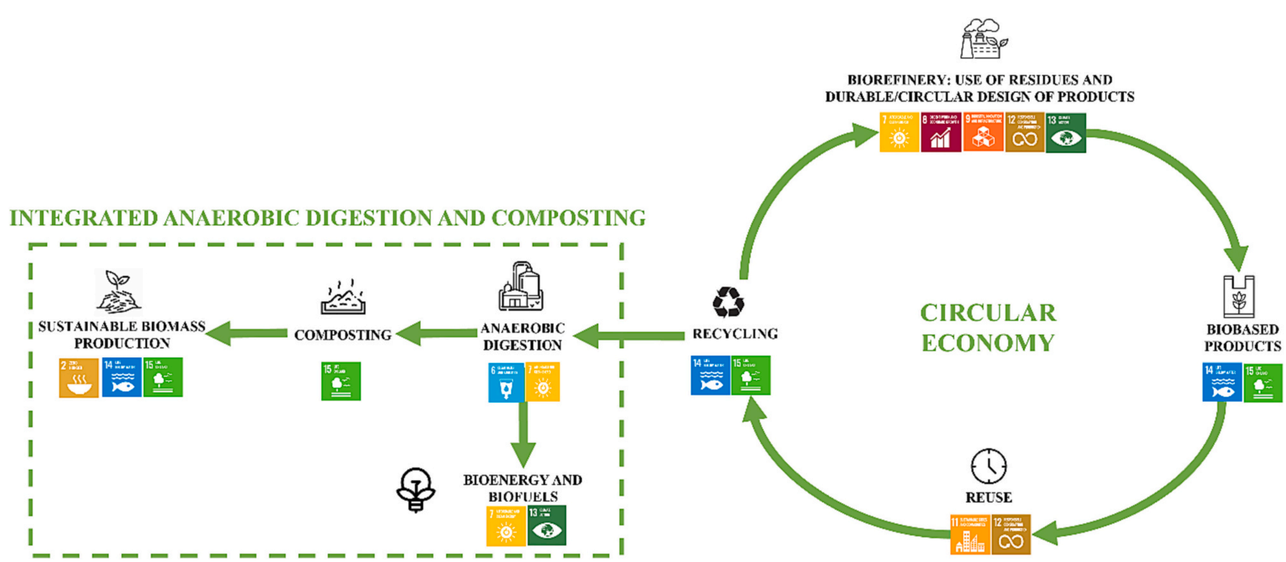

Fig. 3. Integrated anaerobic digestion and composting of organic wastes in the framework of Circular Economy and Sustainable Development Goals (SDGs).

Table 4
Integration of anaerobic digestion (AD) and composting for the recovery of biomethane and biofertilizers from organic wastes: literature review.

Organic waste	Scale	AD technology	Biogas production/ utilization	Composting technology/ procedure	Sustainability assessment	References
AIR[a]+AM[b]	Full-scale	Dry batch mesophilic co-digestion	379 m^3 tVS_{feed}^{-1}; biogas utilized by combined heat and power generation engines	Turned windrow co-composting in piles	High environmental credits on global warming potential; Reduction in eutrophication potential, global warming potential, acidification potential, and ecotoxicity potential; Locating the anaerobic digestion plant and composting facility on the farm was advantageous for all life cycle impact categories	(Li et al., 2018)
AIR + AM	Full-scale	Wet continuous mesophilic co-digestion	Biogas utilized by combined heat and power generation engines	Composting of the solid fraction of digestate	Integrating a compost plant with a biogas plant can significantly increase the carbon credits of the process	(Hamedani et al., 2020)
AIR + AM	Pilot-scale	Wet batch mesophilic co-digestion	335 m^3 tVS_{feed}^{-1}	Static thermophilic co-composting	n.a.[f]	(Cucina et al., 2022b)
AIR + AM[g]	Pilot-scale	Wet semi-continuous mesophilic co-digestion; HRT[c] = 6–11 days	0.2–0.7 m^3 $L_{reactor}^{-1}$ day^{-1}	Mixed actively aerated thermophilic co-composting	n.a.	(Michalopoulos et al., 2019)
MOW[d]	Full-scale	Dry plug-flow low thermophilic digestion; HRT = 22 days	358 m^3 t_{feed}^{-1}; biogas upgraded to biomethane for transport vehicle use	Static thermophilic co-composting in biocells (active phase) and closed sheds (maturation)	Primary Energy Demand, Global Warming Potential and Fossil Fuel Depletion analysis proved the environmental sustainability of the process	(Le Pera et al., 2022)
MOW	Full-scale	n.a.	Biogas utilized by combined heat and power generation engines	n.a.	99.7 % reduction of GHGs emissions with respect to landfilling of MOW	(Leow et al., 2020)
MOW	Pilot-scale	Dry batch mesophilic digestion	135 m^3 tTS_{feed}^{-1}	Static mesophilic co-composting	n.a.	(Cucina et al., 2021c)
SS[e]	Pilot-scale	Wet batch mesophilic co-digestion	390 m^3 tVS_{feed}^{-1}	Static thermophilic co-composting	n.a.	(Cucina et al., 2017)

[a] Agro-industrial residues.
[b] Animal manures.
[c] Hydraulic retention time.
[d] Municipal organic wastes.
[e] Sewage sludge.
[f] Not available.
[g] AD was carried out with the liquid fraction of the feedstock, whereas composting was carried out with the solid fraction of the feedstock.

IADC of food waste, Le Pera et al. (2022) reported the sustainability assessment of the dry plug-flow low thermophilic digestion (HRT = 22 days) and subsequent static thermophilic co-composting of digestate in biocells (active phase) and closed sheds (maturation). Primary energy demand, global warming potential and fossil fuel depletion analysis proved the environmental sustainability of the process, being the replacement of natural gas with biomethane for transport sector the greatest contributor for all the examined categories. In another study, different scenarios for MOW treatment in Malaysia (i.e., landfill, pilot-scale composting, full-scale composting, IADC) were compared in terms of environmental sustainability and economic return (Leow et al., 2020). Although the best environmental performance was obtained by IADC (i.e., GHGs emissions were reduced of about 100 % with respect to landfilling scenario), the minimal return time was higher for the integrated treatment than the only scaling up of composting (6.2 and 3.1 years, respectively). This was mainly due to the high investments needed to implement the AD facilities.

Few papers can be found in literature dealing with IADC treatment of GMW and SS, and most of them were carried out using pilot-scale experiments, not providing sustainability assessment that are needed to the full-scale implementation of this technology (Cucina et al., 2017).

4.2. Fate of contaminants during integrated treatment

In the last decades, the fate of contaminants during biological treatment of OW has emerged as an important topic since these compounds have been increasingly detected in OW and since they might be able to (i) inhibit the biological treatment and/or (ii) compromise the quality and utilization of the recovered biofertilizers (Congilosi and Aga, 2021). Generally talking, all xenobiotics present in OW and not derived directly from the transformation process originating the OW can be considered contaminants (i.e., heavy metals, pharmaceuticals, mycotoxins). In the present review, the degradation of bioplastics during the IADC was also discussed since these materials are considered as inert materials when their residues are detected in biofertilizers (i.e., digestate and compost) from the European Regulation of fertilizers (European Parliament, 2019) (Table 5). In addition, the concentration of bioplastics in MOW is expected to increase rapidly following policy indications, thus becoming a concern for biological processes development and biofertilizers quality if not properly degraded (Cucina et al., 2021c; Papa et al., 2023).

Both AD and composting have been studied for their effectiveness to degrade various contaminants (i.e., antibiotics, pharmaceuticals, personal care products, antibiotic resistance genes – ARGs), showing a wide range of contaminants removal, mainly depending on process condition and xenobiotic characteristics (Congilosi and Aga, 2021). Overall, the aerobic microbial consortia operating composting are more effective than anaerobic microbial consortia present in the anaerobic digester due to more efficient metabolic processes (Biel-Maeso et al., 2019), whereas some contaminants need subsequential anaerobic and aerobic conditions to be degraded (i.e., halogenated solvents) (Tiehm and Schmidt, 2011). These evidence were in accordance with the results of literature review carried out in this paper (Cucina et al., 2022b, 2017; Gurmessa et al., 2021b) (Table 5). When treating Aflatoxin B1 contaminated corn and pig manure through AD and subsequent digestate composting, Cucina et al. (2022b) found that AD removed about the 70 % weight bases of the mycotoxin, and that the removal was completed by composting. Similarly, Cucina et al. (2017) reported a removal of about 70 %

Table 5
Fate of contaminants in organic wastes during integrated anaerobic digestion (AD) and composting.

Contaminant class	Contaminant	Treatment description	Organic waste	Duration (days)	Degradation (%)		References
					AD	AD + composting	
Mycotoxins	Aflatoxin B1	Wet mesophilic AD + thermophilic composting	AIR[a]+AM[b]	90	69.7	100	(Cucina et al., 2022b)
Pharmaceuticals	Daptomycin	Wet mesophilic AD + thermophilic composting	SS[c]	90	69.4	100	(Cucina et al., 2017)
ARG[d]s	erm(B), tet(K), tet (M), tet (O), tet(S)	Wet mesophilic AD + thermophilic composting	AIR+AM	90	n. a.[e]	>80	(Gurmessa et al., 2021a)
Inerts	PLA-based bioplastic	Dry mesophilic AD + mesophilic composting	MOW[f]	90	3.7	15	(Cucina et al., 2021c)
	Starch-based bioplastic	Dry mesophilic AD + mesophilic composting	MOW	90	29.5	48.1	(Cucina et al., 2021c)
	Starch-based bioplastic	Wet thermophilic AD + thermophilic composting	SS + MOW	90	23.8	100	(Cucina et al., 2022b)
	CA-based bioplastic	Wet mesophilic AD + thermophilic composting	MOW	101	66.8	73.8	(Gadaleta et al., 2022)
	Modified CA-based bioplastic	Wet mesophilic AD + thermophilic composting	MOW	101	51.4	54.7	(Gadaleta et al., 2022)
	PLA-based bioplastic	Wet thermophilic AD + thermophilic composting	MOW	47	0	n.a.	(Bandini et al., 2020)
	Starch-based bioplastic	Wet thermophilic AD + thermophilic composting	MOW	47	85.8	100	(Bandini et al., 2020)

[a] Agro-Industrial residues.
[b] Animal manures.
[c] Sewage sludge.
[d] Antibiotic resistance gene.
[e] Not available.
[f] Municipal organic wastes.

weight bases of the antibiotic daptomycin during SS AD, and that no antibiotic traces were detectable in the compost produced through digestate composting. Also Sertillanges et al. (2020) have reported that integrating AD and composting lead to a high removal of tetracycline from OW, and that the concurrence of several decontamination agents during the IADC treatment (e.g., diversified microbial consortia, high temperature, ammonium-N presence, light irradiation) may be probably responsible of the high effectiveness for contaminants removal. Composting of digestate resulted effective also for the removal of ARGs (i.e., erm(B), tet(K), tet(M), tet(O), tet(S)) from a mixture of AIR and AM, thus representing a suitable treatment to reduce the spread of ARGs into the soils (Gurmessa et al., 2021b).

When describing the degradation of bioplastics during biological treatments, it is crucial to highlight that bioplastics biodegradation depends on process conditions and bioplastics characteristics, being process temperature the most important factor (Papa et al., 2023). For instance, thermophilic temperatures of 55–58 °C are necessary to obtain an effective biodegradation of bioplastics due to the achievement of the glass transition temperature that turn the crystalline structure of bioplastics into amorphous one. This explained the low degradation of bioplastics reported by Cucina et al. (2021c) during mesophilic AD and subsequent composting of MOW and GMW (i.e., at the end of composting the degradation of polylactic acid and starch-based bioplastics was 15 % and 48 % weight bases, respectively). Conversely, starch-based bioplastics completely degraded when thermophilic composting followed thermophilic AD (Bandini et al., 2020; Cucina et al., 2022a). In the same paper, Bandini et al. (2020) have also reported that polylactic acid-based bioplastics did not degrade during thermophilic AD, proving that not only process conditions, but also bioplastics characteristics, drive their biodegradation. Also cellulose acetate-based bioplastics showed high removal during IADC of MOW, reaching up to the 75 % weight bases of degradation (Gadaleta et al., 2022).

Summarising, coupled anaerobic-aerobic conditions were proved to degrade effectively different types of contaminants, thus reducing the risk of environmental contamination following biofertilizers soil application. With concerns to bioplastics in MOW, it should be highlighted that being biodegradable, the effects of their residues into the soil might be negligible (i.e., accumulation of bioplastics appears unlikely since they have proved to degrade into the soil in few years) (Papa et al., 2023). Nevertheless, until when bioplastics residues will be considered inert materials affecting digestate and compost quality, their degradation will represent a potential limitation to biofertilizers application. In this context, pushing their degradation during AD of MOW would be preferable due to the contextual conversion of bioplastics into biogas and their reduction in the digestate (Papa et al., 2023).

4.3. *Agronomic quality of biofertilizers from integrated anaerobic digestion and composting*

Considering the context of mineral fertilizers market and environmental impact of their utilization presented in Section 1, production of biofertilizers (i.e., digestate and compost) to be used in agriculture in partial or total substitution of mineral fertilizers appears as important as biogas production to make the IADC treatment sustainable from an environmental and economic point of view (Le Pera et al., 2022). Generally, digestate is considered as an organic fertilizer (usually N organic fertilizers) due to the high amount of mineral N and other nutrients that make it suitable for fertilization of crops (Pigoli et al., 2021). Conversely, compost is usually defined as an amendment, useful to increase soil OM content, also providing nutrients in slow-releasing forms (i.e., organic N) (Cucina et al., 2018). Nevertheless, environmental and agronomic benefits of biofertilizers application in agriculture can be fully exploited only if the quality of these products meets certain requirements.

Table 6 reports an overview of agronomic quality of digestate and composting coming from studies dealing with IADC treatment of OW. To elucidate biofertilizers' quality, chemical-physical parameters (TS and pH), organic matter and nutrients (N, P and K) contents, as well as maturation and stability indexes (C/N, germination index – GI, and dynamic respiration index -DRI) were considered.

Although digestate from highly performing AD processes have proven to be suitable for direct application to the soil both in terms of

Table 6
Literature review of agronomic quality of biofertilizers obtained from integrated anaerobic digestion (AD) and composting processes of organic wastes.

Organic waste	Biofertilizer	TS[a] (%)	pH	OM[b] (%)	TN[c] (%)	NH_4^+-N (%)	C/N	TP[d] (%)	TK[e] (%)	GI[f] (%)	DRI[g] ($mgO_2\ gVS^{-1}\ h^{-1}$)	References
SS[h]	Digestate	3.8	7.4	82.8	9.4	n.a.[l]	4.4	0.56	0.67	1	n.a.	(Cucina et al., 2017)
	Compost	51.9	8.5	60.8	2.7	n.a.	11.2	0.62	1.78	83.7	n.a.	
SS	Digestate	n.a.	6.6	43.8	3.9	n.a.	6	3.3	0.3	n.a.	n.a.	(Rékási et al., 2019)
	Compost	n.a.	6.9	41.2	2.4	0.0007	9.9	2.2	0.7	n.a.	n.a.	
AIR[i] + AM[j]	Digestate	6.2	7.4	31.8	6.5	6.3	2.4	1.4	7.4	0	n.a.	(Cucina et al., 2022b)
	Compost	45.1	7.9	43.2	2	0.1	10.8	0.3	1.5	100.6	n.a.	
AIR+AM	Digestate	38.4	8.1	83.7	1.5	n.a.	25.8	0.1	14.1	0	n.a.	(Gurmessa et al., 2021b)
	Compost	n.a.	7.3	80	2.3	n.a.	17	0.2	20	50	n.a.	
AM	Digestate[m]	21.6	8.6	89.8	2.2	0.98	20.1	n.a.	n.a.	n.a.	n.a.	(Tambone et al., 2015)
	Compost	45.1	8.5	91.2	1.5	0.02	30.7	n.a.	n.a.	83.3	0.4	
AM	Digestate[m]	n.a.	6.8	69.9	2.6	n.a.	14.5	n.a.	n.a.	47.2	n.a.	(Bustamante et al., 2014)
	Compost	n.a.	6.4	49.3	2.6	0.06	9.2	1.6	0.8	83.5	n.a.	
MOW[k]	Digestate	27.5	8.3	68.8	4.5	0.7	7.7	n.a.	n.a.	0	n.a.	(Song et al., 2021)
	Compost	n.a.	7.6	82	2	0.02	20.5	n.a.	n.a.	80	n.a.	
MOW	Digestate	30.2	8.2	38.5	1.9	0.4	10.1	n.a.	n.a.	n.a.	n.a.	(Zeng et al., 2016)
	Compost	53.1	7.2	47.2	1.2	0.009	19.7	n.a.	n.a.	n.a.	n.a.	
MOW	Digestate	42.4	n.a.	42.4	0.8	n.a.	27.4	n.a.	n.a.	n.a.	n.a.	(Núñez et al., 2022)
	Compost	91	n.a.	32.7	0.7	n.a.	27.9	n.a.	n.a.	112.6	0.13	
MOW	Digestate	25	8.2	n.a.	n.a.	0.65	6	n.a.	n.a.	n.a.	n.a.	(Manu et al., 2022)
	Compost	n.a.	7.8	80	2.9	0.045	13.8	n.a.	n.a.	90	n.a.	

Data are expressed on dry matter bases.
[a] Total solids.
[b] Organic matter.
[c] Total N.
[d] Total P.
[e] Total K.
[f] Germination index (cress).
[g] Dynamic respiration index.
[h] Sewage sludge.
[i] Agro-industrial residues.
[j] Animal manures.
[k] Municipal organic wastes.
[l] Not available.
[m] Solid fraction of digestate.

fertilizers replacement value and environmental impacts (Pigoli et al., 2021; Zilio et al., 2021), usually digestate application rises concerns due to the possible N-losses, spread of contaminants and pathogens, low stabilization of the OM and low maturation (Alburquerque et al., 2012). N-losses usually take place through ammonia-N emissions into the atmosphere and/or nitrate leaching into groundwater that are associated to the application of digestate rich of mineral N coming from protein hydrolysis and characterized by low C/N ratios (Janz et al., 2022). The reviewed digestate showed high ammonium-N/total-N ratios ranging from about 20 % to 95 % depending on the source materials (Table 6), thus causing potential N-losses if their application is carried out in conditions that do not allow for a rapid assimilation of ammonium-N from crops. Apart from the persistence of contaminants and pathogens that is commonly noticed in digestate coming from mesophilic AD processes, other major issues of digestate application to the soil is their low OM stabilization and their scarce maturation that may lead to phytotoxic effects. Unfortunately, only few data are available dealing with digestate stability and maturation from studies of IADC (Bustamante et al., 2014; Cucina et al., 2022b, 2017; Gurmessa et al., 2021b). Overall, digestate showed high residual phytotoxicity (GI ranging from 0 % to 50 %), and most of the research explained these effects because of high ammonium-N and soluble salts concentration, as well as of the presence of easily degradable organic compounds (i.e., volatile fatty acids) residue from AD. Finally, digestate are usually characterized by low TS content, which makes their management expensive and reduces their fertilizing value. Composting of digestate is a suitable strategy to overcome all the drawbacks reported for digestate (Table 6). First, during the active phase of composting temperature increases reaching 60–70 °C, causing significant water evaporation, thus reducing moisture content of compost and making its management easier and cheaper. The high temperature reached during composting also allows to significantly reduce the content of organic contaminants and pathogens, as already reported in Section 4.2. Although composting causes some OM and N-losses, resulting in OM and TN concentrations lower in the compost than in the digestate, compost allows to reclaim important amounts of OM and plant nutrients in agriculture, reducing the dependence from synthetic fertilizers. The predominance of organic-N in compost with respect to ammonium-N (often representing more than the 95 % of the TN) also allow for a slow release of N into the soil, avoiding the risks of environmental pollution and providing a constant fertilization to crops during the vegetative season (Cucina et al., 2018). The main consequences of composting digestate have been identified as the increased OM stabilization and maturation. The reviewed compost showed a DRI under the maximum limit established by the new European Regulation for fertilizers (i.e., 25 $mmolO_2\ kg_{OM}^{-1}\ h^{-1}$) (Núñez et al., 2022; Tambone et al., 2015), and a C/N ratio compatible with agricultural reuse ranging from about 10 to 30, depending on the OW treated. Composting also allow to reduce phytotoxicity, and all the reviewed compost produced from digestate showed absence of phytotoxicity (GI > 50 %). Nonetheless, some samples showed GI > 100 %, thus showing biostimulant properties (Cucina et al., 2022b; Núñez et al., 2022).

To sum up, composting of digestate is a key tool to enhance nutrients recovery avoiding environmental concerns. In this sense, composting may represent a post-treatment of digestate useful to improve its agronomic properties. It must be highlighted that digestate composting usually requires shorter time than OW composting to reach the same quality of the final product (i.e., 45–60 days instead of 90). This means that coupling AD and composting would not require longer time and would not reduce the treatment capacity.

5. Research gaps and future research

Although the IADC presented in this review can represent a valid approach towards achieving a complete CE system for OW treatment, further research is envisaged to overcome the research gaps emerged during the literature review carried out.

From a technical perspective, there is still a lack of information about using SS as feedstock for the IADC system. Considering the large amount of energy and nutrients recoverable from this waste stream, the claim for further investigation is evident. Although pilot-scale studies furnish important evidence about the suitability of OW for anaerobic and aerobic treatment, this research is of limited relevance to assess the sustainability of the proposed approach. Therefore, there is an urgent need to implement full-scale studies dealing with the evaluation of the environmental impact of IADC, in order to allow the implementation of this approach under real conditions. Economic sustainability of IADC has been evaluated only in few papers and there is an evident need of more studies that take in consideration also this technical aspect, defining potential costs of the facilities, benefits from energy and biofertilizers production, and time expected to return the initial investments.

Literature review has pointed out that biogas production from IADC is the process that improves mostly the global sustainability of the OW treatment. Therefore, improving AD performance becomes mandatory to enhance the implementation of IADC for OW management. Biogas production from scarcely biodegradable OW (i.e., GWM, some AIR and SS) may be effectively enhanced through pretreatments of the feedstock prior to AD (Atelge et al., 2020; Janz et al., 2022). Different pretreatment technologies have been applied to enhance biogas production from biomasses maintaining a net energy production (i.e., mechanical, thermal, chemical), but there are no studies of IADC where OW are pretreated prior to the AD step. Therefore, this sort of biorefinery (pretreatment followed by IADC) should be investigated to evaluate its global sustainability. Optimization of AD performance could be also carried out by pushing towards more efficient systems such as thermophilic AD and/or dry AD. Thermophilic AD is indeed proved to enhance OW conversion into biogas, as well as to improve the degradation of contaminants and the elimination of pathogens (Pigoli et al., 2021). Conversely, dry processes may lead to reduced volumes of digestate to be stabilized through composting, decreasing the costs related to its management (i.e., reduced amount of bulking agents, reduced transportation costs). Since the OM degradation would be forced during the anaerobic step, more performing AD processes may also help reducing the duration of composting, permitting to increase the volumes of OW treated. Nevertheless, there are still little evidence coming from IADC process using thermophilic and/or dry AD processes. Finally, development of processes to recover biogenic CO_2 from biogas upgrading unit and to limit fugitive emissions that may further decrease IADC environmental impact are worth of investigation.

The quality of biofertilizers recovered from IADC emerged to be as important as biogas production in a CE perspective. To achieve high quality standards, the quality of OW should be enhanced in terms of purity and absence of non-biodegradable materials and contaminants that may affect process development and products quality. For instance, improving MOW separate collection by citizens is an important activity that will need to be carried out, through a greater and more widespread information to citizens, to minimise the quantity of MOW unwanted materials that will go to landfill, negatively affecting the global sustainability of IADC. Although there are some evidences in literature dealing with efficiently removal of organic contaminants during IADC of OW, further research is needed to assess the fate of other emerging classes of organic contaminants (i.e., ARGs, pharmaceuticals, hormone-like compounds). Elucidating the mechanisms by which the contaminants are removed during IADC process will also be increasingly important, to understand if a complete mineralization of the contaminants takes place or they are transformed into other potentially more toxic compounds.

6. Integration of anaerobic digestion and composting: policy aspects

As reviewed in the previous Sections, integration of anaerobic digestion and composting may represent a sustainable strategy to effectively recover energy and nutrients from OW, reducing the environmental impact of OW management and enhancing the circularity of European economies. Nevertheless, policy aspects are of crucial importance to favour the application of sustainable technologies for OW treatment. Indeed, treatments that are technically feasible and sustainable are often limited in their application due to incomplete or incoherent policy frameworks (i.e., biodegradable bioplastics use is still limited by Single-Use Plastic European Directive that did not discriminate between fossil-plastics and bioplastics) (Cucina, 2023; Zorpas, 2020). In this context, this Section aims to summarise the actual policy framework in Europe dealing with OW management and to present a tentative policy roadmap to favour the spread of IADC.

The European Union has enacted a number of strategies and initiatives to address OW management issues already before the last three years (2019–2022) crisis (Section 1), with the goals of promoting a sustainable and circular economy, lowering waste, boosting resource efficiency and security, and limiting climate change. These strategies include the European Green Deal and the Circular Economy and End-of-Waste strategies, which are all strictly related to the Sustainable Development Goals (SDGs) defined by the United Nations General Assembly in 2015, as part of the 2030 Agenda for Sustainable Development (European Commission, 2018, 2019, 2020; European Parliament, 2008; United Nations, 2015).

The goal of becoming climate neutral by 2050 lies at the core of the European Green Deal. To achieve this, greenhouse gas emissions (GHGs) must be significantly reduced, and sustainable economic models must be supported. One of the cornerstones of the Green Deal is the Circular Economy (CE) strategy, which aims to encourage a more sustainable and effective use of resources by minimising waste, increasing recycling, and minimising the extraction of raw materials (Le Pera et al., 2022). Bioeconomy, which uses renewable biological resources to produce food, materials, and energy, is a crucial part of the CE concept. Another component of the CE approach is the End-of-Waste (EoW) criteria established by the European Waste Framework (European Parliament, 2008), which work to guarantee that waste materials are turned into useful resources that can be recycled, recovered, or repurposed. When waste stops being *waste* and turns into a *product* or *secondary raw material* is clearly defined by the EoW criteria. By encouraging material reuse and recycling, lowering waste production, and minimising raw material extraction, this strategy aids in the growth of a CE. CE, bioeconomy, and End-of-Waste criteria are closely aligned with the SDGs, which provide a comprehensive framework for achieving sustainable development addressing social, economic, and environmental challenges (i.e., poverty, hunger, climate change, and biodiversity loss) (AlQattan et al., 2018; Dantas et al., 2021; Østergaard et al., 2020). By fostering a more sustainable and CE, the European reliance on non-renewable resources and fossil fuels can be minimised, whereas resource efficiency and security can be boosted while new job possibilities can be created. By lowering GHGs, bioeconomy can also help fight climate change, and the EoW criteria can ensure that wastes are turned into useful resources. Overall, the SDGs' implementation can promote sustainable growth and support the creation of resilient society and economies (Dantas et al., 2021; Østergaard et al., 2020).

In this potentially positive policy framework, policy makers are asked to do a step forward and drive the stakeholders (i.e., citizens, waste management companies) towards more sustainable waste management systems. To enhance the efficient OW valorisation through IADC in the CE context, a serious of challenging modification to the current policies should be addressed in Europe to define an effective policy roadmap (Fig. 4).

First, the main objective of the European policy, in line with the definition of the waste hierarchy, should be to encourage the prevention and reduction of waste production. Waste hierarchy was first defined in the European Waste Framework in 2008 (European Parliament, 2008), indicating waste prevention as the preferred option, and sending waste to landfill the last resort. Accordingly, a set of targets may be defined to reduce wastes to be treated at the source. With the waste hierarchy fully applied, the inevitable amount of residues produced by human activities to be treated would decrease, reducing the overall environmental and economic costs of human activities.

Having ensured the full application of waste hierarchy, the following step could be the establishment of challenging targets of organic waste recycling to finally meet the “no landfill” objective. Actually, EU has set to reduce the amount of municipal waste for the landfilling to <10 % by 2035, while the amount of municipal waste for the reuse and recycling operations must meet the 60 % by 2030. These targets, which are already challenging for some European countries, should be extended also to other OW (i.e., sewage sludge, agro-industrial organic wastes and animal manures) to favour their valorisation and reduce disposal through landfilling. Considering the high environmental impact of landfilling of organic wastes (Siddiqua et al., 2022), it could be also reasonable to set a target of 0 % of organic waste for landfilling by 2050 or even earlier. Another important step forward to favour the spread of sustainable treatment technologies for OW valorisation such as IADC could be the establishment of a set of targets of energy recovery from OW. This would promote the application of technologies that allow energy recovery from putrescible biomasses (i.e., AD-based systems), enhancing the energetic, economic, and environmental sustainability of the entire waste management system. Another aspect that could be supported by creating new targets in Europe could be the quality of the OW collected. As previously reported, ensuring the quality of OW through the definition of quality standards for biological recovery appears mandatory to avoid processes inhibition and ensure products quality. For instance, MOW separate collection appears as the only way to have a high-quality fermentable substrate with limited amounts of undesired non-biodegradable contaminants (i.e., plastics, glass, metals). Setting target for sorted collection of MOW, along with quality standards for biological recovery, may allow for an efficient recovery of energy and nutrients from MOW.

A clear definition of EoW criteria for OW going to IADC treatment are needed to define harmonized conditions to be followed to finally drive out OW from the *waste* definition, meeting the objectives of CE and SDGs. According to European Waste Framework (European Parliament, 2008), certain specified waste ceases to be waste when it has undergone a recovery operation (including recycling) and complies with specific criteria: (1) the substance or object is commonly used for specific purposes, (2) there is an existing market or demand for the substance or object, (3) the use is lawful, and (4) the use will not lead to overall adverse environmental or human health impacts. All these requirements may be easily satisfied by OW entering a IADC plant, thus making their declassification from waste to secondary source possible. Clearly, policy makers are requested to define the limits within the recycling operations should take place, as well as the quality requirements for the raw material and the final products recovered (i.e., digestate and compost).

Finally, policy makers in Europe should also reduce the market barriers for processing, trading, and selling of materials recovered form OW. This includes: (i) free trading of resources and products from OW with an end-of-waste status within the EU, and (ii) a revision of the burden of proof that there is a market or demand for a material. This latter point could also favour to accomplish one of the four requirements that have to be satisfied to obtain the declassification from waste to secondary source. In this context, the new European Regulation on Fertilizers 2019/1009 (European Parliament, 2019) represents a first step in the creation of a free common European market of recovered biofertilizers, but much work is still needed to also include sewage sludge and animal manures in this framework.

7. Conclusions

Benefits and research gaps of IADC for organic wastes treatment were reviewed in the present paper. Overall, IADC appears as a promising process that needs to be further implemented due to its reduced environmental impact (i.e., reduced GHGs emission, removal of organic contaminants) and to the potential production of high-value products (i.e., biogas, biomethane, compost). By allowing their sustainable recycling and reducing dependence from fossil-fuels and synthetic fertilizers, IADC enhances circularity of organic wastes, meeting the principles of circular economy and achieving SDGs. Nevertheless, further research is still needed to evaluate at full-scale the sustainability of IADC of poorly studied organic wastes (i.e., sewage sludge), to boost energy recovery during AD, and to get a deep knowledge of degradation pathways of contaminants. Also policy makers should help promoting IADC by harmonizing the existent legislation and standards for organic wastes quality and recycling.

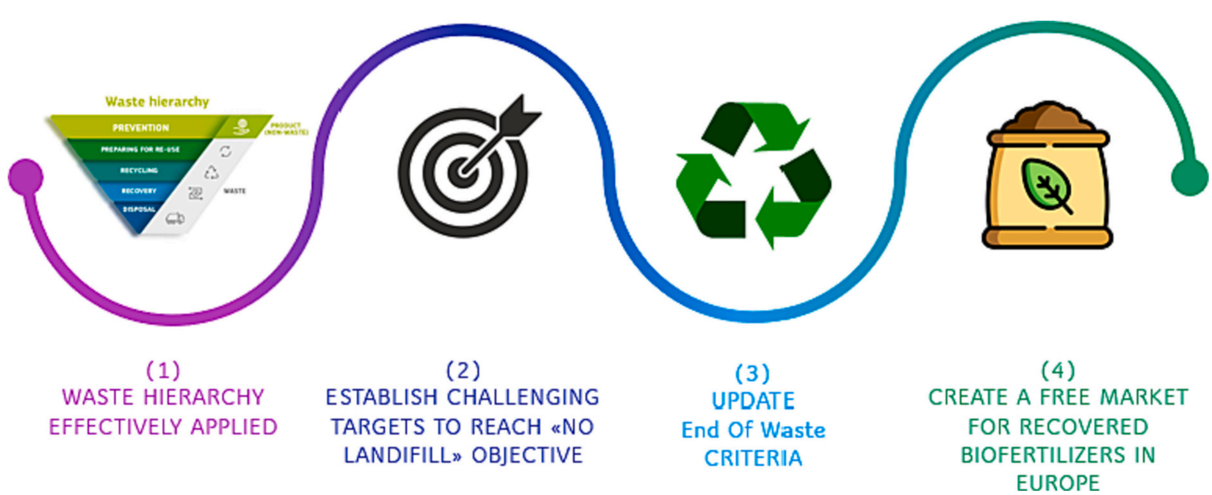

Fig. 4. Tentative policy roadmap to favour integrated anaerobic digestion and composting systems for the treatment of organic waste in Europe in the context of Circular Economy.

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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.

Data availability

Data will be made available on request.

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