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Anaerobic digestate management, environmental impacts, and techno-economic challenges

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Abstract

Digestate is a nutrient-rich by-product from organic waste anaerobic digestion but can contribute to nutrient pollution without comprehensive management strategies. Some nutrient pollution impacts include harmful algal blooms, hypoxia, and eutrophication. This contribution explores current productive uses of digestate by analyzing its feedstocks, processing technologies, economics, product quality, impurities, incentive policies, and regulations. The analyzed studies found that feedstock, processing technology, and process operating conditions highly influence the digestate product characteristics. Also, incentive policies and regulations for managing organic waste by anaerobic digestion and producing digestate as a valuable product promote economic benefits. However, there are not many governmental and industry-led quality assurance certification systems for supporting commercializing digestate products. The sustainable and safe use of digestate in different applications needs further development of technologies and processes. Also, incentives for digestate use, quality regulation, and social awareness are essential to promote digestate product commercialization as part of the organic waste circular economy paradigm. Therefore, future studies about circular business models and standardized international regulations for digestate products are needed.

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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.

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Keywords

Anaerobic digestion; Nutrient pollution; Organic waste; Fertilizer; Digestate

1. Introduction

Anthropogenic global climate disruption, caused by burning fossil fuels, improper disposal of wastes, and unsustainable agricultural activities (Houghton, 2005), endangers the future of humankind and ecosystems. Promoting alternative energy from natural sources and improving waste management for the recycling and recovery of valuable products are important for addressing this global problem. One sustainable and possible way to mitigate current environmental challenges is by converting biodegradable organic waste into renewable energy in the form of biogas, with a stable and useful remaining residue, called digestate, typically used as a soil amendment (Hublin et al., 2014; Panuccio et al., 2016). Of the various methods for dealing with organic waste, anaerobic digestion (AD) is the most promising (Lee et al., 2009), since it converts more efficiently organic waste into valuable resources (Yu and Huang, 2009), thus contributing to the economy while reducing greenhouse gas (GHG) emissions, water pollution, and the volume of waste that goes into landfills (Dennehy et al., 2016).

AD is a process that occurs in nature (e.g., in cow stomachs), but in a biogas plant it can be controlled and optimized to yield more methane (Al Seadi and Lukehurst, 2012). Biogas consists of methane (CH_4) (45–75%, V/V), as a renewable energy source, carbon dioxide (CO_2) (25–55%), and small amounts of hydrogen sulfide (H_2S) and hydrogen (H_2) (Panuccio et al., 2016). The remaining slurry, called digestate, which can be around 90–95% of what was fed into the AD process is a nutrient-rich by-product. Depending on the feedstock composition and AD system design, 20–95% of the organic matter is broken down (Moller ¨ and Müller, 2012).

The application of digestate as fertilizer in agriculture is one of the simplest management solutions to avoid or minimize negative environmental impacts and improve the economic sustainability of biogas production (Iacovidou et al., 2013). Also, returning vital nutrients to the soil, such as nitrogen and phosphorus, can contribute to offsetting soil erosion (Slepetiene et al., 2020). Digestate is an excellent alternative to reduce chemical fertilizer application since it improves plant-available nutrients given its high content of micro-and macro-nutrients (Möller and Müller, 2012). Also, it is more hygienic, microbially stable, and rich in ammonium, as compared to undigested organic waste (Pivato et al., 2016). On the other hand, if improperly applied, digestate can harm plant growth and the soil (Rigby and Smith, 2013), and due to its chemical composition, it can lead to problems for its sustainable disposal. For example, early application of digestate and its longer retention time in the soil without usage by crops might cause the loss of nutrients and their translocation towards deeper soil layers or NO_3 emissions into groundwater (Formowitz and Fritz, 2010). Moreover, digestate pH values above 8 might lead to additional volatilization losses (Formowitz and Fritz, 2010). Therefore, each type of digestate has its strengths and weaknesses and should be characterized to determine its most sustainable application. In addition, designing appropriate logistics network management strategies that store, mobilize, and process digestate, makes it possible to balance and recycle nutrients more effectively and with this, control the timing and location of nutrient runoff to water bodies (Hu et al., 2019; Sampat et al., 2019). Hence, avoiding the disposal of digestate in soils currently saturated and impacted by nutrient legacies after years of inefficient and excessive application of nutrient-rich organic waste and conventional fertilizers.

Digestate can be spread like liquid manure on fields, or it can be pretreated for optimizing its characteristics and benefits resulting from its use. The most common treatments are solid–liquid separation, filtration, chemical (e.g. flocculation, precipitation, ionic exchange), dilution, membrane technology, and drying (Möller and Müller, 2012). Currently, data about digestate composition are scarce. Regarding the content of pollutants and other compounds, there are considerable and influencing variations according to the type of organic waste feedstock (Pivato et al., 2016). It is interesting to note that in many countries, the use of digestate as fertilizer is legally restricted because of unfamiliarity with it and scarce information about its quality and safety (Mangwandi et al., 2013).

Very few environmental and human health risk evaluation studies have investigated the impact of digestate on soil, water, and air (US EPA, 2004). Moreover, this lack of information limits the use of standard risk and impact assessment methodologies and tools, such as life cycle assessment (LCA) (Scientific Applications International Corporation, 2006) and ecological risk assessment (ERA) (US EPA, 1998). However, a recent article described the risk assessment for quality-assured source-segregated composts and anaerobic digestates in the United Kingdom (UK), assessing that these wastes play an important role in the circular bioeconomy (Pardo et al., 2014). For these reasons, stressors (substances causing effects), pathways (e.g., water, air, soil), exposure routes (e.g., ingestion, inhalation, biotic and abiotic interactions), receptors (e.g., populations, ecosystems, workers), and hazards (e.g., HABs (Harmful Algal Blooms) development and toxins, ecosystem conditions, illness) for human health and environmental risk assessments should be performed to improve our understanding of the interactions between the environment, ecosystems, communities, and organic waste contaminants (Kapanen and Itävaara, 2001). Some ecotoxicological tests for risk assessment have been proposed for compost application (Pivato et al., 2014), then used in research (Bendixen, 1994), and implemented for digestate application as fertilizer in crop fields (Pivato et al., 2016), indicating that quality assurance is fundamental to increase market confidence and improve its application and economic value (Panuccio et al., 2016).

Therefore, due to the growing use and demand of AD digestate as a valuable feedstock, this manuscript examines the current productive use of digestate by analyzing its feedstocks, processing technologies, economics, product quality, and impurities. Also, this contribution creates a synthesis of the best resources available for the sustainable management of digestate, incentive policies, and regulations. Finally, this work describes potential new research areas to explore in the future to address digestate environmental impacts, techno-economic challenges, nutrient pollution, and energy security needs.

2. Feedstock influence in the quality of digestate production

2.1. Digestate from animal manure

The characteristics of digestate animal manure vary according to the different feedstocks (pig, cow, poultry, etc.). For example, poultry litter and cattle manure present a lower bio-degradability in comparison with pig slurry, because they contain a bigger fraction of lignified compounds (from cereal straw and sawdust) (Iocoli et al., 2019).

Methanogenic AD of swine excrement produces digestate, which has been reported in the literature (Huang et al., 2016; Laureni et al., 2013; Lencioni et al., 2016; Nkoa, 2014; Steinfeld, 2006). NH_4 constitutes about 80% of the total N in digestate from pig manure. In addition, the hydrolysis of urea, and the mineralization of organic N in pig slurry releases large amounts of NH_4^+ (Pampillón-GonzáLez et al., 2017), and the conversion of organic N during AD into NH_4-N enhances the benefits of applying this kind of digestate among crop plants (Möller and Müller, 2012). Also, the AD of swine slurry kills most of the pathogens (Nicholson et al., 2005), but the number of Fecal coliform bacteria nonetheless remains high. Fortunately, the addition of quicklime (CaO) at the end of the digestion process has been suggested to reduce coliforms (Pampillón-GonzáLez et al., 2017; Posmanik et al., 2017). Therefore, pig digestate has been classified as a type B biosolid, which can be applied safely to the soil, however, attendants should not avoid doing it repeatedly unless they are carefully monitoring the salt content in the soil (Pampillón-GonzáLez et al., 2017). High salt content (e.g., the sodium content of 1.27 ± 0.65 kg Na m^{-3}) and chloride concentration of 5.12 ± 2.61 kg Cl m^{-3} have been reported in a chemical study carried out on finishing pig slurries (Katerji et al., 2003; Moral et al., 2008). Digestate application with salt content at these levels may result in higher crop yields and increased plant biomass, although this depends on the plant stage of growth (Nkoa, 2014). If too much is applied to young plants, it can be toxic to them (Alburquerque et al., 2012b). Further, direct contact of sludge with germinating seeds for young plants should be avoided, and instead, it should be applied by mixing with irrigation water (Chen et al., 2012). On the other hand, a study using an enhanced dry AD system for swine manure was reported, demonstrating that thermal treatment could increase the methane production rate of dry AD by 390% (Huang et al., 2016).

AD of cow manure is an effective waste treatment option for the reduction of total solids. It is interesting to note that when the cow diet is richer than simply grass (e.g., corn, soybeans), the digestate produced results in a more nutritious fertilizer (Mendonça Costa et al., 2016). However, the presence of pathogens requires a post-treatment of the effluent (Castro et al., 2017), because the total number of coliforms in the digestate would allow only a restricted irrigation use, according to the World Health Organization (WHO) guidelines for the safe use of wastewater, excreta, and greywater (Alfa et al., 2014). Also, storage of the digestate for a longer period reduces the pathogen content to acceptable levels to avoid attendant health problems (Alfa et al., 2014). As reported in the literature, AD of poultry excrement produces digestate (Kelleher et al., 2002; Nicholson et al., 2005; Posmanik et al., 2017; Sürmeli et al., 2017) and guidelines for its management, use, and feasibility for energy production have been discussed and reviewed (Dróżdż et al., 2020; Ribeiro et al., 2018; Sürmeli et al., 2017).

Due to the presence of emerging contaminants to include antibiotics used for medical and growth purposes, it has been reported that the application of digestate from animal feedstock can affect ecosystem health (Nõlvak et al., 2016). When given to the animals about 50–90% of the drug intake is not absorbed, and subsequently are excreted in the manure in concentrations ranging (Liu et al., 2020) from 1 to 136 mg/kg of dry matter (Ezzariai et al., 2018). This makes animal manure one of the organic contaminants threatening aquatic species and ecosystems; therefore, to use it as a fertilizer, it must be pre-treated or processed. Conventional treatments such as incineration, and composting have been used on manure, but they do not sufficiently remove the antibiotic content. A new approach, presented in a recent study (Liu et al., 2020), proposes the biotic treatment of engineered intestinal microbes (*Escherichia. coli*) to degrade antibiotics and remediate contaminants directly inside the animal gut. This method has the potential to be applied for preventing the presence of antibiotics in livestock manure (Syafiuddin and Boopathy, 2021).

2.2. Digestate from agricultural and municipal organic wastes

The characteristics of food-based digestate depend on the type of feedstock. For example, vegetables produce less N than mixed food wastes (Nicholson et al., 2017); however, this digestate has a higher N content and also yields a greater methane production than that which comes from animal excrement (e.g., cattle, and pigs), resulting in a higher potential of N losses into the environment. The N content, together with the high pH of the food-based digestate, leads to greater losses of N after its application on both fields, and pastures via (NH_3) volatilization, which is influenced by the application time (season) (Nicholson et al., 2017). Although studies about nitrous oxide (N_2O) emissions from municipal wastewater (Czepiel et al., 1995) and poultry manure digestate have been reported (Posmanik et al., 2017). Nitrogen air emissions as N_2O after applying compost and food-based digestate in agricultural lands have not been studied yet (Nicholson et al., 2017).

While AD of biomass with low fiber content produces a small amount of digestate (Negri et al., 2016), AD of biomass containing high fiber quantity (e.g., wheat straw) produces a lower water content digestate (Luste et al., 2012). Also, soil application of digestate from the AD of crops wastes, such as paddy, wheat, maize, barley, triticale, and other energy crops could enhance soil quality. Because crops are lignocellu-losic material with a complex structure, they are resistant to biodegradation (Zhong et al., 2011), and their digestate contains semi-degraded organic matter which has residual nutrients that are useful as soil conditioners (Lansing et al., 2010; Zacharof et al., 2015). If crops are pre-treated with chemicals to solubilize the lignin, more biogas is produced (Nizami et al., 2010; Sukhesh and Rao, 2018), but the fertilizer value of the digestate is reduced (Taherdanak and Zilouei, 2014). Despite this, wheat straw pretreated with 6% potassium hydroxide (KOH) produces digestate that is rich in calcium, magnesium, and potassium, and this is an excellent soil conditioner (Jaffar et al., 2016). Also, digestate from maize silage has been characterized and used as fertilizer (Provenzano et al., 2018; Reza et al., 2014).

Recently, it has been assessed that the pretreatment of wheat straw with liquid digestate can enhance biogas production (Liu et al., 2019). This finding agrees with a study conducted about recirculation of the crop digestate in its system, which states that using liquid digestate improves methanogenic population, increases pH, nutrients, and moisture content, and reduces the lag phase time for starting the AD process (Sukhesh and Rao, 2018). Moreover, in addition to recirculating the liquid fraction of the digestate as a way of returning the active biological media to the system to avoid washout, this practice improves system mixing, facilitates the removal of gas-phase products, and minimizes some AD process performance issues like biomass flotation, gas clogging, foaming, and stratification. Another beneficial characteristic of crop digestate is its high concentrations of biologically available potassium (K) that enhance the quality of agricultural products, the physical properties of the soil, and the disease resistance of plants (Römheld and Kirkby, 2010).

A review of the physical, chemical, and bromatological characteristics of the organic fraction of municipal solid waste (OFMSW) has been conducted, considering 43 cities in 22 countries. The production of methane and the quality of digestate produced not only depend on the characteristics of OFMSW but also the process condition of the AD (Campuzano and González-Martínez, 2016). Campuzano and Gonález-Martínez (2016) states that the composition of OFMSW and its relative methane production varies nationally, depending on geographic regions, and their social conditions, different cultures, food habits, seasons, and collecting strategies. Moreover, OFMSW is not defined equally in all the world, for example in European Union (EU) it is defined as a mixture of wastes from parks, gardens, and kitchens, while in the United States as a mixture of food, garden wastes, and paper. Due to the possible presence of unwanted harmful substances in the municipal organic waste, its digestate cannot be applied as fertilizer on crop soil when the separation of waste is mechanical, according to European law (The European Parliament and the Council of the European Union, 2019).

Also, wastes containing high carbohydrates provide the lowest methane production while the highest level of methane was produced from waste rich in fat, and oils (Alibardi and Cossu, 2015). The AD of municipal organic waste is a sustainable alternative to landfilling and incineration in the management of waste, production of energy, and fertilizing needs, thus turning OFMSW recyclable. The management of digestate produced by OFMSW AD, its use as fertilizer or soil improver, and its characteristics are summarized in a recent review (Logan and Visvanathan, 2019). This OFMSW presents a weakly alkaline pH (8.30) and conserves the mass content of macronutrients (N, P, K, Ca, S, and Mg), and micronutrients (B, Cl, Mn, Fe, Zn, Cu, Mo, and Ni) already detected in the feedstock, successively converted in other chemical forms during AD. 60% to 80% of the total nitrogen content in the sludge is represented by ammonia, and the percentage of carbon that is not degraded in AD stabilizes the organic material in the soil where this digestate is applied. Moreover, the liquid fraction of the sludge contains 35% to 45% of the total phosphorus (55% to 65% remains in a solid fraction of the digestate) (Logan and Visvanathan, 2019). For example, municipal organic waste has lower volatile solids (VS), higher levels of total N, and total P, higher Pb, Ni, Cr, and Hg concentrations (Beggio et al., 2019). Although inorganic contaminants and heavy metals can threaten the quality of OFMSW, proper segregation of the organic fraction of municipal waste can reduce the number of impurities to a level approved by legislation or their complete removal.

2.3. Digestate from mixed feedstock

Co-digestion of different feedstocks is one of the measures to improve stability during long-term, continuous AD reactions. Even though most operations digest a single type of material, the co-digestion of animal manure with other organic wastes is becoming more popular, because there is synergy between the feedstocks that produce more biogas, with a higher percentage of methane than manure alone (Al Seadi and Lukehurst, 2012; Li et al., 2017).

This synergistic effect depends on the co-substrate ratios; however, if the mixing ratio is far from an optimal value, the co-digestion may result in an antagonistic effect. The optimal co-substrate ratio is determined experimentally in the laboratory or by modeling and simulation. Some comprehensive studies summarized in Table 1 describe co-digestion studies, which can provide crucial data in terms of co-substrate ratio, digestion technology, and process operating conditions. Also, a representative experimental study for determining optimal operating conditions of co-digestion processes for mixed feedstocks (e.g., food waste with dairy manure) is described by Masih-Das and Tao (2018).

Recent studies have been focused on the co-digestion of sewage digestate, and animal manure together with food waste, energy crops, agricultural residues, and microalgae (Begum et al., 2020; Koch et al., 2016; Li et al., 2017). Studies on co-digestion of animal manure with food waste or crop residues have also been published (Bres et al., 2018). Animal manure has been the most commonly used co-substrate for food waste digestion (Komilis et al., 2017). For example, cheese whey, food waste, and slaughterhouse wastes have been mixed with municipal solid wastes, and animal manure (Rico et al., 2015), and animal manure has been combined with straw, cheese whey, and, olive wastes and citrus pulp (Muscolo et al., 2017). Co-digestion of agricultural, vegetable, and animal waste is beneficial to the environment, even in cases where their stabilization and treatment have been carried out before applying it to the soil. Because it reduces their pollution impact effect (air, soil, and water releases) and transforms their chemical composition so that they are assimilable by the plants (Nayal et al., 2016). The characteristics of the digestate resulting from co-digestion depend on the quality of the various kinds of feedstock and the energy balance is also variable (Morero et al., 2017); hence, the application of digestate produced by co-digestion should be evaluated case-by-case.

3. Digestate processing and products

Numerous methods have been suggested for processing digestate for its safer use (Ma et al., 2018; Zubair et al., 2020). The required processing depends on the physicochemical characteristics of the digestate, which will determine its final use as well. These approaches include biological (i.e., bioremediation), physical (e.g., screening, flotation, settling), and chemical (e.g., oxidation processes (Wacławek et al., 2016)). However, some of these processes are expensive due to their high energy requirements, low material efficiency, and early development stages (Herbes et al., 2020; Yola et al., 2016). Chemical processes for digestate improvement have difficulty in recovering and reusing chemical reagents or additives used in the process (Tyagi and Lo, 2013). A promising way to convert the waste effluent digestate into a fluid rich in nutrients, and valuable products, but free of pollutant particles, is membrane filtration (Zacharof and Lovitt, 2014). This liquid–solid phase separation process enables using the aqueous phase rich in dissolved organic nutrients as growing media of microbes, algae, and plants. The remaining less nutritious solid phase can be used as an organic soil amendment (Silkina et al., 2017). Table 2 shows a summary list of the most relevant and promising technologies for digestate processing. Sustainable physical treatments that only require low inputs of energy include dilution, sedimentation, and pressurized membrane filtration. Even if some of these physical processing options are still at early research and development stages, they represent potential economic options, since they are easy to apply, and do not require phase changes or chemical additives (Silkina et al., 2017). With membrane technologies, particles can be separated depending on their sizes and using a wide range of membrane pore sizes (i.e., microfiltration, ultrafiltration, nanofiltration, reverse osmosis) clarify the liquid fraction of the digestate (Gerardo et al., 2015; Zacharof et al., 2016; Zacharof et al., 2015). Even nutrient content can be adjusted, and pathogenic bacteria and viruses can be removed, depending on the pore size, and in combination with leaching and acidification steps (Silkina et al., 2017). The resulting effluent is a more sustainable fertilizer than those produced via synthetic media, considering the sustainability principles of "reducing, reusing, and recycling." It is important to point out that these technologies allow the productive recycling of material without (o minimum) needs for synthesizing new chemical materials/substances (Banzato, 2018).

In general, these summarized processes help prevent and mitigate potential environmental impacts caused by nutrient pollution, such as eutrophication, soil toxicity, HABs, microbial contamination, among other factors. Therefore, digestate post-processing enables the sustainable use of the digestate value-added products in agricultural practices. Likewise, the sustainable management of digestate allows a circular economy of nutrients by substituting the use of chemical fertilizers and minimizing the uncontrolled disposal of organic waste in landfills or directly into the environment (Jurgutis et al., 2021). These improved technological developments can be associated with increased revenues, a lower environmental burden, as well as social benefits. However, it does not imply that positive environmental effects depend solely on technological approaches. Instead, other key aspects like supply chain management, life cycle assessment, government regulations/incentives, and receptor system properties (agricultural systems) must be included when performing a holistic evaluation of such sustainable benefits. Some recent publications demonstrate how a coordinated market for organic waste management, material/energy recovery, techno-economic assessments, and geo-spatial nutrient pollution vulnerability and balance can be combined to develop sustainable management of organic waste for minimizing nutrient pollution impacts in soil and water for an entire region (Hu et al., 2019; Sampat et al., 2018). For instance, the Great Lakes area is a region with intensive farming, livestock facilities, and is affected by nutrient pollution. Therefore, a sustainable management of nutrients can provide a holistic solution to eliminate and minimize environmental impacts and simultaneously achieving economic and social benefits (Martín-Hernández et al., 2021a, 2022).

Fig. 1 shows a comprehensive diversion map for the sustainable management of organic waste and the recovery of energy and value-added materials. Some of these materials and energy products include biogas, nutrients for crop fertilization, chemical products, the food industry, and transportation fuels (Martín-Hernández et al., 2021b; Sampat et al., 2018). From left to right, it is noticeable that primary transformation processes need lower capital and operative expenditures (CAPEX and OPEX). However, the obtained products provide low revenues and environmental benefits. The second and third transformative process stages dramatically increase the options for commercialization, generate more revenue, enhance eligibility for receiving higher economic incentives, and help to maximize some environmental and social benefits. Despite the additional CAPEX and OPEX, these processes avoid economic impacts due to nutrient pollution ecosystem effects like HABs of up to 74.5 USD/kg of released phosphorus (Sampat et al., 2021). However, due to early research and development stages for these novel syntheses, routes, and processes. CAPEX and OPEX values increase dramatically, and there is high uncertainty and variability of potential economic benefits.

4. Digestate product quality standards and -applications.

The feedstock used for the digestion process influences the AD digestate. Therefore, it is crucial to characterize and determine the feedstock's quality, impurities, and microbiological and pathogen content. Knowing these quality aspects aid in estimating the best potential technology routes to maximize economic benefits (recovered products) and the optimal management of the remaining materials to minimize their EoL environmental and human health impacts. Also, some feedstocks containing toxic chemicals like heavy metals, per- and poly-fluoroalkyl substances (PFAS), and pesticides need extra management since, without proper treatment, these substances remain after the AD process. Thus, causing human health and environmental risks and affecting processing performance, product quality, and energy recovery capacity. Therefore, the feedstock digestate quality and its characterization can be used to shape policies, incentives, ensure safety for digestate use and management. In this way, it is possible to support current and new commercial initiatives to make the most economical and environmentally friendly use of it as a fertilizer substitute and obtain some value-added products. These initiatives will increase the economic profitability of AD processes for current energy recovery purposes. The European end-of-waste criteria for compost and digestate is a comprehensive analysis of the economic, environmental, and legal impacts to support a change of material categorization from waste to upcycled material by processing, grading, and recycling (Saveyn and Eder, 2014). Also, this analysis demonstrates under which reference of threshold standards and specifications for digestate quality, the use of upcycled digestate provides a high level of environmental, health, and safety protection, together with environmental, social, and economic benefits. These unified criteria constitute a good foundation to standardize the regulations and certifications of the sustainable use of digestate in the future.

Countries like Denmark, Germany, Austria, Netherlands, Canada, USA, Switzerland, and the UK, have adopted national regulations on the quality and uses of raw digestate (Al Seadi and Lukehurst, 2012; Logan and Visvanathan, 2019). For example, SPCR 120 in Sweden establishes the limit levels of Cd, Pb, Hg, Ni, Zn, Cu, and Cr in 1, 100, 1, 50, 800, 600, and

100 mg × kg^{-1} DM (dry matter) respectively. While BSI-PAS-110: 2010 (British Standards Institution Publicly Available Specification 110: 2010) in the UK, the limit levels of Hg, Ni, and Cr are equal to the Sweden Regulations; however, Cd, Pb, Zn, and Cu changed up to 1.5, 200, 400 and 200 (mg × kg^{-1} DM). In addition, this BSI-PAS-110: 2010 standard sets the limits of the microbiological parameters of digestate, *E. coli* 1,000 CFU (colony-forming unit) g^{-1} fresh matter, and *Salmonella* spp. absent in 25 g of fresh matter. Other parameters that are monitored to assess the quality of digestate include pH, nutrient content, the content of dry organic matter, homogeneity, the concentration of chemical pollutants (heavy metals, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, pesticides, crop protection products, and disinfectants), and pathogens. Germany and UK standards, respectively the Bundesgütesgemeinschaft Kompost and British Standards Institutions PAS 110:2010, define when AD digestate is considered no longer a waste but a safe, trusted product to apply to land (Edwards et al., 2015).

In the case of the USA, the National Organic Program (NOP) develops the rules and regulations for the production, handling, and labeling of organic products, defining guidelines for “Processed animal manures in organic crop production” (USDA, 2011) and “Materials for organic crop production” (USDA, 2016). The NOP is based on U.S. law, Code of Federal Regulations (CFR) specifically on the “Soil fertility and crop nutrient management practice standard” (US Government Publishing Office, 2011). Anaerobic digesters must meet local, state, and federal regulatory and permitting requirements for air, solid waste, and water according to the United States Environmental Protection Agency (US EPA). These requirements vary by location and are frequently changing (USDA, 2020). Similarly, in Australia, regulations are set individually by states (Edwards et al., 2015). There are many European QA Quality assurance systems for compost usage as fertilizer (Saveyn and Eder, 2014). However, digestate for fertilizer applications does not have the same level of certification, which indicates research and development needs and opportunities for supporting commercializing digestate products as a high-quality and safer fertilizer. These findings will allow government entities to incorporate digestate use regulations based on scientific evidence. At the same time, industry-led voluntary quality certification schemes are needed to make digestate more valuable when beneficially used. For example, the American Biogas Council’s Digestate Standard Testing and Certification Program (American Biogas Council, 2017) is an industry-led voluntary program describing the testing methods and quality management system for characterizing digestate products and their use as fertilizer. The program describes the physical and agronomic properties of digestate products.

These quality assurance standards aim to incentivize the digestates reuse, mainly as a commercial fertilizer that can replace conventional chemical fertilizers, thereby incentivizing the recycling of nutrients and organic matter, increasing the revenue of farmers, and lowering costs for fertilizing crops. However, current challenges are preserving the soil for agricultural applications and simultaneously protecting and improving the environment and ecosystem services (Saveyn and Eder, 2014). Also, since AD reduces the abundance of pathogens, it contributes to the safest applications of digestate for crop cultivation. However, it is important to use decontaminated AD feedstocks because AD is not able to completely degrade all types of pollutants. For this reason, countries usually have a list of acceptable and unacceptable feedstocks for AD processes. The following compounds have been studied as disturbance and inhibitory components of AD: pesticides, antibiotics, detergents, salts, food additives, silica gel, sand, plastic or metal packaging material, metal refining waste, and batteries that contain heavy metals (Steffen et al., 1998). In the EU, Council Regulation 1069/2009 assesses the conditions and categories of wastes that are allowed to be used as AD feedstocks (Al Seadi and Lukehurst, 2012). Not only must the quality of AD feedstocks and their preparation be controlled, but it is also fundamental to check all the steps of digestion and digestate processing, storage, and application. In many cases, pre-sanitation of feedstocks is necessary to prevent contamination of the final digestate, even though most pathogens and viruses are killed during mesophilic and thermophilic digestion (Bendixen, 1994).

The AD process has a sanitation effect by inactivating most pathogens present in the feedstock mixture inside the digester. If the survival of pathogens in the digestate is verified, it is recommended a post-processing digestate sanitation (e.g., pasteurization, pressure sterilization, etc.) (Al Seadi and Lukehurst, 2012). In this sense, controls, good practices, and prevention must be carried out during every phase, and precaution must be taken to prevent recontamination and re-growth of pathogenic bacteria after sanitation (Bagge et al., 2005). Practices such as increasing the digestion temperature (thermophilic process) and more extensive hydraulic retention time (HRT) are used to help reduce pathogens to tolerable levels (Alfa et al., 2014). Also, vacuum thermal stripping has been recently implemented for the recovery of ammonia (NH_3) and other volatile organic compounds (VOCs) from the digestate as valuable feedstocks that can be used for the synthesis of chemical fertilizer and to prevent potential releases of hazardous air pollutants and GHGs after AD (Tao et al., 2018; Ukwuani and Tao, 2016).

The concentration of Na and other ions such as Cl can induce detrimental effects on the soil, the plant, or both. Therefore, an important parameter to control is the concentration of Na in the digestate. When applied to fields, the high concentration Na digestate can inhibit the hydraulic conductivity of the soil, inducing soil hardening and a reduction in aeration (Castro et al., 2017). The effect on the soil’s physical properties is measured through the sodium adsorption ratio (SAR), which refers to the concentration of monovalent cations (mainly Na) to divalent cations (Ca, Mg) in the water-soluble extract of the soil. SAR indicates the probability of degradation of the soil structure (Turner et al., 2010). This is a potential risk of detrimental harm to land that continuously receives digestate application and particularly for soil with high sodicity (Pawlett and Tibbett, 2015). According to (Summer et al., 1998), soil with a SAR > 13, and an electrical conductivity > 4 dS m^{-1} is considered saline-sodic, which restricts plant growth that is not resistant to these conditions.

By contrast, the presence of macromolecules (proteins, carbohydrates, lipids) and volatile fatty acids (VFA)s in the digestate indicates that AD occurred successfully (Castro et al., 2017). Also, these organic substances are the immediately decomposed fraction by microbial mineralization for plants and food sources for soil microorganisms. Hence, digestate land application can prevent a negative priming effect on organic matter mineralization (Fontaine et al., 2003). Therefore, digestate composition quality assurance is not only essential for safety, but also the improvement of AD technologies and uses, so that farmers, politicians, food industries, and the public may perceive digestate as a safe and advantageous fertilizer product.

As discussed, digestate composition is conditioned by several factors, like the feedstock composition and the feed ratio, the type of digester, digester operating conditions, pH, nutrient content, impurities concentration, etc. Table 3 summarizes the main physical–chemical properties and aggregated parameters for digestate characterization. Properties like total solids (TS), VS, total organic carbon (TOC), nutrient content (N, P, and K), pathogens, and other compounds such as metals obtained from different digestate substrates and digester processes are presented based on a dry solid (DS) assessment. Please note these results differ in substrate composition and substrate dilution in water. For example, a tubular digester gives less N, P, and K content than a fixed dome or a complete mixture digester since, in the tubular digester, the manure/water ratio is diluted (1:3). Finally, there are other parameters such as the type of technology (mesophilic, thermophilic, stirred, etc.), retention time, among others that make it difficult to standardize the results. The quality of the digestate must be standardized and the tests regulated as they exist in other products (sugar, biogas, etc.). In a general sense, the data shown in Table 3 are reported on a dry basis for comparing the resulting digestate quality. However, variations in the feedstock composition, feed rate, and technology operating conditions need to be studied to determine the optimal input and operating conditions to maximize the quality and production rate of the produced digestate.

4.1. Digestate as fertilizer

Digestate has the potential to be utilized as an efficient biofertilizer for crop production, thanks to its content of nitrogen-fixing and phosphate solubilizing organisms (Owamah et al., 2014; Zacharof et al., 2015). Also, it can be produced anywhere via the anaerobic digestion of organic waste (Bernard and Gray, 2000; Rigby and Smith, 2013; Zeng et al., 2012). For its sustainable use as fertilizer, quality must be controlled in all phases of the AD cycle: from the feedstock to the fertilizer production and use phases. Therefore, assessing the potential of using digestate as a fertilizer requires investigation to determine its agronomic properties, quality performance, efficiency, and health and safety risks via experiments with crops (Haraldsen et al., 2011). Recent studies have investigated the effects of repeated applications (during two years and three fertilizing cycles per year) of anaerobic digestate on soil microbial communities (Coelho et al., 2020).

Digestate is used as a soil amendment and slow-release fertilizer through gradual microbial mineralization (Müller-Stöver et al., 2016), improves soil quality and increases crop yields (Monlau et al., 2016). For example, it has been reported that applications of digestate from the AD of crop residues increase crop production yield between 15% and 28% (Lopedota et al., 2013; Möller and Müller, 2012). Also, life cycle analysis studies have shown positive results in plants fertilized with digestate from other agricultural waste (Krzyżaniak et al., 2018; Stoknes et al., 2016). Table 4 shows some results of digestate research in different crops. The application of different types of digestate tends to have a positive effect on crops as some studies report an increase of yield up to 50% in comparison with experiments without fertilization, with compost, vermicompost, cattle manure control, and mineral fertilization. Additionally, reports of Altiplano Bolivian farmers have mentioned that digestate can be used to protect the crops from freezing and that the foliar application of digestate in quinoa, potato, and onion crops prevented up to 60% of the plant's losses (Martí-Herrero et al., 2014).

4.2. Alternative uses for digestate

Table 5 summarizes the findings of alternative uses of digestate. In addition to agricultural fertilizer, digestate has other uses. One interesting application is the feeding of microalgae within aquaculture for phytoremediation and generation of specialized chemical products (Fig. 1 Route 1) (Uggetti et al., 2014). In such systems, digestate is characterized chemically, pre-treated, and then fed to algae cultivated in aerobic tanks. The use of digestate as a substrate for algae mass production increased biomass growth and the production of protein, fatty acids, carbohydrates, and vitamins up to 50% higher over standard substrate medium (Usharani, 2012). If the algal products are for human consumption, heavy metal contaminants, such as cadmium, must be analyzed (Hultberg et al., 2017). Algae can also be used in a closed-loop system, in which digestate feeds the microalgae that feed the biogas digester. Although there are some current design and operating obstacles in the implementation of these approaches (Lavrič et al., 2017).

Digestate has been valorized as an additive to animal feed (chicken, pig, fish, and shrimp) in some countries (e.g., China) (Logan and Visvanathan, 2019). Although, this application is limited by national legislation and public acceptance. It has been used as growth media for other microbes by taking advantage of the abundant nutrients found in it (Kougias et al., 2017). In particular, solid-state fermentation (SSF) enables microorganism growth on solid surfaces, and it is a valuable alternative for digestate valorization, allowing its conversion into bio-products such as biofuels (Teater et al., 2011; Uggetti et al., 2014), biosurfactants (Cerda et al., 2019; Montoneri, 2017), fragrances, and hydrolytic enzymes. Interestingly, digestate has been valorized as a biopesticide, undergoing SSF with the inoculum of *Bacillus thuringiensis* (Bt) (Rodríguez et al., 2019). Its application could be an alternative to chemical pesticides. Even if the main challenges of SSF processes are upscaling, and reactor design, it has been demonstrated that the production of biopesticide starting from digestate is feasible at different scales, and under different operational conditions. However, more research and development efforts are needed to create commercial-scale chemical processes.

An alternative application for digestate is the bioremediation of petroleum contaminated soils. Since the bacteria contained in digestate can degrade diesel hydrocarbons, they may serve as inoculum, and nutrient source for bioremediation (Gielnik et al., 2019). Another promising option for digestate is its utilization for fine chemical production (Fig. 1 Route 2). Several studies (Montoneri, 2017) demonstrated that MSW digestate has chemical composition similarities with humic substances given the presence of aliphatic, aromatic C, acidic, and basic functional groups; therefore, this is a readily available, cost-effective source of soluble organic substances. Furthermore, VFA's can be extracted from digestate, via a hydrolytic-acidogenic fermentation process and thermal treatment (Lü et al., 2021). They have high potential to be applied in chemical, pharmaceutical, and food industries (Fig. 1 Route 1), in bioplastics, biohydrogen, chemical compounds (Wu et al., 2021), and electricity production, apart from being a source of renewable carbon (Logan and Visvanathan, 2019; Lü et al., 2021; Xie et al., 2021).

Digestate as raw material has been used in processes such as the production of electricity (Martinez and Di Lorenzo, 2019), and ethanol (Sambusiti et al., 2016), among others (Fig. 1 Route 3). The digestate has been utilized for energy recovery or directly as a fuel. Agricultural digestate is more suitable for fuel purposes, in comparison to wet MSW digestate (Pawlak-Kruczek et al., 2020). Pellets (water content 9.2–9.9%) elaborated from digestate showed calorific value above 15.0 MJ kg^{-1}, similar to the calorific value of pinewood with a water content of 12% (Kratzeisen et al., 2010) (Fig. 1 Route 4). Digestate has also been pyrolyzed for the production of biochar with positive LCA results for other waste management processes such as incineration (Mohammadi et al., 2019). Pyrolysis of digestate represents a promising source of bio-oil as fuel, that could be suitable for engine applications. Both the catalytic pyrolysis and the molten alkali carbonate pyrolysis of digestate's lignin provides phenol, and high-yielding phenolic compounds (Wei et al., 2018) (Fig. 1 Route 3 - Route 1). Additionally, bio-oil can be produced by microwave-assisted direct liquefaction of solid digestate (Barbanera et al., 2018). Other recent studies report the application of microwave-assisted processes for energy recovery. It focuses on grass silage digestate processed with microwave hydrothermal treatment to recover energy from high-quality hydrochar formation (Cao et al., 2021; Deng et al., 2020) (Fig. 1 Route 1).

A recent innovative approach (Martinez and Di Lorenzo, 2019) is the use of fresh untreated digestate in a floating microbial fuel cell (MFC) system to obtain bioelectricity. In this novel design, the digestate is used as a fuel, electrolyte, and bacteria source at the same time, with an immerged anode, and a cathode floating onto its surface. Neither external bacterial inoculum, carbon source, membranes, and oxidation–reduction metal catalysts are needed (Fig. 1 Route 5).

In addition, the solid fraction of digestate can be used as bedding material for livestock, as a material for particleboard manufacture (Teater et al., 2011), or energy recovery through fermentation of bio-ethanol with a yield of 37 g kg^{-1} TS (Sambusiti et al., 2016). This thermal energy is sufficient to cover the energy needs for the solid-digestate drying, before the mechanical processing, and it can be used to reduce the electric energy requirement for the milling step in the bio-digesters plant.

Moreover, liquid digestate has been reused in AD facilities to carry new animal manure, thus reducing water consumption. This digestate must be applied carefully since the continuous recirculation could cause an accumulation of substances that may decrease biogas production (Wu et al., 2016).

5. Digestate economic and environmental challenges

There is little information reported in the literature on the determination of the digestate economic value. A recent study (Czekała et al., 2020) performed on three selected agricultural biogas plants in Poland, analyses the economic balance of a biogas plant considering the income resulting from the sale of digestate based on the market prices of fertilizers (N, P, and K content). Results showed that the estimated value of the digestate was several dozen times lower than the selected mineral fertilizers, because of the high hydration of digestate. In the study, the researchers predicted the daily income for a biogas plant with installation power of 1 MW is €1,414, and the digestate produced value is €334.4. This result shows that proper management of digestate per year is a source of profit that improves the economic balance of the plant. In Europe, the bulk digestate selling price is usually lower than its production cost (€5/ton − €30/ton); but it can drastically increase to €150–250/ton if sold to retail as dry pelletized digestate in small bags (Saveyn and Eder, 2014).

Some common challenges for the sustainable development of technologies that transform digestate into valuable materials are: the organic matter is not completely biodegraded, the presence of certain complex organic pollutants (e.g., herbicides, fungicides, industrial wastes, hormones (Shargil et al., 2015)), and the excessive concentration of salts, and pathogenic bacteria (Fecal coliforms $3.60 \times 10^4 – 1.0^6 \times 106$ CFU g^{-1} TS). Also, data on organic pollutants and other compounds are scarce, and variable, because of the feedstock composition heterogeneity, and the type of digestion process. Also, another crucial challenge is the wide variety of possible superstructure combinations (feedstocks, process technologies, operating conditions, valuable products, impurities). Therefore, it would need the application of multiple criteria decision-making techniques (e.g., multi-objective optimization) before drawing general conclusions. Moreover, digestate has a high-water content, which makes its storage and transportation expensive (Boulamanti et al., 2013; Herbes et al., 2020; Silkina et al., 2017). AD plants treating municipal bio-waste (MBW) are often far from agricultural land where it is applied (Babson et al., 2013). For this reason, any improvements in the separation of solids and liquids would be beneficial (Al Seadi and Lukehurst, 2012). Dewatering digestate to reduce its volume and concentrate its nutrients would increase efficiency and profitability. For example, before dewatering procedures, liquid digestate from food waste represents 79% of the total mass of feedstock, but after these procedures are applied, the fertilizer product concentrate represents just 16% of the feedstock’s initial mass (Tampio et al., 2016).

Because digestate might contain materials toxic to humans, living organisms, and ecosystems, its disposal is problematic (Jomova and Valko, 2011; Silkina et al., 2017). Also, exposure limits are becoming a matter of more stringent regulations (Gerardo et al., 2013). Digestate might contain heavy metals (Cd, Pb, Hg, Ni, Zn, Cu, and Cr), persistent organic pollutants (POPs), like polychlorinated biphenyls (PCBs), unintentional products from industrial processes like dioxins (e.g. polychlorinated dibenzodioxins (PCDD)), and furans (e.g. polychlorinated dibenzofurans (PCDF)), products of incomplete combustion such as polycyclic aromatic hydrocarbons (PAHs), plasticizers (e.g. phthalates), flame retardants (e.g. polybrominated diphenyl ethers (PBDE)), medicines, personal care products, persistent pesticides (e.g. dichlorodiphenyltrichloroethane (DTT), and hexachlorocyclohexane (HCH)), trace amounts of other pesticides, antibiotics, new emerging contaminants, and chemicals used in agriculture.

Digestate must be stored, handled, and processed correctly to minimize and mitigate air releases of pollutants. These air releases include NO_x, NH_3, CH_4, odors (e.g., organic acids, aldehydes, alcohols, carbonyls, esters, amines, sulfides, mercaptans, aromatics, and nitrogen heterocyclic compounds (Zilio et al., 2020)), and aerosols (e.g., NH_4^+, endotoxins, airborne microorganisms (Traversi et al., 2015)). Hence, it might constitute a nuisance and a loss of nutrients. Appropriate storage, handling, and processing practices should be developed to minimize and mitigate air emissions of these pollutants. The amounts of VFA in the digestate are responsible for undesirable odors, which is a measure of the decomposition process (Zhu et al., 1999).

During biogas production, the presence of ammonia as an impurity is a measure that AD was inhibited, which occurs in basic pH environments. Under these pH conditions, CO_2 formation is favored with the consequent decrease in CH_4 production due to the formation of ammonium carbonate (Clare et al., 2010). When the digestate is going to be part of other processes as raw material, its VFAs (and its unpleasant odors) can be eliminated when it is treated again in a two-stage anaerobic process and, in this way, decrease its VFA concentration. Examples of double digestion for digestate stabilization are provided in (Trzcinski and Stuckey, 2011).

Research has demonstrated that digestate produced with a retention time of 127 days still contains a negligible concentration of pathogens (e.g., *E. coli* and *Salmonella*) and minimal odor, in addition to being very stable (Walker et al., 2017). Another undesired phenomenon of AD is, for example, the formation of harmful aromatic hydrocarbons like toluene during the AD of activated sludge. In addition, the sludge may form a solid layer cake at the bottom of the digester that can cause unsuitable mixing, equipment malfunctioning, increase energy consumption, develop membrane fouling, decrease membrane productivity, and require frequent cleaning (Zacharof and Lovitt, 2014).

The potential for AD to reduce GHG emissions has been studied and compared with other types of treatment for Municipal Solid Wastes (MSW) (Møller et al., 2009), farm residues (Massé et al., 2011), and food waste (Walker et al., 2017). In comparison to landfills, the GHG reduction from the AD of MSW varies, because of the different characteristics, and contaminants that could make the latter not admissible for the use as fertilizer (Walker et al., 2017). Food-waste digestate exhibits high-quality functionality as fertilizer, given its low content of potentially toxic elements and GHG emission reductions compared with using the undigested organic material and digestate from other feedstocks (Walker et al., 2017). Therefore, regulated threshold values of chemical, microbiological, and emission parameters in an AD digester should be taken into account during the design of these systems (Wäger-Baumann, 2011). An important step is a secondary treatment of the digestate to reduce the mineralization of organic N (Francavilla et al., 2016).

6. Government incentives for the production, regulation, and use of digestate

Despite all the promising applications for digestate, its actual valorization is dependent on national regulations) and public perception. Often misinformation about the quality and economic-environmental impact of digestate leads to low exploitation of its potential, resulting in an inefficient waste management process. Accordingly, governments are implementing regulations and incentives to promote the use of digestate.

While diversion of organic waste away from landfills is now a goal in Europe, Australia, and many states in the USA, the approaches, and incentives for digestate, and waste management are not the same all over the world. Waste valorization has been encouraged by the EU with directives that aim to reduce biowaste diversion to landfills (1999/31/EC). The EU is updating and issuing regulations, such as the action plan for the circular economy (in 2017), for the promotion of waste recycling across the member states to achieve the objective of 70% of the municipal solid waste (MSW) recycled and 5% of landfilling by 2030. In Australia, there are landfill tipping fees, but there is no legislation to incentivize the process of diverting organic waste from landfills. In contrast, California’s legislation requires municipalities to install AD facilities for organic waste diversion (Clarke, 2018). In some countries regulations about digestate are ambiguous, and in others, the process for reuse is relatively clear (Edwards et al., 2015).

Not only are there directives that incentivize the diversion of organic waste and the use of digestate through a sustainable circular economy. Other economic, legal, and tax incentives for organic waste diversion are proposed at the local, country, and regional levels. Some incentives include landfill tax, demand for organic fertilizer and renewable energy, carbon trading, high fossil fuel taxes, and end-of-waste criteria. Landfill taxes and stringent regulations have a significant correlation with the increase in the number of AD facilities and optimization of the AD process for increasing the production of biogas and digestate (Logan and Visvanathan, 2019).

UK, Germany, and the USA are countries leading these incentive policy programs. For example, in the UK, several government programs and supported entities such as the Waste & Resources Action Program (WRAP) (Waste and Resources Action Programme WRAP, 2020), the AD Quality Protocol (ADQP) of the Environment Agency, and the AD, and Bioresource Association (ADBA) have been created. The WRAP program developed the PAS 110 that aims to encourage the development of the digestate market by creating an industry technical standard for producers to check and ensure that digested materials are of consistent quality and fit for the desired purpose. Also, it sets out the minimum qualifications required for the digestate, separated liquor, and separated fiber which may be used as a fertilizer or soil improver (Pell Frischmann Consultants Ltd, 2012). The ADQP aims to provide increased market confidence in the quality of products made from waste, and so encourage greater recovery and recycling. This protocol is a set of criteria to produce quality digestate from the AD of material that is biodegradable waste, including the whole digestate, the separated fiber fraction, and the separated liquor. Producers and users are not obliged to comply with the quality protocols. If they do not comply, the quality digestate from AD will be waste, and waste management regulations will apply to its handling, transport, and application. The ADQP is currently being reviewed by the UK Environment Agency (UK Environment Agency, 2014). This regulation allows classifying the digestates produced and encouraging producers to improve their quality (UK Environment Agency, 2014). Finally, the ADBA focuses primarily on consulting services for the improvement of the entire life cycle of biogas and digestate generated at an industrial scale.

The German Renewable Energy Act (REA), in its different versions, has provided the legal foundation for the development of the biogas sector in Germany. This law and its regulations have created advantageous conditions (incentives) for the access of biogas to the electricity markets, as well as measures for a safe investment, and financing of biogas plants (Thrän et al., 2020). This is due to the experience, and continuous development of biogas production in Germany (Pfeiffer and Thrän, 2018). Ongoing works are evaluating the impact of this law on the economy, increasing capacity (Scheftelowitz et al., 2018), energy efficiency, and flexible energy supply, as well as the impacts on structural change in agriculture, and investment decisions (Sorda et al., 2013). During its progression, this law has addressed all the elements of the biogas life cycle, and recent versions include incentives and regulations on the use of digestate as fertilizer. The RAE tries to resolve conflicting objectives that may exist between energy and agricultural legislation.

In the USA, the US EPA and the USDA have created specific programs to include the AgSTAR program (EPA-USDA) (US EPA, 2020a) and the Rural Energy for American Program (REAP) (USDA, 2015). The AgSTAR program has developed a set of guides, regulations, information, technologies, and tools to encourage the production of biogas and digestate (US EPA, 2020a; US EPA, 2020b). The USDA's REAP focuses on providing financing to small rural businesses to promote the use of renewable energy that includes the production of biogas (USDA, 2020).

Other governments and financial incentives applied by the US EPA are Renewable Identification Numbers (RIN) under the Renewable Fuel Standard Program (US EPA, 2020c), Renewable Energy Certificates (RECs) (US EPA, 2020d), and Nutrient Credits (Ross, 2012). These incentives promote the reduction of organic waste discharged into the environment and instead use it as a bargaining chip for both producers and consumers. The exchange of these credits applies to both fuels and fertilizers to encourage the use of biofuels and biofertilizers.

The introduction of quality control of digestate has been a crucial point for its reuse and valorization. Regulation, certification, and quality standards of digestate reinforce the confidence of users in applying digestate safely and in a manner that respects health, environment, and legal requirements. Although markets and consumers are accustomed to compost, digestate should be marketed as a biofertilizer and not as compost. Digestate has very different properties from compost. Compost is a long-term soil improver, while digestate is more of a fertilizer. For example, with digestate, most nitrogen is readily available for plant uptake, while compost may offer less than 10% of the nitrogen for plant absorption during the first year of application (Edwards et al., 2015).

Although research on the upgrading of biogas and biomethane production from AD continues to be of interest to the scientific community (Ardolino et al., 2021), the digestate generates increasing interest due to the variety of products that can be obtained (Kumar Khanal et al., 2021). Achieving a better consumer perception and understanding of the value of digestate is the key point to promote the use of digestate in a circular economy and a promising feedstock to produce different products and byproducts and the biorefinery concept could be developed.

7. Conclusions

This contribution analyses the current state of the art regarding potential uses of digestate in terms of product quality, feedstocks, processes, environmental impacts, and techno-economic challenges. The use of digestate as a biofertilizer because of its nutrient content is one of the most promising applications to minimize and avoid direct and indirect impacts on the environment and human health and improve the economic profitability of biogas production systems. Many works demonstrate an increment of plant-available nutrients and crop yields applying digestate. Other uses of digestate include its application as a growth medium for microorganisms of industrial interest.

For achieving sustainable and safe use of digestate, regulations must consider its life-cycle environmental impact, toxic substance content, pathogenic load, and agronomic properties. As evidenced during this contribution, all the analyzed studies concluded that feedstock, processing technology, and process operating conditions highly influence the digestate product characteristics.

Obtaining digestate from different feedstocks must focus on controlling the nutrient content since unbalanced and excessive applications as fertilizer will lead to environmental problems such as eutrophication and harmful algal blooms. There is a current need to develop efficient and cost-effective production-scale technologies for nutrient recovery and removal of undesirable impurities (e.g., hazardous organic substances, heavy metals, PO4-, NH3, emerging contaminants, etc.) to improve and optimize the AD process and digestate quality. Also, the utilization of digestate as a valuable feedstock should contribute to the holistic sustainability of AD systems for energy and material recovery.

Finally, the development and implementation of incentive policies and regulations for the sustainable management of organic waste by AD and producing digestate as a valuable product show that it can be beneficial. Some incentive policies focused on reducing taxes for product commercialization and increasing economic support for product manufacturing. Also, more stringent regulations support diverting organic waste from landfills. However, there are not many quality assurance certification systems for digestate usage as fertilizer and other applications. The absence of standardized testing methods and quality management systems for characterizing digestate products and their use indicates research and development needs and opportunities for supporting commercializing digestate products. These findings will allow government entities to incorporate digestate use regulations based on scientific evidence. At the same time, more industry-led voluntary quality certification schemes will make digestate more valuable when beneficially used. These efforts should describe the physical and chemical properties of digestate products. To conclude, future studies about circular business models and standardized international regulations for digestate products are needed.

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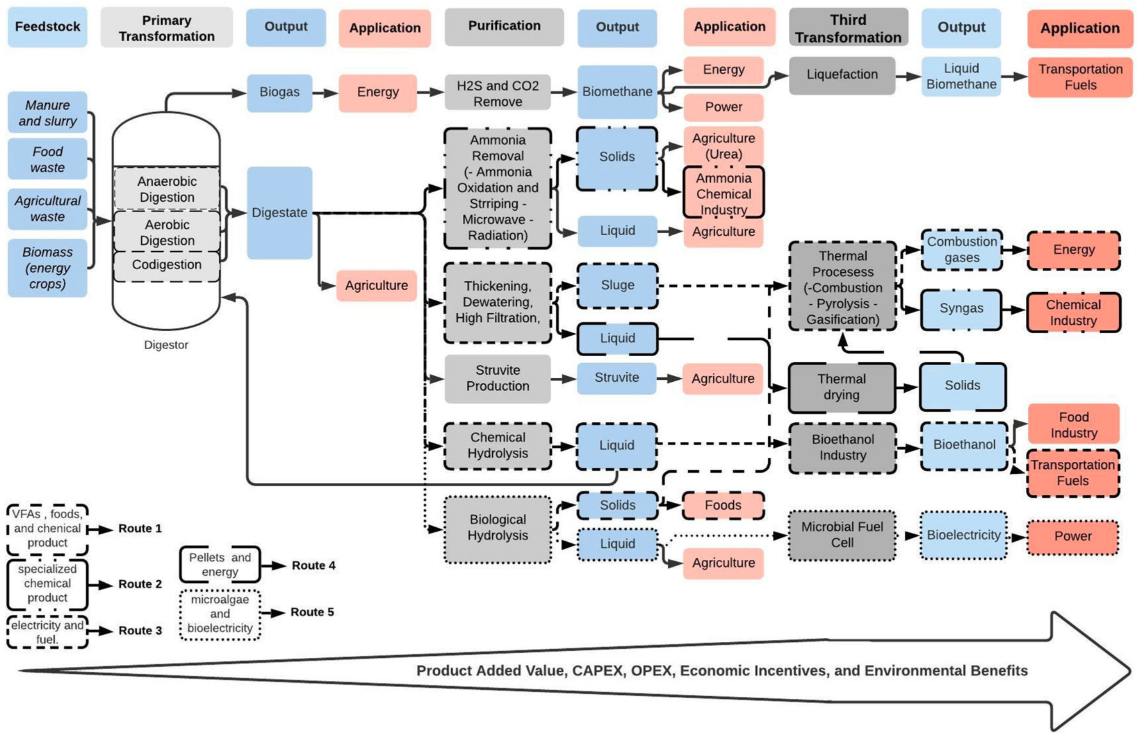

Fig. 1.

A diversion map for the sustainable management of organic waste and the recovery of energy and value-added materials.

Table 1

Summary of digestate studies with mixed feedstock.

Type of mixed feedstocks	Optimum co-substrate ratio	Type of digester	Temp. (°C)	HRT, (day)	Location	Ref.
Dairy manure/ chicken manure/rice straw	42.4%–29.3%–28.3% [a]	Lab scale/ batch digestion	35	30	Yangling, China	(Wang et al., 2013)
Dairy manure, swine manure and rice straw	42.1%–31.6% 26.4% [a]	Lab scale/ batch digestion	35	30	Yangling, China	(Wang et al., 2013)
Chicken manure, swine manure and rice straw	24.9%–41.4%–33.7% [a]	Lab scale/ batch digestion	35	30	Yangling, China	(Wang et al., 2013)
Poultry Manure co-digested with fruit and vegetable waste.	1:1 [a]	Semi-continuous bench scale (19L) stirred tank reactors 2 gVS/L. d (organic load rate)	34.5	28	Argentina	(Bres et al., 2018)
Cattle manure/ onion waste	5:1 [b]	Lab scale/ batch digestion (2 dm^3, manual agitation)	22–25	60	Buenos Aires province, Argentina	(Iocoli et al., 2019)
Poultry litter/ onion waste	5:1 [b]	Lab scale/ batch digestion (2 dm^3, manual agitation)	22–25	60	Buenos Aires province, Argentina	(Iocoli et al., 2019)
Pig slurry/ onion waste	5:1 [b]	Lab scale/ batch digestion (2 dm^3, manual agitation)	22–25	60	Buenos Aires province, Argentina	(Iocoli et al., 2019)
Cheese whey and the screened liquid fraction of dairy manure	15%:85% [c]	Continuous stirred tank reactor (CSTR)	Mesophilic	15.6	Heras, Cantabria, Spain	(Rico et al., 2015),
Animal manures, milk serum, maize silage and in minor amount with olive waste and citrus pulp	60%:20%:20% [c]	Industrial digesters: 7420 m^3	40	60	Reggio Calabria, Italy	(Muscolo et al., 2017).
Olive waste, citrus pulp and animal manure and maize silage	30%:30%:40% [c]	Industrial digesters: 7500 m^3	40	60	Reggio Calabria, Italy	(Muscolo et al., 2017).
Cheese whey/ dairy manure	1:1 [a]	One-stage CSTR	35	42	Villastellone, Turin, Italy	(Comino et al., 2012)
Cheese whey/ Poultry manure	1:1 [c]	One-stage CSTR	35	18	Argos region, Greece	(Gelegenis et al., 2007)

HRT: Hydraulic Retention Time

a: dry weight

b: wet mass

c: wet volume

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Table 2

List of the most relevant and promising technologies for digestate processing.

Processes	Application	Main characteristics	Cons	Stage of development	Cost	Ref
Thickening. Including: gravity settling, filtration, air flotation and centrifugation	Separation of the liquid and solid fractions of the digestate	Digestate is concentrated up to 5–10% of suspended solids	Need other treatment for nutrient recovery efficiency	Full-scale	Low CAPEX & OPEX: 13–50 US $/inhab	(Monfet et al., 2018)
Dewatering. Including: filtration (belt filter press, chamber filter press, vacuum filtration) and centrifugation	Elimination of water and concentration of suspended solids in solid fraction	Solid fraction is dewatered to a solid concentration from 15 to 35%	Need other complementary treatment to obtain greater nutrient recovery efficiency	Full-scale	CAPEX & OPEX: 13–50 US$/inhab	(Chernicharo, 2006)
Membrane filtration. Including: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and forward osmosis (FO)	Removal of suspended solids, microorganisms, macromolecules, and small organic molecules and ions from liquid fraction Permeates are rich in K and N and can be used as green fertilizers	Simple physical process that does not require addition of chemicals. Particles can be separated depending on their sizes. Operation and maintenance costs are lower than for other separation processes	Membrane blocking & scaling High maintenance and power requirements	Full-& lab scale	High CAPEX & OPEX: 4–13 € m^{-3} Depends on mass transfer Similar costs as stripping	(Guo et al., 2012; Masse et al., 2007; Vaneeckhaute et al., 2012)
Struvite precipitation: magnesium ammonium phosphate precipitation	Physicochemical technology that recovers main plant nutrients (80–90 % P, 10–40 % N) from liquid fraction	The precipitate can be used as balanced fertilizer. Precipitation in piping/equipment. Pollution with organic compounds. Stable and controlled production	Salts of magnesium are expensive. Chemical use (NaOH, Mg), Fe/Al use; Landfill; Sludge handling and disposal; Cleaning of struvite deposits	Full-scale	Can be profitable	(Capodaglio et al., 2015; Morales et al., 2013; Vaneeckhaute et al., 2012)
Ammonia stripping: air and steam stripping	Removal of ammonia from liquid fraction. The stripping can be applied directly to digesters, decreasing costs of removal and recovery of ammonia	The stripped ammonia can be recovered and transformed into an ammonium salt which can be valorized in agriculture or chemical industries	It is necessary to increase the pH from 10.8 to 11.5, an adsorption unit and high consumption of energy increasing costs of ammonia removal. Chemical use for cleaning	Full-scale	CAPEX: 0.5–15 € million, OPEX: 4.5–8.6 € m^{-3}, both for 800 m^3 day^{-1} at 2.4 g N m^{-3} (90% recovery). Overall: 2.0–8.1 € m^{-3} for 70 m^3 h^{-1}	(Capodaglio et al., 2015; Serna-Maza et al., 2014)
Ammonia oxidation: ozonation, peroxone oxidation, photocatalytic oxidation, electrochemical and bio-electrochemical	Removal of ammonia from liquid fraction	Oxidation of ammonia into nitrate or diatomic nitrogen	This technology is not applied on a large scale for the treatment of digestate	Lab/Pilot scale	High cost (no data available)	(Ou et al., 2008; Rodríguez Arredondo et al., 2015)
Microwave (MW) radiation and MW stripping	Removal of ammonia from liquid fraction	MW radiation causes the evaporation and stripping of ammonia	This technology is not applied on a large scale for the treatment of digestate	Lab. Scale	Low cost (no data available)	(Lin et al., 2009; Remya and Lin, 2011)

Processes	Application	Main characteristics	Cons	Stage of development	Cost	Ref
Chemical hydrolysis: ozonation and alkaline hydrolysis	Breakage of cells and macromolecules to increase biodegradability of suspended solids and dewaterability of solid fraction. chemical (e.g., oxidation reactions by the addition of persulfates for the sludge treatment	Hydrolyzed digestate can be recycled to digester to increase biogas yield. The alkaline treatment increases the hydrolysis of fibers using enzymes to use sugar in fermentation post treatments	High chemical use requirements	Full-scale	No data available	(Wacławek et al., 2016)
Thermal drying	Elimination of water from dewatered solid fraction using forced convection of heated air	Dried solid fraction can be pelletized to improve its management with the aim to valorize it by thermochemical processes or as a source of animal litter	High energy consumption	Full scale	R&D needed	(Pedrazzi et al., 2015)
Combustion	Energetic valorization of dried solid fraction to produce heat	Dried solid fraction presents a heating value of 14 MJ/kg or highest which, is attractive to produce heat.	Not environmentally sustainable	Full-scale: incinerated sludge; Lab: incinerated digestate, but often not authorized	R&D needed	(Li et al., 2013; Pedrazzi et al., 2015)
Pyrolysis. Including: dry pyrolysis, wet pyrolysis, hydrothermal carbonization (HTC)	Biomass is decomposed in energetic products (biooil, char, and syngas). Biooil can be valorized to extract chemical block molecules (organic acids, aromatics, etc.), char as soil amendment, and syngas to synthesize chemical block molecules (alcohols, alkanes, etc.)	The energetic values of pyrolyzed products are highly competitive: pyrolytic oil is 46 MJ/kg, and gas heating power is 23 MJ/Nm^3, like natural gas	This technology is not applied on a large scale for the treatment of digestate	Lab scale	R&D needed	(Moltó et al., 2013)
Gasification	Thermochemical, Production of syngas which can be valorized as hydrogen for energetic or chemical purposes or to produce chemical block molecules	Gas heating power is 23 MJ/Nm^3, like natural gas. High potential to produce hydrogen from renewable sources	This technology is not applied on a large scale for the treatment of digestate	Lab scale	R&D needed	(Aznar et al., 2009; Moltó et al., 2013)
Ultrasound	Treatment to solubilize organic matter and to increase dewaterability of solid fraction	It has been studied for wastewater sludge treatment and presents high potential to increase dewaterability of digestate	This technology is not applied on a large scale for the treatment of digestate	Lab scale	R&D needed	(Gonze et al., 2003)
Biomass production and harvest	Biological technology, for nutrient recovery of the liquid fraction digestate (84–98 % N, and 90–99 % P)	Reduced light penetration; Dilution often required	Large surface area requirement, and toxic if N > 60 mg L^{-1}	Pilot/Full-scale: duckweed Mostly lab: algae	CAPEX: > 80,000 € ha^{-1} Overall (macrophytes): 12–33 € person equivalents $(PE)^{-1}$ $year^{-1}$ Overall (algae): 4–300 € kg^{-1} dry weight	(Vaneeckhaute et al., 2017)

Note: R&D = Research and Development

Table 3

Physical-chemical properties and aggregated parameters for digestate characterization.

Substrate	Digester technology	TS, %	VS, TS, %	TOC, mgL^{-1}	pH	N-NH4+, mgL^{-1}	P-P2O5, mgL^{-1}	K, mgL^{-1}	Pathogens	Others, Metals, mgL^{-1}	Ref
Guinea pig manure	Tubular biodigester, HRT: 60–75 d	0.70	43.56	139.30	7.10	201.83	188.94	250.9	*E. coli:* 1.70 × 107 MPN mL^{-1} Total Coliforms: 1.70 × 108 MPN mL^{-1}	–	(Garfí et al., 2011)
Food and agricultural waste	Liquid mesophilic anaerobic co- digestate	5.25	–	–	8.2	11.3	6.47	37.6	–	–	(Rigby and Smith, 2013)
Food waste (mixture of bread, cooked meat, fruits, and vegetables)	Liquid co-digestate thermophilic	17.1	–	–	4.4	3.50	3.81	5.44	–	–	(Rigby and Smith, 2013)
Pig manure	Large-scale anaerobic digester, HRT: 15–20 d	10.09	–	901.2	7.49	815.2	112	880.4	–	Zn:20.66 Cu 16.34 As: 0.26	(Jin and Chang, 2011)
Cow manure	Large-scale anaerobic digester, HRT: 15–20 d	10.35	–	1292.5	7.66	674.4	187.4	547.3	–	Zn:17.45 Cu 3.29 As: 0.06	(Jin and Chang, 2011)
Cattle manure	Mesophilic tubular digester, HRT: 35 d	–	–	–	7.47	96	114	158.0	Fecal coliforms 1.06 × 10^6 $CFUg^{-1}$ TS, *Helminth* eggs: 24 HH 4 g^{-1} TS, Absence of *Salmonella* spp.	Na: 390 Mg: 150 Ca: 880 Al: 20	(Castro et al., 2017)
Pig slurry plus animal byproducts	Industrial-scale digester, HRT: 21 d @ 37 °C	1.95	–	115.50	8.2	68.25	3.9	39	–	Na:14.16 Ca:4.25 Mg: 1.31 Zn: 0.68 Cu:0.08	(Alburquerque et al., 2012b)
Cattle slurry plus agroindustry residues	Industrial-scale digester, HRT: 25 d @ 38.5 °C	9.01	–	3036.37	7.5	216.24	72.08	279.31	–	Na: 67.21 Ca: 362.74 Mg: 62.89 Zn: 2.50 Cu: 0.97	(Alburquerque et al., 2012b)
Pig slurry	Mesophilic-thermophilic digester (lagoon type), HRT: 45–55 d	9.8	–	4360.00	8.0	1065	–	–	Total coliform: 240 × 104 CFU g^{-1} TS, Fecal coliforms 3.60 × 104 CFU g_{-1} TS	Pb 7.2 Ca 37 300 Mg 24 266 Cd 3.8 Cr 10.1 Cu 1 796 Ni 16.9	(Pampillón-GonzáLez et al., 2017)
Energy crops, cow manure slurry, and agroindustrial waste	Thermophilic CSTR, HRT: 40 d (digester), 10 d (post-digester)	0.35	75.3	277.86	8.7	79.07	18.83	–	–	–	(Pognani et al., 2009)
Energy crops, cow manure slurry, agroindustry waste, and OFMSW	Thermophilic CSTR HRT: 40 d (digester), 10 d (post-digester)	0.36	68.4	276.34	8.3	75.24	18.47	–	–	–	(Pognani et al., 2009)

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Substrate	Digester technology	TS, %	VS, TS, %	TOC, mgL^{-1}	pH	N-NH4+, mgL^{-1}	P-P2O5, mgL^{-1}	K, mgL^{-1}	Pathogens	Others, Metals, mgL^{-1}	Ref
Beet leaves and other crops waste	Mesophilic batch-fed stirred biodigester	6	–	–	7.4	78	24	252	–	Na: 60 Mg: 24 Zn: 0.3 Cu: 0.06	(Gunnarsson et al., 2011)

Table 4

Obtained crop yields after applying different types of digestate. Although the digestate feedstock influences crops yield, other factors like physicochemical properties of the soil, doses of digestate, and timing influence the efficiency of digestate use as fertilizer.

Substrates Feedstock	Digester technology	HRT	Crop type	Yield	Reference
Guinea pig manure	Low-cost tubular digesters	60 – 75 d	Potato	22.5 t ha^{-1} vs 17.7 t ha^{-1} unamended control	(Garfí et al., 2011)
			Forage	20.5 t ha“1 vs 18.8 t ha^{-1} unamended control	(Garfí et al., 2011)
Farm waste	Biogas slurry	N/A	Sugar cane	71.9 t ha^{-1} vs 76.1 t ha^{-1} conventional fertilizer	(Singh et al., 2007)
Cow/pig manure	Tubular biogas-slurry	N/A	Tobacco, Alfalfa, barley	33%–50% increment in productivity vs unamended control	(Martí-Herrero et al., 2014)
Cattle manure	Biogas slurry	N/A	Wheat	6.21 t ha^{-1} vs 4.40 t ha^{-1} unamended control	(Garg et al., 2005)
Mixture of pig slurry, sludge from a slaughterhouse wastewater treatment plant, and biodiesel wastewaters	Industrial anaerobic co-digestion plant	21 d	Watermelon	47.9 t ha^{-1} vs 42 t ha^{-1} conventional fertilizer	(Alburquerque et al., 2012a)
			Cauliflower	9.8 t ha^{-1} vs 25.6 t ha^{-1} conventional fertilizer	(Alburquerque et al., 2012a)
Beet leaves and another crops waste	Mesophilic batch-fed stirred biodigester	N/A	Red beets	9.1 t ha^{-1} vs 5.94 t ha^{-1} unamended control	(Gunnarsson et al., 2011)

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Table 5

Alternative uses of digestate.

Products	Valorization type	Description	Major concern	Scale	Ref
Fertilizers	Agricultural purposes	Liquid fraction from raw digestate mechanical separation	Relative low nutrient concentration, salinity, pathogens, chemical and organic contaminants	Commercial	(Al Seadi and Lukehurst, 2012; Nkoa, 2014)
		Struvite (magnesium ammonium phosphate, K, and calcium phosphate) obtained from crystallization in raw digestate liquid fraction mainly	Nutrient accessibility can be low especially in alkaline soils. In addition, it could contain heavy metal	Commercial	(Vaneeckhaute et al., 2017; Yetilmezsoy et al., 2017)
		Incineration ashes product of combustion of dried digestate pellets	No nitrogen P-accessibility tends to be poor	N/A	(Christel et al., 2014)
		Microalgae and macrophyte biomass from liquid fraction pre-treated digestate	High operational cost	Pilot	(Uggetti et al., 2014; Xia and Murphy, 2016)
Soil improver	Agricultural purposes	Solid fraction fibers, cake, obtain from raw digestate mechanical separation	It could contain inert material as stones, plastics, glass, and metal parts. Low nutrient concentrations and it is not as stable as compost	Commercial	(Al Seadi and Lukehurst, 2012; Teglia et al., 2010)
		Compost from solid fraction composting digestate	Heavy metal and inert material (stones, plastics, glass, and metal parts) contents	Commercial	(Dahlin et al., 2015; Teglia et al., 2010)
		Vermi-compost from solid fraction digestate	Heavy metals and pathogens contents.	Commercial	(Quintern and Morley, 2017)
		Biochar obtained from pyrolysis of dried digestate pellets	Low nutrient accessibility	Commercial	(Christel et al., 2014)
		Humic-like substances obtain from raw digestate alkaline extraction	R&D needed	Laboratory conditions	(Montoneri, 2017)
Biofuel/ Biomass	Energy	Dried pellets from raw digestate or solid fraction	High ashes content and low calorific value	Pilot/Commercial	(Kratzeisen et al., 2010).
		Bio-ethanol from post-treatment for digestate fermentation	Research needed	Laboratory conditions	(Monlau et al., 2015)
		Bio-oil from pyrolysis of dried digestate pellets.	Removal of tars	Industrial/Pilot	(Balat et al., 2009; Wei et al., 2018)
		Bio-hydrogen from post-treatment for digestate fermentation	Research needed	Laboratory conditions	(Uggetti et al., 2014)
		Bio-diesel from microalgae harvesting and extraction	Research needed	Pilot	(Uggetti et al., 2014)
		Bio-methane from post-treatment for digestate post-digestion or recirculation	Minimum 35% methane in biogas needed for combustion in Stirling engines	Commercial.	(Monlau et al., 2015)
		Syngas from pyrolysis or gasification of the dried pellets	Necessary gas conditioning, especially the removal of tars. Fermentation: low gas solubility	Commercial	(Balat et al., 2009)
Biomaterials	Other industrial	Biopesticide from raw digestate or solid fraction as growing media after inoculation of the *B. thuringiensis*.	Research needed to Solid State Fermentation upscaling process and reactor design	Laboratory conditions	(Rodríguez et al., 2019)

Products	Valorization type	Description	Major concern	Scale	Ref
		Duckweed or microalgae biomass, from phototropic raceway pound with pre-treated liquid fraction	Low protein content	Not clear	(Uggetti et al., 2014; Vaneeckhaute et al., 2017)
		Mushrooms from composting digestate or solid fraction with the addition of bulking material	R&D needed	Not clear	(Stoknes et al., 2016)
		Biochar (raw or activated) from dried pellets pyrolysis or gasification	Biochar commercial production is still mainly	Commercial	(Hagemann et al., 2018; Wu et al., 2017)
		Bioplastics (poly-vinyl alcohol-co-ethylene) obtain from hydrolysis and extraction of organic matter complex soluble of the digestate	R&D needed	Laboratory conditions	(Franzoso et al., 2016)
		Biosurfactants (the glycolipid, sophorolipids) from digestate by using a yeast *(Starmella bombicola)* inoculum under aerated conditions	High operational cost	Laboratory conditions	(Cerda et al., 2019)

Note: R&D = Research and Development.