Chapter 1. Anaerobic digestate management: an introduction

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Abstract

Anaerobic digestion is a key technology in the current transition from a linear to a circular economy. As such, the number of anaerobic digestion plants has increased considerably in the last decade, and it is expected to further increase substantially in the coming years. This, together with the implementation of policies to foster resource recovery, call for the development and implementation of digestate management approaches that allow the recovery of resources contained within digestate (*e.g.*, water, nutrients, carbon, or energy). Traditional techniques such as thermal drying, incineration, composting, or landfilling allow a safe digestate disposal (and in some cases a certain degree of resource recovery). The development of new technologies such as enhanced precipitation, enhanced thermal conversion processes, photoautotrophic biomass production, or enhanced filtration, is opening the door to a more intensive and efficient recovery of resources. To ensure the implementation of these novel technologies, policies favouring their application must be clearly defined, and legal frameworks must be updated. This book presents a comprehensive review of the state-of-the-art of AD digestate management. Traditional and novel resource recovery approaches are addressed, as well as the main technological challenges that these technologies face (*e.g.*, ecotoxicities issues). To give a holistic overview, the current legal framework regarding digestate reutilisation is also assessed, as well as options for process integration and future perspectives.

Keywords

Biogas effluent; digestate; anaerobic digestion; resource recovery; circular economy

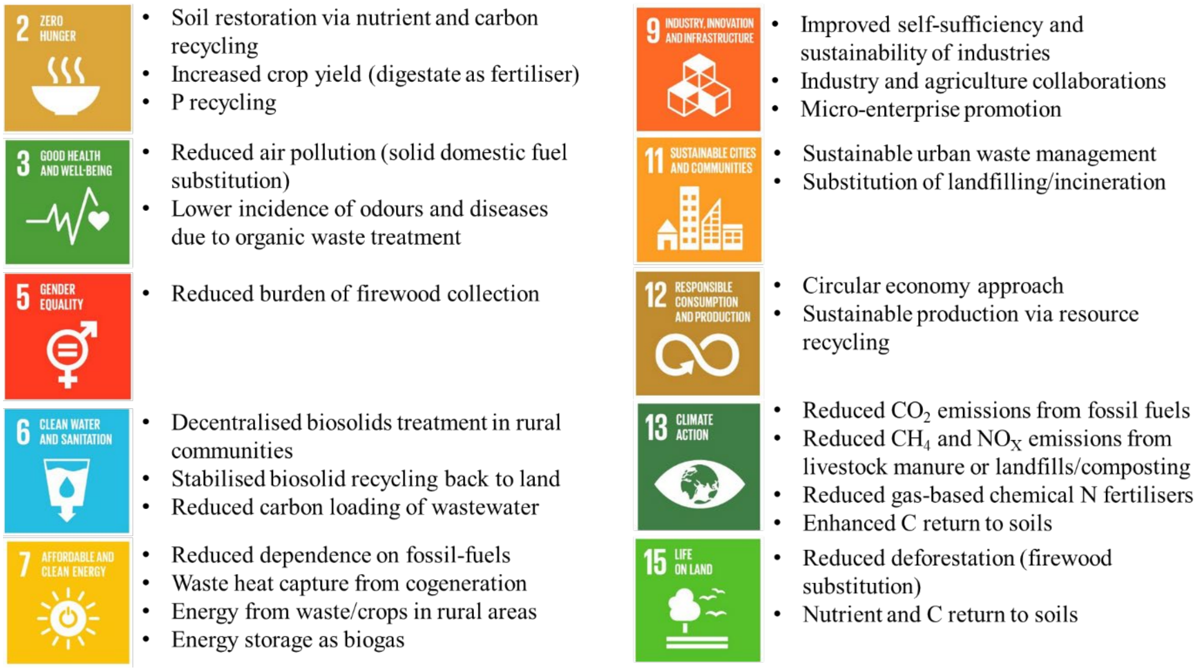
1.1. What is AD, what is digestate?

1.1.1. AD as crucial tech for waste management on a circular economy

Traditional and most current economic systems are based on a linear approach, where resources are extracted from the environment, used to produce goods, distributed, consumed, and eventually disposed as waste when they are no longer useful. This linear resource use is by definition unsustainable. In addition, the unprecedent economic growth that occurred since the industrial revolution has been made possible by the consumption of fossil fuels, which, although incredibly convenient, are non-renewable in a human time scale. The impact of the current linear, fossil-based economy on the global environment has been an increasing concern in the last decades. The most notorious latest example is the first instalment of the Sixth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC). This document states that, if current practices in terms of fossil fuel consumption are continued, the average temperature of the planet will increase over 1.5°C due to the emission of greenhouse gases, which will have considerable impacts on the global climate, affecting both the environment and human populations (IPCC, 2021). Another example of increasing awareness on issues related to an unsustainable economic system are the Sustainable Development Goals (SDGs) of the United Nations (UN), with 9 out of 17 being directly related to the environment or to production systems (UN Environment Management Group, 2021).

With this problematic in mind, a change from a linear towards a circular economy must occur. In the latter, waste as such is minimised, and resources are recovered and recycled, entering again the production-consumption loop. To implement a more sustainable development process, is it also essential to gradually move away from fossil fuels as energy vectors, substituting them by more sustainable (and eventually renewable) energy sources. The US Green New Deal or the European Green Deal are examples of policies that are being implemented worldwide to achieve this goal (European Commission, 2019; House of Representatives, 2019). A main challenge for the implementation of renewable energy sources is the development of efficient, cost-effective energy storage alternatives. At the current technological state, energy storage is mostly carried out using batteries, which is far from being cost-effective and has serious environmental concerns due to the large quantities of non-abundant metals needed. A potential solution for this conundrum is the so-called dual gas-power network (Brémond et al., 2021). In this approach, power from renewable sources would be transformed into high energy density gaseous carriers, such as hydrogen (*e.g.*, via water electrolysis, to be used directly as fuel) or methane (*e.g.*, via hydrogen methanation, to be injected into the gas grid). This integration of the gas and power systems is in the core of the European Green Deal, with the hydrogen and decarbonised gas market package currently being prepared, aiming at updating the energy market, and including the decarbonisation of the production and consumption of hydrogen and methane.

Other than technologies allowing the production of hydrogen, biomethane or syngas from power, processes such as anaerobic digestion (AD) or biomass gasification will also be crucial in the gas-based, sustainable, circular economy described above (Brémond et al., 2021). Opposed to most of these technologies, AD is already a fully commercial technology. AD is an anaerobic biological process offering a triple role: (1) production of biogas (a mixture mostly composed of methane and carbon dioxide), (2) waste treatment and stabilisation, and (3) generation of a nutrient rich digestate (Appels et al., 2011; Capson-Tojo et al., 2016). With over 132,000 small, medium or large-scale digesters operating worldwide (and additional 50 million micro-scale digesters serving homes/small communities), AD is already playing a main role as a technology generating a green fuel and allowing the recovery of resources other than energy (*e.g.*, nutrients such as nitrogen and phosphorus) if digestate is used, for example, as fertiliser (World Biogas Association, 2021). The multiple benefits that AD has to offer become obvious when assessing how AD can help to achieve multiple UN SDGs (see Figure 1.1).



- Soil restoration via nutrient and carbon recycling
- Increased crop yield (digestate as fertiliser)
- P recycling

- Reduced air pollution (solid domestic fuel substitution)
- Lower incidence of odours and diseases due to organic waste treatment

- Reduced burden of firewood collection

- Decentralised biosolids treatment in rural communities
- Stabilised biosolid recycling back to land
- Reduced carbon loading of wastewater

- Reduced dependence on fossil-fuels
- Waste heat capture from cogeneration
- Energy from waste/crops in rural areas
- Energy storage as biogas

- Improved self-sufficiency and sustainability of industries
- Industry and agriculture collaborations
- Micro-enterprise promotion

- Sustainable urban waste management
- Substitution of landfilling/incineration

- Circular economy approach
- Sustainable production via resource recycling

- Reduced CO$_2$ emissions from fossil fuels
- Reduced CH$_4$ and NO$_X$ emissions from livestock manure or landfills/composting
- Reduced gas-based chemical N fertilisers
- Enhanced C return to soils

- Reduced deforestation (firewood substitution)
- Nutrient and C return to soils

Figure 1.1. Summary of potential contributions of AD to the Sustainable Development Goals of the United Nations (adapted from World Biogas Association (2018) and UN Environment Management Group (2021)). A focus on digestate management is given (vision from the authors).

Due to its advantages and thanks to policies favouring its implementation, the number of AD plants has grown tremendously in the last decades (see Figure 1.2). In the EU, the major biogas producer with a capacity for power generation of 209 TWh from biogas in 2018, the main feedstocks are crop-derived (mostly in Germany and UK), but also manure, slurries and sewage sludge are used (*e.g.*, in France, Denmark, and others). Agricultural energy crops are currently slowing down, but changes in policies regarding waste management/valorisation will surely boost AD (see Capson-Tojo et al. (2016) for an example in France, where the valorisation of commercial food waste through soil return is now mandatory). Indeed, current policies are expected to cause a 10-fold increase in biomethane demand by 2030, with up to 370 TWh coming from gas (both hydrogen and methane; see National Energy and Climate Plan by the European Commission; (Pflüger, 2020)). China is the 2nd major biogas producer (84 TWh), having many small-scale digesters treating agricultural and food wastes in rural areas. In the coming years, China plans to expand its biogas industry by building industrial-scale digesters. Similarly, India intends to double their biogas capacity in the coming years, and other countries are following this trend (*e.g.*, Nepal, Malysia, Vietnam, etc.) (Akhiar et al., 2020). The third world player is the USA (42 TWh), producing biogas mostly from food and municipal solid wastes. The rest of the world (47 TWh) relies mainly on small digesters fed with agricultural and food wastes. See World Biogas Association (2021) for more information about biogas production worldwide.

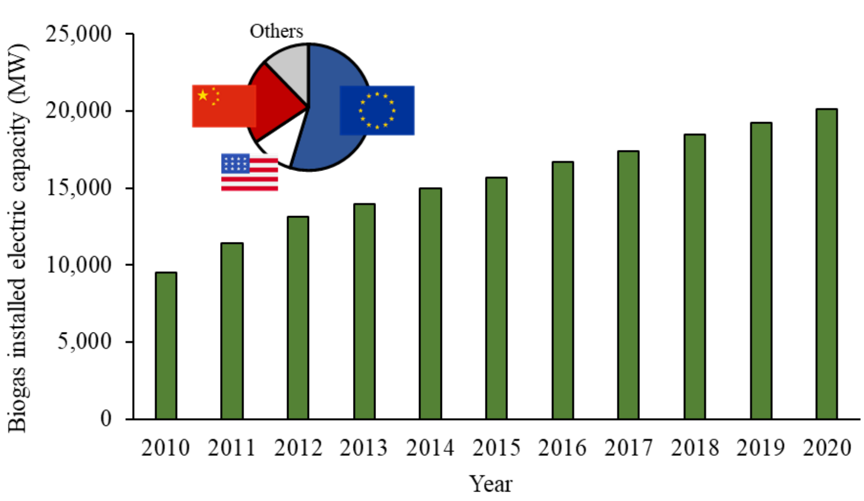


Figure 1.2. Evolution from 2010 to 2020 of the global biogas installed electric capacity. The pie chart shows the geographic distribution of the biggest biogas producers in 2018 (as percentage of total capacity).

Although there is already a wide application of biogas technologies around the world, the industry is still in its initial stages of development, implying that there is a huge potential for future development. As of 2019, only 1.9-2.2% of the overall potential of AD was being exploited worldwide (World Biogas Association, 2019). The potential for growth of the biogas industry is thus extraordinary, and virtually involves every country. If major feedstocks (*e.g.* agricultural biomass, manure, food waste, or municipal solid waste) were actually recovered, we could generate 26-37% of the current natural gas consumed, or 16-22 % of the electricity consumed worldwide (World Biogas Association, 2019). Africa is a clear example of untapped AD potential. Indeed, AD is still at an early stage of development in the continent. Nevertheless, several countries have implemented national biogas programs (*e.g.* Kenya, Uganda, Ethiopia, Tanzania, Rwanda, Cameroon, Burkina Faso or Benin) (Roopnarain and Adeleke, 2017). Recognising the potential of AD in this region of the globe, the International Energy Agency (IEA) has proposed their Sustainable Development Scenario (which meets in full the world's goals to tackle climate change), where biogas provides a source of clean cooking to an additional 200 million people by 2040, half of which are in Africa (International Energy Agency, 2020).

In developed countries (*e.g.*, USA or EU), the drivers for further AD expansion will surely be based on novel policies (*e.g.*, favouring decarbonisation or penalising traditional management processes), as well as on technological developments. An example of the latter is biogas upgrading to biomethane for direct injection in the natural gas grid (opposed to power production via co-generation). This approach is still far from widespread application, but it is a practice gaining importance, and will surely boost AD growth in the future, as upgrading technologies become more cost-effective and policies aimed at gas supply decarbonisation are implemented (International Energy Agency, 2020).

In summary, although the future of AD is not without challenges, the prospects are promising. This is particularly true when considering that, from a holistic point of view, most relevant actors (*i.e.*, technological, economic, social, and political) are all working together towards the further implementation of AD as key technology in future, more renewable societies.

1.1.2. AD digestate: definition and current context as fertiliser

The increase in the number of AD plants and capacity will obviously result in greater amounts of digestate to be dealt with. The European Biogas Association defines digestate as "the solid or liquid material from controlled anaerobic fermentation processes of biodegradable material" (European Biogas Association, 2015). Approximately, for every tonne of feedstock treated in a digester, around ~50-85% by weight emerges as digestate, mostly depending on the water content of the influent (World Biogas Association (2021); the characteristics of the digestate, which mostly depend on the reactor feed, will be further discussed later). To give an idea of the global magnitudes to be dealt with, it has been estimated that the EU28 alone generates around 180 million tonnes$\cdot$yr^{-1} of digestate, 120 from agricultural AD, 46 from municipal solid waste AD, and 7 from source-sorted waste treatment (data from 2013-2018, sewage sludge apparently not included (Corden et al., 2019)). Extrapolating these numbers to other countries, we could state that around 290-300 million tonnes$\cdot$yr^{-1} are currently produced worldwide, a value that could be increased 10-fold by 2030 if AD development predictions are fulfilled (it must be considered that worldwide comprehensive data on digestate production is still difficulty available and that the presented values must be taken as estimates). Therefore, efficient digestate management will be crucial in a holistic AD implementation within a circular economy strategy. This is being recognised in several countries, with policies regarding digestate management (considering it as a resource) being implemented. An example is the European

Green Deal, which specifies a transition to a circular economy, with a "zero pollution Europe", and a farm-to-fork strategy.

As most of the nutrients in the influent biomass are retained within the digestate, it is a nutrient-rich effluent. AD digestate generally contains high concentrations of nutrients (*i.e.*, nitrogen and phosphorus), recalcitrant organic matter, and trace elements (Guilayn et al., 2019b). Therefore, digestate can be considered as an organic fertiliser, recovering and recycling resources from treated feedstocks, which otherwise could end up in landfills or water bodies. Furthermore, the nutrient contents in digestate make it a potential replacement for mineral fertilisers. It has been estimated that 1 tonne of digestate used as fertiliser saves the equivalent of 1 tonne of oil, 108 tonnes of water, and 7 tonnes of CO_2 emitted (European Biogas Association, 2015). In addition, digestate has proven to be a much more efficient and safer fertiliser than raw organic materials (commonly used, such as raw livestock slurry or crop residues), offering a more extensive pathogen reduction, an improved nutrient availability for plant absorption, less odours, less invasive weeds, less gaseous emissions, and a reduced risk of water and soil pollution. Because of these advantages, the vast majority of digestate is nowadays already used directly as a fertiliser in the EU28 (Corden et al., 2019). In terms of potential, the use of digestate as soil amendment could replace 5-7% of inorganic fertiliser currently in use (World Biogas Association, 2019).

A crucial benefit of digestate application as fertiliser that is often overlooked is the return of part of the carbon in the feedstock to the soil. Carbon recovery is critical to maintain a healthy soil, and with soil quality in many parts of the world at risk of depletion of organic carbon, replenishment of nutrients and carbon has become critical. Indeed, the worldwide intensive utilisation of synthetic fertilisers (without any carbon supply due to the lack of organic matter), together with poor land management practices, have led to soil degradation worldwide, with 30% of the world's cropland becoming unproductive in the last 40 years (FAO, 2015; World Biogas Association, 2021). Carbon recovery via digestate application as fertiliser is a sustainable solution for this problem.

Taking into account all the above, it is clear that the traditional mindset of only-energy-focused AD processes is changing, considering digestate as a secondary product, rather than as a waste stream to be disposed. Nevertheless, despite the advantages of digestate utilisation for resource recovery purposes, several challenges must be tackled to make this practice a worldwide reality. Each digestate stream must be properly managed according to its characteristics, which will ultimately depend on the AD entries/substrates (and therefore can be predicted to some extent). In addition, the AD process will also affect the digestate characteristics to some extent (*e.g.*, lower presence of pathogens in thermophilic operation). Even the benefit of digestate application as fertiliser will also vary significantly depending on external factors other than the feedstock type, such as soil type, crop needs, climatic conditions, or relevant regulations. This might create the need of transporting the digestate over long distances, jeopardising the economic feasibility of this approach and increasing its environmental impact. Another limitation is that digestate might contain potentially harmful substances/microorganisms, such as pathogens, heavy metals, bisphenol, phthalates, pharmaceuticals, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), polyfluoroalkyl substances (PFAs), and/or microplastics (Corden et al., 2019). Furthermore, unproper digestate management can also result in the spread of virulent and/or antibiotic resistant genes and bacteria, favouring the spread of pathogenic superbugs. Therefore, risk assessment and management protocols must be developed and implemented. Technical solutions must also be developed to ensure a safe digestate utilisation, including the improvement of existing post-processing methods and the development of novel technologies. Finally, the lack of legal framework and the clash with existing legislation must also be addressed, aiming to stablish a safe and logical system that enables an optimised used of resources (European Biogas Association, 2015).

1.1.3. What resources are contained within digestates?

As aforementioned, digestate is the stream where unbiodegradable materials and excess nutrients are concentrated. Excluding a small fraction of water that ends up as vapour collected together with biogas (whose extent will mostly depend on the digester's working temperature), the water present in the substrate will end up in the digestate. Therefore, most of the raw digestate (in weight) is composed of water (see Figure 1.3). This implies that water is the most obvious resource that can be recovered. Examples of how this can be achieved are the production of high-quality purified water (*e.g.*, via filtration techniques) or crop irrigation with the digestate liquid fraction (with or without post-treatment). Although this practice is not currently a common objective of digestate management, recent governmental initiatives favouring water recovery and reuse will surely promote this approach in the future (see, for example, Frijns et al. (2021)). It is however important to consider that water long distance transportation is not economically neither environmentally reasonable, and that the overall water flow of digestate is modest (around 0.5%) compared to agricultural needs (40 billion m^3 in Europe in 2010 (eurostat, 2021a)).

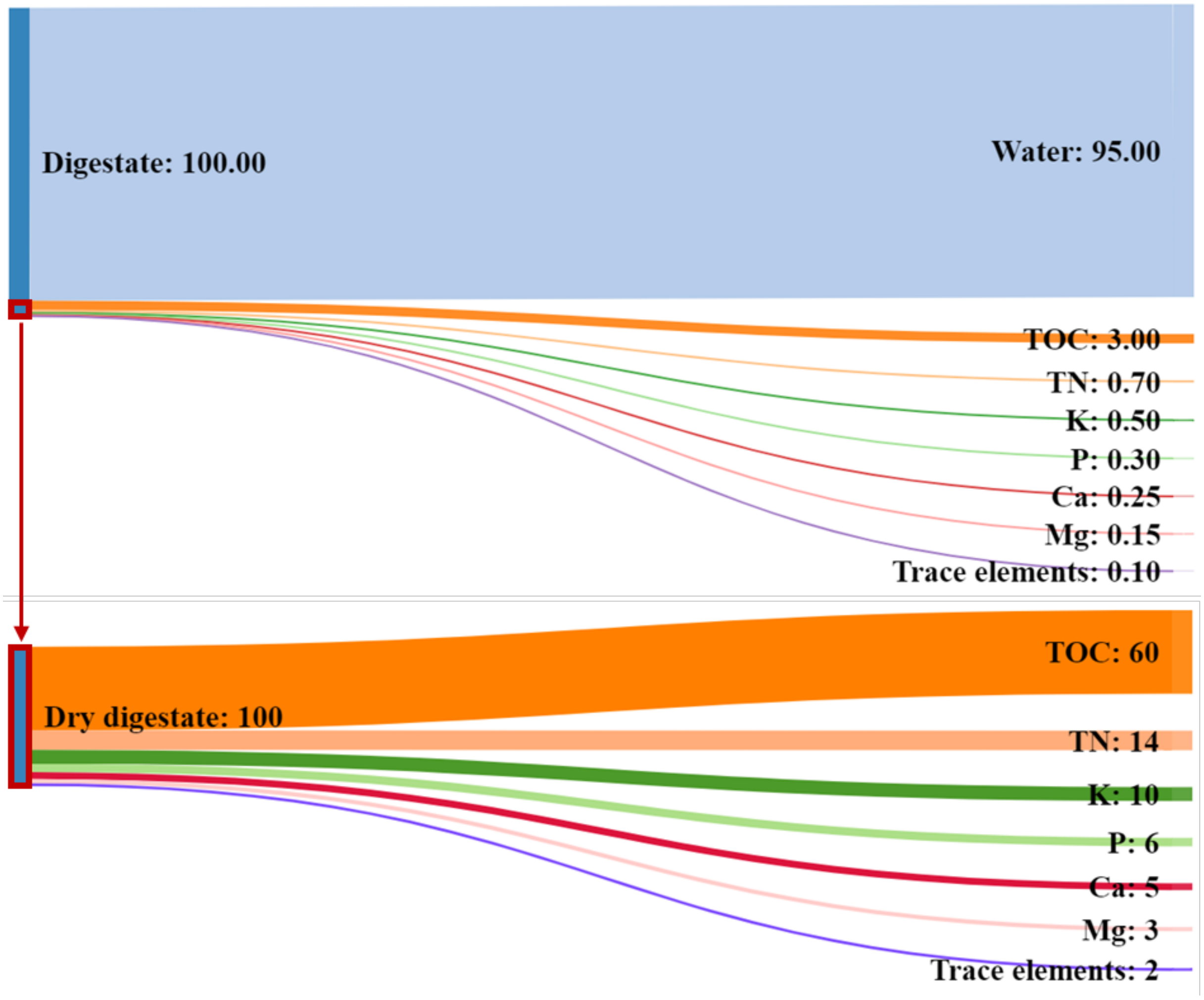


Figure 1.3. Common valuable resources contained within digestate (data from an internal database (SUEZ) and from Monlau et al. (2015) and Vaneeckhaute et al. (2017)). The upper figure shows typical values for whole (raw) digestate and the figure below a “zoom” after excluding water. Values represent weight percentages.

As introduced above, digestate is a stream rich in carbon, nutrients, and macro/micro nutrients (Figure 1.3). All of those are potentially valuable and their recovery is essential in a circular, sustainable economy. These compounds are commonly present in both solid and liquid forms, such as soluble and solid organics, NH_3/NH_4^+ and organic-bound N for nitrogen, or PO_4^{3-} and ortho-phosphate salts (*e.g.*, struvite) for phosphorus. This implies that their maximised recovery must include a holistic, integrated, process, involving different stages within a biorefinery approach. Coming chapters will elaborate on the recovery of each of these valuable compounds.

Although the contents of resources other than water shown in Figure 1.3 might seem low, the recovery potential can be huge considering the current digestate flows. To put these carbon and nutrient flows in perspective, a rough estimation of the resource recovery potential can be done by considering a figure of 200 million metric tons produced in the EU (lower end of current estimates) and an average digestate composition. To allow for the consideration of statistics, data from an internal database (SUEZ) was used, assuming an average of 5% dry matter (DM) for this digestate, as well as the interquartile ranges (IQRs; where 50% of the observations are situated) for digestate composition in terms of ammoniacal nitrogen, total nitrogen, volatile solids (as a proxy for the organic matter contents), total phosphorus (expressed as P_2O_5) and total potassium (expressed as K_2O). These values are shown in Figure 1.4 (all expressed in a DM basis). By comparing the obtained numbers with eurostat data, it can be observed that the total nitrogen, phosphorus, and potassium contained in the 200 Mt of digestate could represent around 9%, 4% and 7% of the total European needs of fertilizers (for nitrogen, phosphorus, and potassium, respectively; see Table 1.1). Certainly, these figures do not consider any coefficient for techno-economic feasibility, neither the bioavailability of these nutrient flows for the plants. However, it must be considered that AD is a trending technology, and therefore the digestate flows will surely increase (see previous section). In addition, several political stimuli will promote the reduction of nutrient losses in the food production chain, while promoting nutrient recycling, favouring resource recovery applications, and leading to a reduction of the total fertilizer needs.

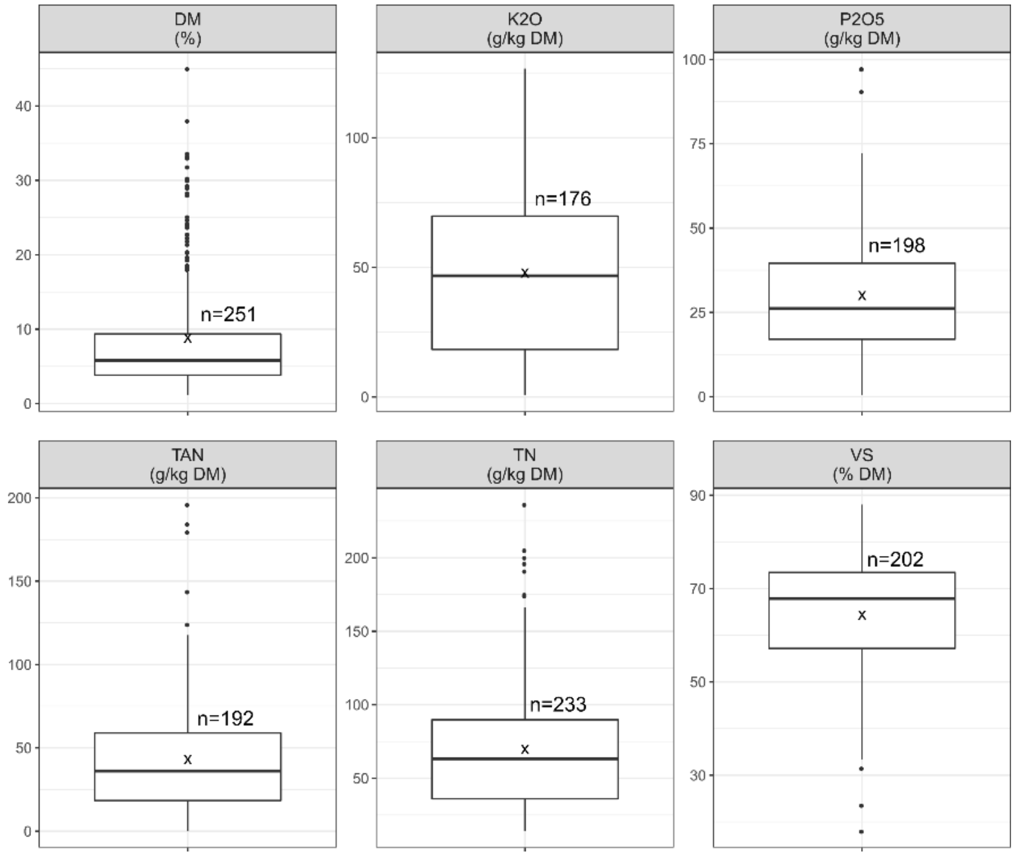


Figure 1.4. Composition of digestates based on a heterogenous large internal database (SUEZ). Tukey-style boxplots. "x" represents the mean and "n" the number of observations. DM stands for dry matter, TAN for total ammoniacal nitrogen, TN for total nitrogen and VS for volatile solids.

Table 1.1. Digestate potential flows in the EU27. DM stands for dry matter, IQR for interquartile range, TAN for total ammoniacal nitrogen, TN for total nitrogen and VS for volatile solids.

Parameter	Digestate range (%DM, IQR)	Flow [a] ($kt\cdot y^{-1}$)	EU27 reference ($kt\cdot y^{-1}$)
TAN	1.8 - 6.0 (n = 192)	183 - 596	10,039 [b,c]
TN	2.8 - 9.1 (n = 233)	284 - 907	10,039 [b,c]
P_2O_5	1.7 - 4.0 (n = 198)	168 - 399	1,114 [b,d]
K_2O	1.8 - 6.9 (n = 176)	180 - 693	2,371 [b,e]
VS	57.4 - 73.5 (n = 202)	5,741 - 7,345	N/A

a. Based on 200 $Mt\cdot y^{-1}$ of digestates with an average of 5% DM.
b. Data from 2019 (eurostat table code TAI01), EU28 not available.
c. Nitrogen fertilizers.
d. Phosphorus fertilizers.
e. Potassium fertilizers.

Regarding organic matter contents in digestates, 1 ton of volatile solids (VS) can be considered as 0.5 tons of carbon (a usual conversion factor). Considering the flows in Table 1.1, the corresponding carbon flow would represent the CO_2-equivalent in greenhouse gases emissions of up to 1.6 million European inhabitants (average of 8.2 ton per capita in the EU28 in 2019 (eurostat, 2021b)). As for the nutrient flow analysis, a coefficient for techno-economic feasibility should be considered, as well as a correction factor to consider only the fraction of carbon that is actually stable over long term (after soil return). In the future, the digestate-carbon flow is expected to increase, while the per capita net greenhouse gases emissions should decrease sharply, meaning that these numbers could be far more positive regarding potential digestate carbon recovery, especially if coupled to trending carbon-stabilizing technologies, such as pyrolysis for biochar production.

Other than water and components, great amounts of energy are contained within digestate. The amount of energy carried as chemical energy (COD) in digestate is considerable (COD of 1.62 g $COD\cdot g\ VS^{-1}$; (Logan and Visvanathan, 2019)), and should be utilized to the greatest extent possible, either via the production of added-value reduced compounds (*e.g.*, biofuels or fatty acids), or by the recovery of energy as heat. Several thermochemical processes exist for the latter purpose. Incineration or pelletization of dried digestate are options allowing partial energy recovery by combustion. More efficient recovery options aim at generating a biofuel, transforming the contained energy into a useful form. Examples are gasification/pyrolysis processes for bio-oil/syngas generation or fermentation for biohydrogen or bioethanol production (Guilayn et al., 2020). These technologies will be discussed in coming sections of this book.

Another form of energy contained within digestate that is commonly overlooked is thermal energy, particularly if AD is carried out under thermophilic conditions (50-55 °C). It has been recently estimated that 90% of the practically recoverable energy embedded in municipal wastewater is thermal energy (being the remaining 10% present as chemical energy) (Hao et al., 2019). Similar values could be expected for digestate, as despite being a more concentrated stream than wastewater, it is also found at much higher temperatures (*i.e.*, 35-55 °C). If recovered, this thermal energy could be utilized for general heating/cooling requirements in the plant, for drying dewatered sludge, and obviously for reactor temperature control. This thermal energy could indirectly offset considerably the energy demand of the plant. As pointed out by Hao et al. (2019) for wastewater, the limitations in thermal energy recovery are generally not due to technical difficulties, but due to supply distances and/or governmental policies.

1.2. Proper digestate management as a necessary step in a circular economy

1.2.1. Importance of digestate management

In AD facilities, digestate management practices can vary from relatively simple processes (such as storage and direct spread) to highly complex processing lines including holistic advanced post-treatment plants. This treatment process complexity/cost compromise is closely related to the plant scale and to local factors, such as local nutrient surplus (notably nitrogen) or the land-spreading distance. As it can has been shown in previous works (see, for examples Fuchs and Drosg (2013)), these local factors can be key, as they might determine the economy feasibility of a defined treatment train. In any case, from the simplest to the most complex process line, any AD designer or operator must consider a complex series of environmental, economic, regulatory, and social constraints, which will drive the choice of an appropriate, feasible, digestate management strategy.

Other than post-treatment processing, proper digestate management comprises a package of good practices within the plant. For instance, any digestate storage volume should be coupled to an equivalent volume of retention, to avoid the contamination of nearby soils and water bodies in case of leaking. Indeed, the most essential digestate management practices should be described, framed, enforced, and controlled by regulatory bodies, such as local environmental authorities and labelling systems, being well described, and constantly evolving in the countries where AD is a well-developed technology. This is an ongoing, never-ending task that is not covered in this book in detail, as this would end up in a series of dedicated case-studies almost in a country basis, which is out of the scope of this document. Entities such as the World biogas Association or the European Biogas Association regularly publish reports on this topic. Nevertheless, the current general legal framework regarding digestate reutilisation is assessed in this book, identifying critical points, and giving recommendations for future modifications.

When digestate or any by/co-product exits the AD plant, a first glaring consideration for its management is that land spreading is associated to environmental risks (Nkoa, 2014), being usually a highly regulated activity, especially in the EU, where digestate is usually under a waste status. Different chapters of this book will cover the current essential and emerging pollution risks. Other than obvious product-use quality criteria, regulations and environmental authorities in place must impose a series of innocuity criteria, spreading method restrictions, or land application restrictions (such as season/weather limitations and spreading limits), which commonly impose the need of an integrated environmental assessment of local and regional impacts. Under current EU regulations, land spreading of raw digestates is thus a pure cost to operators, mainly due to its waste status. Nevertheless, if managed properly, this approach can be conceived as the most economic and environmentally efficient solution for smaller plants surrounded by farmlands (common case for agriculture digesters). Digestates being a liquid-wet product (65-97% moisture contents are common), average transportation distances as low as 10 km can already be economically prohibitive and environmentally unreasonable (Möller et al., 2010). Chapter 2 covers the essential aspects of digestate “direct” spreading in farmlands, either as a fertilizer or as a soil amendment product.

In the EU, achieving an end-of-waste status is a fundamental aspect for marketing digestate (by-)products. End-of-waste status can be achieved mainly through national standards, and more recently through EU labelling standards (CE 2019/1009), which impose a reasonable amount of innocuity/fertilizing/amendment value (according to stablished quality criteria) and might even impose upstream processing. Raw digestates (with no post-treatment at all) tend to be either not included in, or not conforming to such quality criteria. They are usually too diluted when compared to mineral fertilizers standards (N, P and K contents), or too poor to fulfil organic soil amendment standards (Guilayn et al., 2019a). The huge relevance of digestate management is clear in this context.

Depending on the regulatory framework, matching agricultural needs and practices can be challenging, having direct economic implications. To begin with, digestate production is relatively constant in a yearly basis, while agricultural needs are seasonal. This difference is usually buffered by large storage capacities (either in-situ or ex-situ), meaning that the product must be relatively stable over a long period (up to 6 months). Secondly, modern agriculture and farmers are adapted to near-perfect, stable, predictable, and consistent chemical fertilizing products, and its short-term economic benefits are easily considered and difficult to beat. On the contrary, digestates and other organic fertilizers tend to present a significant quality variation over time, and the well-proved long-term benefits (also economic) can be less appealing and are indeed more difficult to quantify from an economic perspective. As of today, this short-term vision in agricultural productivities is a known worldwide problem that has already been around for decades. It is a proven fact that conventional intensive agriculture results in soil carbon depletion, erosion, desertification, and/or loss of biodiversity, which jeopardizes its own economic profitability in the long run, not to mention the long list of associated environmental, social and human-health impacts (Tilman et al., 2002). Resource recovery via a proper AD digestate management can be an immediate, effective palliative to this crucial challenge.

If AD is only regarded as energy-producing technology, the fact that other renewable energies are rapidly lowering its Levelized Cost of Energy (LCOE) might challenge its development (Brémond et al., 2021), and this is causing a “natural” pression for decreasing subsidies on AD as a renewable energy-producing technology. Research and innovation in digestate management is undoubtedly a key aspect for the future of AD as a fully-sustainable and economic attractive technology. Table 1.2 illustrates this issue through a rapid exercise. Without any compensation from AD positive externalities, and with low perspectives for significant AD cost reduction, a significant positive net result from digestate management would be necessary by considering CH_4 valorisation prices competitive with todays’ LCOE for solar energy (steadily decreasing) or natural gas (could increase significantly with carbon taxation). In this context, increasing the value that can be added to digestates either by targeting added-value agricultural products or by accessing new markets is a core research topic around digestate management.

Table 1.2. Current yields and revenues needed for AD to be a competitive solution (*i.e.*, with a combined methane and digestate revenue able to provide a net methane production cost of 0). These values do not consider gate fees (feedstock prices) nor reductions due to AD Levelized Cost of Energy (LCOE) solution. Units are given per wet ton of material.

Parameter	**Unit**	**AD plant in optimist scenario today (today's selling prices)**	**AD plant with methane prices competitive to solar energy today**	**AD plant with methane prices competitive to natural gas today**
Methane yield	$Nm^3\ CH_4 \cdot t_{feedstock}^{-1}$	600	600	600
Feedstock organic matter content	$t \cdot t^{-1}$	20%	20%	20%
Organic matter conversion rate	$t \cdot t^{-1}$	90%	90%	90%
Digestate "yield"	$t_{digestate} \cdot t_{feedstock}^{-1}$	82%	82%	82%
Imposed AD's CH_4 valorisation price	€$\cdot MWh^{-1}$	100	30 to 70 [c]	20 to 40 [d]
AD's LCOE [a]	€$\cdot MWh^{-1}$	-79	-79	-79
Minimum digestate handling revenue for feasible operation [b]	€$\cdot t_{digestate}^{-1}$	-31	+13 to +70	+72 to +86

a. Digestate handling excluded (eurostat, 2021c).

b. For achieving economic equilibrium ("CH_4 net production cost = 0"), the negative value indicates a maximum possible cost while positive values indicate minimum necessary revenues for being competitive compared to solar energy and natural gas LCOE's as reference for AD CH_4 selling price.

c. Solar energy LCOE in different European (Lugo-Laguna et al., 2021).

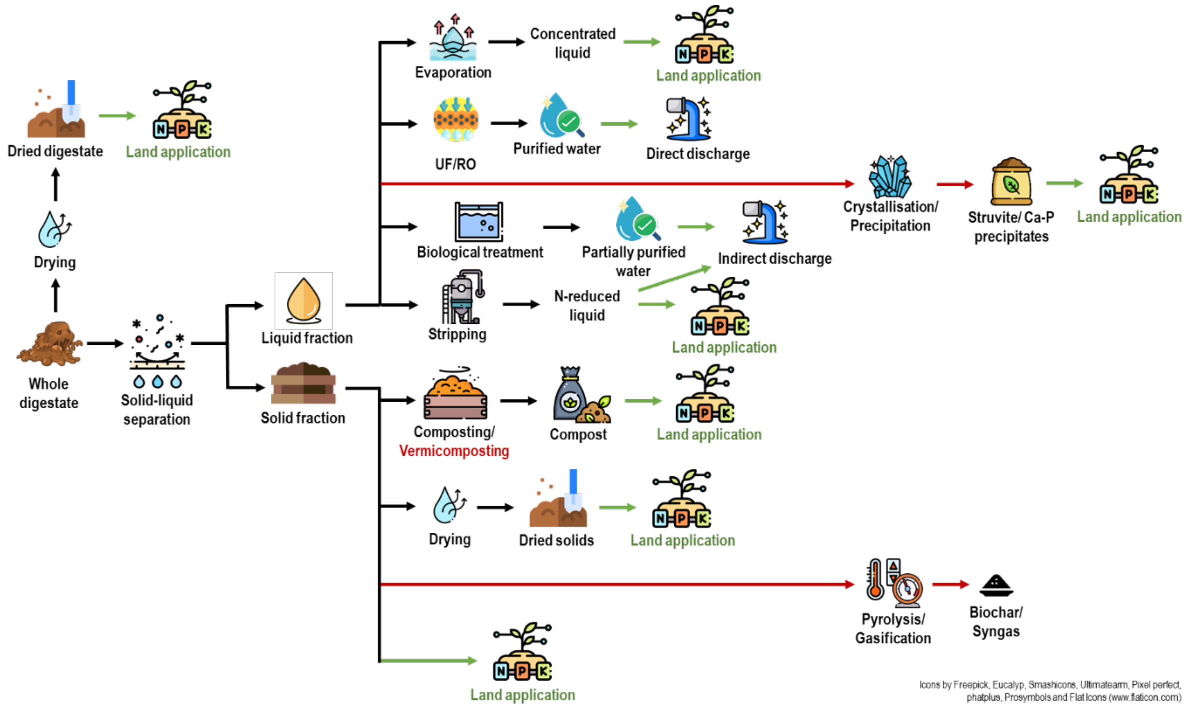
d. Natural gas price ranges in Europe excluding taxes, first half of 2021 (eurostat, 2021c).

Overall, digestate management is a complex field, as several factors must be considered in a holistic approach. Nevertheless, it is essential to ensure safe waste disposal, to allow resource recovery processes, and to fulfil current and future regulations. In addition, efficient digestate valorisation might be key for the economic feasibility of future AD installations. This will only be achieved if proper digestate management practices are implemented.

1.2.2. Current state of digestate management practices

Almost every AD plant counting with digestate post-treatment will count with, at least, a phase separation step. This is the first crucial step, after which posterior post-treatment processes (if any) are applied. Considering phase separation, digestate is typically present in three forms: (i) whole digestate, being the material coming straight out of the digester, often with less than 5% DM content (no separation applied); (ii) liquor, being the liquid fraction of the whole digestate, where most of the DM has been excluded; (iii) fibre, which corresponds to the solid fraction after separation, containing the remaining separated DM (World Biogas Association, 2021). Digestate mechanical separation promotes a series of operational benefits that allow a more efficient digestate management and enhance resource recovery (Guilayn et al., 2019b). To begin with, the liquid fraction is better pumpable, stored, transported, and spread as liquid. The solid fraction is also easier to transport, in this case as a solid and stackable material. From a resource recovery point of view, the liquor will carry soluble components, concentrating nitrogen (mostly as NH_4^+/NH_3) and potassium, both in soluble forms readily accessible to plants. The solid fraction will carry the larger particles and insoluble matter, concentrating recalcitrant organic matter, phosphorus (notably present as precipitates or adsorbed onto solid organics), and the residual slow-release organic nitrogen, also contained within solid organic compounds. Without any further post-treatment, phase separation by itself allows a better resource management by generating a product closer to an "organic fertilizer" (liquid fraction) and a product closer to a "soil amendment" (solid fraction), while partially separating nitrogen from phosphorus, the usual limiting parameters for land spreading.

Current full-scale post-treatments practices for the solid fraction are still quite limited, and generally involve composting (usually with a large proportion of a bulk material), landfilling (not included in Figure 1.5), and thermal drying. Full-scale liquid fraction post-treatments are even less common, as the liquid is generally simply stored in basins, land spread, and sometimes sent to wastewater treatment plants. Some post-treatment options that exist include (vacuum-)evaporation, membrane filtration, nitrogen stripping and scrubbing, nitrification/denitrification, struvite recovery (quite limited to sewage sludge digestate), and some combinations of these unitary processes. Figure 1.5 presents some of the processes currently being applied for each digestate fraction.



Icons by Freepick, Eucalyp, Smashicons, Ultimatearn, Pixel perfect, phatplus, Prosymbols and Flat Icons (www.flaticon.com)

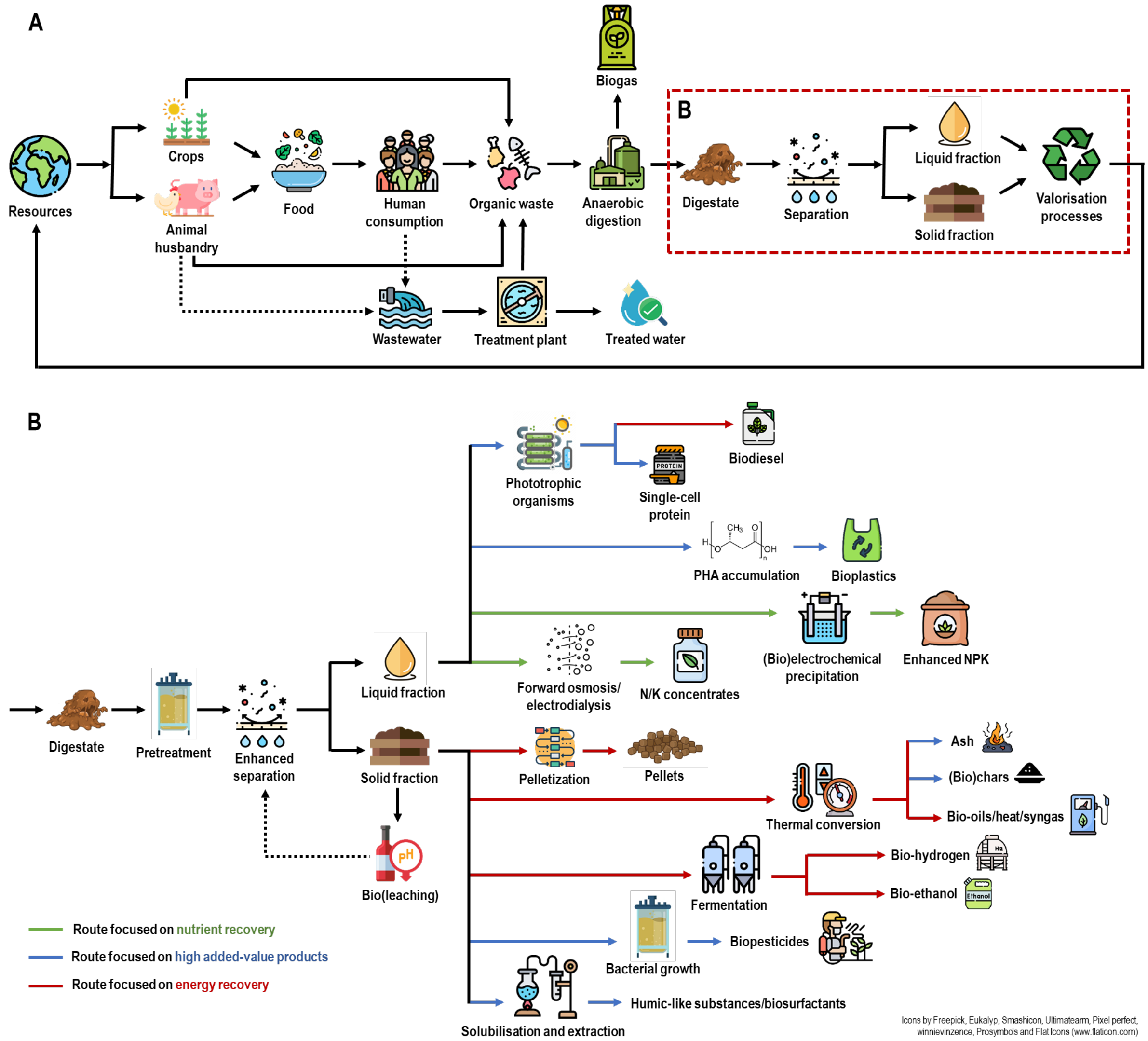
Figure 1.5. Current full-scale commercial technologies for digestate management identified in a state-of-the art review from 2013 (Fuchs and Drosg, 2013) and in a recent review focused on the same topic (Guilayn et al., 2020). The new technologies identified only in the latest review are highlighted with red arrows. This shows that little has changed in over 10-20 years. Figure adapted from Fuchs and Drosg (2013).

Over the last 20 years, when it comes to digestate treatment lines/processes, academic researchers have proposed a series of innovative and promising technologies (*c.f.* next section and coming chapters). However, many professionals in the field feel that little has changed at full-scale within the same period: the state-of-the art of fully developed commercial techniques (technology readiness level 9) seems quite untouched (Figure 1.5). Indeed, most of the technologies identified in a recent state-of-the art review of full-scale techniques (Guilayn et al., 2020) were already a reality in the precedent decade (see Fuchs and Drosg (2013)). Moreover, the two “new” technologies in the recent review have been around for several decades. Full-scale struvite recovery started to be reported in wastewater treatment plants in the early 2000’s (Ueno and Fujii, 2001). The same can be said of industrial biomass pyrolysis/gasification (mostly wood (Meier and Faix, 1999)). It can be expected that recent political/social engagements towards a circular economy and towards fighting climate change will boost the adoption of new technologies creating more value from digestates, but this leap is still to be taken.

The AD industry is not to be blamed for this lack of mobility. How can a waste-derived product (still considered as a waste-status product) be competitive against lower-cost, better-performing, almost internationally borderless products derived from traditional petrochemical-based industries? Recent political and social plans/pressures such as the EU/USA Green Deal, net zero emission targets, consumer behaviour evolution plans, carbon taxation, and regulatory advances, must be effectively implemented to promote end-of-waste pathways, which will boost the upscaling and adoption of bio-sourced and upcycled products. In this context, regulatory/legislative advances are crucial. The implementation of more advanced technologies for digestate management, aiming towards the production of value-added products can be expected over the next decade. An overview is provided in the next section, and the most promising approaches (as well as currently applied processes) are discussed in detail in the coming chapters, covered by experts from each field.

1.2.3. Novel/promising technologies for digestate management

Despite the remarkable academic/scientific progress on digestate management that has occurred in the last decade, there is still a large room for improvement, particularly for the development of processes allowing a safe and optimal resource recovery. Research on the latter has been mainly fuelled by increasing market demands (*e.g.,* of high-quality fertilisers) and by regulatory drivers, favouring the implementation of circular economic strategies (see Figure 1.6.A for a corresponding scheme).



Icons by Freepick, Eukalyp, Smashicon, Ultimatearm, Pixel perfect, winnievinzence, Prosymbols and Flat Icons (www.flaticon.com)

Figure 1.6. Schematic representation of (A) a general efficient digestate management focused or resource recovery, and (B) different novel options for resource recovery from digestate, including the generated products.

Regardless of the technology or approach used, the need for efficiently separating the liquid and solid digestate fractions appears essential for an effective resource recovery, as this allows at optimal resource management, with different dedicated valorisation process for each fraction (Guilayn et al., 2019b). Because of this, large efforts are being put on the development of digestate pretreatments technologies that improve digestate dewatering, favouring phase separation. The whole idea is to convert bound/interstitial water into free water, as mechanical dewatering processes can only separate the latter (Wang et al., 2021). This can be achieved by, for example, destroying extracellular polymeric substances (EPS), which form gel-like substances that jeopardize dewatering. Other than dewatering, pretreatment methods also aim at improving the digestate qualities, *e.g.*, improving its stability, reducing the amount of metals in the solid fraction, or inactivating pathogens (thus producing biosolids Class A, with unrestricted agricultural reuse and public contact, particularly crucial in sludge-derived digestates (Wang et al., 2021)). While processes already exist to achieve these goals to some extent (see section 1.2.2), novel technologies should aim at, not only improving dewaterability, but also provide an integrated improvement, offering multiple benefits simultaneously while also reducing the costs or current methods. Some examples of promising technologies have been reviewed in Wang et al. (2021), with a focus on sewage sludge (one of the worse cases/concerns in terms of pathogen presence). Among the selected integrative technologies, iron-based advanced oxidation and acidic aerobic digestion recently appeared as promising alternatives, as both improve dewaterability, pathogen reduction, and digestate stabilisation. If needed, both processes could be coupled with novel cost-effective options for metal solubilization, such as bioleaching (bei Li et al., 2021; Yesil et al., 2021). See Figure 1.6.B for a scheme showing how pretreatment, dewatering and bioleaching could be coupled. It must be mentioned that, while the different technologies being developed for digestates from different origins or for particular purposes have been reviewed elsewhere (*e.g.*, Logan and Visvanathan (2019) for municipal solid waste, Guilayn et al. (2020) for urban and centralized plants, Monlau et al. (2015) for agricultural waste, or Vaneeckhaute et al. (2017) for resource recovery technologies), here we present a general discussion. The authors refer the readers to the aforementioned articles for particular information on these topics.

After an efficient solid/liquid separation, most of the valorisation options for any of the fractions can be grouped according to the main resource that they aim to recover: nutrients (*e.g.*, nitrogen, phosphorus or potassium), energy (in the form of solid fuels, diesel, oils, other reduced organics, heat, hydrogen, syngas, etc.), or high added-value products (*e.g.*, single-cell protein, polyhydroxyalkanoates (PHAs), biopesticides, or humic-like substances).

Starting with the liquid fraction, the most researched option for its valorisation has been the recovery of nutrients in the form of either liquid concentrates or solid precipitates (*e.g.,* struvite). Although these approaches have been considerably studied, novel processes under development have a great potential to increase recovery efficiencies (Vaneeckhaute et al., 2017). Examples of promising options where further research is needed are forward osmosis (Camilleri-Rumbau et al., 2021; Ferrari, 2020; Zhao et al., 2012), electrodialysis (Camilleri-Rumbau et al., 2021; Shi et al., 2019), or enhanced precipitation via (bio)electrochemical processes (Cusick and Logan, 2012; Fraunhofer Institute for interfacial engineering and biotechnology, 2012). These approaches have shown that they might enable a more efficient recovery, lowering the amounts of chemicals dosed, increasing the final nutrient concentrations, and potentially generating high-quality products due to high rejections. Research is still needed for an efficient upscaling and to investigate potential economic limitations. Another approach being researched for liquid-digestate valorisation is the generation of high value-added products, such as biomass (mostly as single-cell protein source) and/or PHA. The latter is a precursor of bioplastics, and most research so far has focused on using filtered digestate as growth media for biological PHA accumulators, such as *Cupriavidus necator* or others (Afreen et al., 2021; Kovalcik et al., 2017; Papa et al., 2020; Passanha et al., 2013). If the carbon source used is from a renewable/sustainable/profitable origin, this might be a promising option for generating a high-value product with a bright future ahead. Regarding biomass production via phototrophic organisms, most research has focused on microalgae as mediators for nutrient uptake, either for the production of biomass itself (single-cell protein), or for biodiesel generation after lipid transesterification (Guilayn et al., 2020; Monlau et al., 2015). Although this approach has already reached industrial pilot scale (Uggetti et al., 2014), more research is needed to elucidate if process integration can help to solve a main issue of this technology, which is the instability of the cultivation system, probably due to the presence of bacteria in the influent. Coupling this approach with filtration/purification strategies might be an option to stabilise the process. Other than microalgae, photosynthetic organisms such as plants via hydroponic cultivation systems (Pelayo Lind et al., 2021) or purple phototrophic bacteria (Capson-Tojo et al., 2020) are also promising, although more research is needed.

Regarding solid digestate, advanced processes for energy recovery via thermal conversion (*e.g.*, controlled pyrolysis, hydrothermal liquefaction, or hydrothermal carbonisation) are the most widely researched approach (Guilayn et al., 2020; Monlau et al., 2015). The traditional goal of this idea is to produce a useful form of energy (in the form of heat, oils, syngas, or other fuels) to enhance the overall energy balance of the process. Interestingly, recent research has also focused on the valorisation of the generated chars and/or ashes (as by-products), aiming at an optimised resource recovery. For example, ash valorisation as source of metals (after extraction) and phosphorus has been recently proposed (“Phos4You - We deliver Phosphorus made in Europe,” 2021). In addition, it has been shown that biochar can serve as soil improver (Al-Wabel et al., 2018), as well as bio-adsorbent (Wu et al., 2017). In addition, biochar can also be used to stabilise the AD process (Capson-Tojo et al., 2018; Fagbohungbe et al., 2017). Although biochar production from digestate is not competitive at the moment compared to wood-derived biochar, this might very well be an option in future integrated management processes allowing an optimal digestate valorisation. Another energy recovery option from solid digestate is the generation of biofuels via fermentation. Both biohydrogen and bioethanol have been produced from digestate, generating clean, renewable fuels (Monlau et al., 2015). Challenges of this approach, such as the need of a pretreatment for fibre hydrolysis and/or low volumetric production rates, might limit its implementation, but recent developments are moving the field forwards (Stoumpou et al., 2020). Finally, the production of high added-value compounds from solid digestate has also gained attention lately. Relevant examples are the generation of biopesticides, enzymes, or biosurfactants via solid-state fermentation (Cerda et al., 2019). Although this approach is still under development, the high value of the obtained products, and increasing markets, have the potential of pushing it forwards (always coupled with other valorisation alternatives). Another added-value product that can be generated from solid digestate are humic-likes substances. In this case, these compounds can be directly extracted from the digestate, and after purification they can be used as soil improvers or biostimulants (Guilayn et al., 2020). To maximize the extraction of these substances from digestates, a strong alkaline treatment for their solubilisation is needed, which might limit the application of this option (Montoneri, 2017).

Obviously, the processes described above for product generation are not mutually exclusive. On the contrary, optimal digestate valorisation will surely rely on process integration, following the concept of environmental biorefinery (Capson-Tojo et al., 2016; Moscoviz et al., 2018; Venkata et al., 2016). This facility mimics the idea of an oil refinery, where substrate valorisation is maximised via the integration of several processes. In the case of digestate management, a holistic valorisation approach will obviously include options for the conversion of both the liquid and solid digestate fractions. Moreover, sequential valorisation steps from highest to lowest valuable products are also needed to optimise recovery (*e.g.*, extracting high added-value compounds early on the treatment train and use its residual effluent for less profitable alternatives, ideally leaving low-value energetic valorisation for the last fraction). Other than sequential integration strategies, several processes can be coupled, enhancing performances, and reducing environmental impacts. Some integration examples are: (i) the uptake of CO_2 from biogas via photoautotrophic organisms for single-cell protein production, acting as carbon source and serving for biogas upgrading; (ii) recycling of the bioleaching effluent for integrated treatment with the liquid fraction; (iii) the use of biochar for enhancing the digestion performance and thus the digestate quality; or (iv) the use of compounds from solid digestate fermentation as carbon source for microorganisms growing using the nutrient-rich liquid fraction as growth media (*e.g.*, purple phototrophic bacteria for single-cell protein (Capson-Tojo et al., 2020)). Process integration aiming at maximising resource recovery and high added-value generation will surely be the core of future modern digestate management facilities.

The optimal technology (or integrated technologies) to be applied will depend on many factors. Other than obvious constraints such as readiness level or legal approval, local, national, and even international factors will affect the selection process (*e.g.*, legal agreements and policies). On a local scale, the distance from potential product buyers might be a critical factor, as transportation is known to be a major cost. In addition, the nature and the stability of the plant entries will also affect considerably the post-treatment technology to be selected. A typical example is the dichotomy between small plants in rural areas and large plants for urban/centralise treatment. On one hand, small plants are often focused on fertiliser production, as this product can be applied directly on-site (or close by), and because the plant entries are usually stable over time (*e.g.*, agricultural waste). In addition, these regions do not have high energy demands. On the other hand, large plants in urban areas might move away from this option, as their scale allows for a larger capital expenditure, thus permitting more complex and ambitious processes within a full-valorisation scheme. In addition, these installations have a much larger influent variability, which makes difficult to ensure product quality in simple digestate treatment approaches (*e.g.*, drying and/or composting). Furthermore, high value-added products and/or energy recovery might be favoured in this situation, as potential buyers will be around, and urban regions have high energy demands. As example, Tampio et al. (2016) found that, in their case, evaporation combined with reverse osmosis was the most efficient nutrient recovery technology for generating a transportable fertilizer from digestate, mainly due to the low product mass and the reduced energy consumption for transportation. In their study, the selection of the treatment technology was heavily dependent on the location of the AD plant relative to the agricultural land, and on the type of fertilizer products needed. Summarizing, selecting the right post-treatment train is an arduous task, where several factors must be considered, including economical, technological, regional, and (inter)national constrains.

1.3. Conclusions and book outlook

The increasing number of AD plants and the implementation of policies based on resource recovery and circular economy call for the development and implementation of digestate management approaches that allow the recovery of the resources contains within it (*e.g.*, water, nutrients, carbon, or energy). While traditional practices such as thermal drying, incineration, composting, or landfilling have allowed to dispose digestate in a safe manner (and in some cases a certain degree of resource recovery), novel methods are being developed to allow a more intensive and efficient recovery of resources. Processes such as enhanced precipitation, enhanced thermal conversions, photoautotrophic biomass growth, or enhanced filtration, are promising. While there is a lot of work ahead of us, the tremendous effort currently being put on this task ensures a strong and fast development of the field. Despite research/technological efforts, a particular emphasis should be put on the translation of research development on the field, aiming at the practical implementation of novel concepts at industrial scale. As importantly, legal frameworks must be updated to avoid hindering the application of novel technologies.

This book presents a comprehensive review of the state-of-the-art on AD digestate management. The book introduces the application of digestate as fertiliser, also addressing the challenges that the particular characteristics of digestates produced from different substrates (*e.g.*, manure, municipal solid waste, agricultural waste, or algae biomass) pose. Afterwards, different novel processes for resource recovery from digestate are discussed, including options for nitrogen, phosphorus, or energy recovery, addressing also pre- and post-treatments allowing an enhanced recovery. Novel high added-value products that can be produced from digestate are also discussed, including hydrochar, PHAs (bioplastics), or single-cell protein. The presence of pollutants (including emerging ones) and their relevance are also discussed, together with potential ecotoxicity issues. Results from life cycle analyses are summarised and critically discussed, and the current legal framework regarding digestate reutilisation is assessed, identifying critical points, and giving recommendations for future modifications. Finally, options for process integration within the biorefinery concept and future perspectives are also discussed. Overall, this book gives an excellent overview of the current state and the most promising advances in digestate management, focusing on emerging pollution concerns and the creation of value.

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