*Review*

# Digestate Management and Processing Practices: A Review

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**Abstract:** The implementation of sustainable agro-energy systems that integrate crop, livestock, and bioenergy production is attracting increasing interest from farmers. Livestock produces large amounts of animal manure which can serve as organic fertilizer for crops and pasture growth. However, the nutrients contained in manure can adversely affect air, water, and soil quality and pose a public health risk if not handled properly. Existing manure management practices vary widely on a global scale. Researchers are striving to identify appropriate manure management practices with the aim of environmental protection. Anaerobic digestion of manure and subsequent digestate (DG) processing technologies have been proposed to stabilize manure so that it can be safely used for land applications. DG, which represents digested substrate removed from the anaerobic reactor after recovery of biogas, is a rich source of N, P, K, and S, various micronutrients, and organic matter, the addition of which to the soil can stimulate soil microbial biomass metabolic activities thus improving soil ecosystem function. However, the optimal fertilization properties of DG can be lost if it is neither fully stabilized nor contains biodegradable materials. To overcome these problems, various processing technologies can be used to convert DG into value-added by-products. Composting has been proposed as one such preferred post-treatment that can convert DG into mature, stable, safe, humus- and nutrient-rich compost. Other processing technologies such as thermal drying, gasification, hydrothermal carbonization, pyrolysis, membrane filtration, struvite precipitation, ammonia stripping, and evaporation have also been proposed for DG processing and nutrient recovery from DG. The objective of this review paper was to provide an overview of the current state of the art in DG management regulations and practices and to provide an update on the various processes that have been developed to meet DG stabilization requirements, with a focus on composting as one of the preferred solutions.

**Keywords:** composting; digestate management; fertilization; organic fertilizer; waste valorization

## 1. Introduction

The main role of the agricultural sector is to provide sufficient and high-quality food for an ever-growing population [1], which is expected to reach 9.7 billion people in 2050 [2]. This implies that a significant increase in agricultural production must be achieved. Due to its importance and relevance, agriculture is at the center of policy agendas worldwide [1]. However, it is also a major contributor to climate change through greenhouse gas emissions and air, water, and soil pollution. Intensive soil fertilization with mineral fertilizers, which is carried out to make up the gap between the nutrients required for optimal crop development and those provided by the soil and from available organic sources, has led to several ecosystem and environmental problems, such as decreases in organic matter (OM) content and soil fertility, and increases in environmental degradation [3,4]. Environmental degradation, which includes biodiversity loss, deforestation, erosion, water use, and human interference with the nitrogen (N) and phosphorus (P) cycles has intensified especially in recent decades. On the other hand, intensive livestock farming can also have serious

negative environmental impacts [5]. Livestock farms produce large amounts of animal manure, which can pollute nearby underground and surface waters if not handled properly. However, when properly handled and distributed, manure can be applied to fields as organic fertilizer, mitigating potential contamination of soil and water [1].

The application of intensive mineral fertilizers represents an anthropogenic impact on the soil where humans have the greatest control. Therefore, appropriate soil management practices should be ensured to reverse the trend of soil quality decline [4]. Fertilization with organically derived fertilizer represents an alternative for sustainable agriculture that can provide sufficient nutritious food for all while reducing environmental risk [6]. Manure is the most popular organic fertilizer used in crop production which contains complex molecules as nutrients and diverse microorganisms with the ability to decompose OM. Long-term use of manure can improve physical, chemical, and microbiological soil properties, and can also improve crop nutrition [7]. However, manure may contain pathogens and/or components that compromise food safety, limiting its direct use as a fertilizer. The solution lies in processes such as recycling and recovery of manure. For this purpose, anaerobic digestion (AD) and composting are used to stabilize manure so that it can be safely used for land application. AD, which stabilizes organic waste and reduces pathogens and odors, is a process that converts organic waste into methane-rich biogas and digestate (DG). Biogas is used for energy while DG is usually used as fertilizer in agriculture [8]. DG is a rich source of N, P, potassium (K) and sulfur (S), various micronutrients, and OM, the addition of which to the soil can stimulate microbial biomass and soil metabolic activities and accordingly improve soil ecosystem function [9]. However, the optimal fertilization properties of DG may be lost if it is neither fully stabilized nor contains biodegradable materials. To overcome such a problem, composting has been proposed as a post-treatment of DG. The composting process can transform the DG into mature, stable, safe, humus- and nutrient-rich compost, which offers the relevant advantage over the DG of maintaining and improving environmental quality and conserving resources. Compost is considered an important source of OM and nutrients for agriculture and plays an essential role in maintaining soil biodiversity and horticultural production when used as a component in the preparation of pot substrates. Moreover, the microflora of compost has significant antagonistic effects against various soil-borne phytopathogenic microorganisms, which may play an important role in their control. However, physico-chemical analysis of compost is important as it can provide real information about its composition [10]. Compost may contain an excess of heavy metals (HM) and a high salt concentration which can induce phytotoxic and/or genotoxic effects in crops [11,12]. Moreover, the survival and persistence of pathogenic organisms during composting pose both a potential health risk and an environmental problem when they successively accumulate in human tissues and are taken up by vegetation and biomagnifications via the food chain [13]. Therefore, biological control of compost is also of great importance as it can prevent and control soil-borne diseases caused by soil-borne pathogenic microorganisms [14].

Over the years, traders, consumers, and regulating bodies have expressed concern about the potential for onward contamination of food chains, the degradation of the environment, and perceived loss of brand value and, consequently revenue, for high-value products grown on land where these products were applied. Several questions arise in the context of these concerns: how can compost be made technically safe during composting and when it is used, and what confidence can citizens have in the safety declarations of waste processors and compost users such as farmers [15]? A true understanding of the fertilizer market and end-user requirements is needed to promote the adoption of DG processing technologies and the production of new types of biobased fertilizers on a large scale. In addition, the new biobased fertilizers must be sufficiently competitive with traditional mineral fertilizers [16].

Accordingly, short-, medium- and long-term strategic environmental policy goals are being set worldwide to support the expansion of a resource-efficient and circular economy based on the sustainable production of bio-based products from renewable

biomass. Consequently, innovative research efforts have been generated in recent years to develop and implement technologies to recover valuable resources, while the agricultural sector is forced to adopt more sustainable practices to reduce greenhouse gas and nutrient emissions [17].

The purpose of this review paper is to provide overview of the current state of DG management regulations and practices, and diverse treatment methods that have been developed to meet the needs of modern agriculture and protection of the environment, with an emphasis on composting as one of the preferred solutions.

## 2. Regulations and Standards for Manure Management in the EU

Due to its physicochemical properties, manure is widely used as a soil improver and organic fertilizer. It improves soil's physical and chemical properties due to its high buffer and cation exchange capacity, and the content of essential mineral nutrients such as inorganic N in the form of ammonium ($NH_3$), carbon (C), P, and S, and metals such as zinc and copper. What is more important, manure substantially increases soil C stocks and stabilizes OM content and C/N ratios in a more stable fraction over the long term which is the main driver for soil microbial diversity, enzyme activity, and the abundance of soil fauna. However, the chemical composition of manure varies based on animal feed, species, and processing method and it determines the fertilizing effects of manure and its influence on soil biodiversity. The most common practice is returning manure nutrients to fields with little or no processing which is mostly related to insufficient manure storage capacities. Application of unprocessed manure, meaning introducing pathogens and antibiotic-resistant genes into the soil, can harm soil biota and reduce the diversity of dung fauna [18].

When not handled properly, manure can cause adverse environmental impacts such as soil compacting following grazing activities, water, and soil pollution, greenhouse gas and ammonia emissions into the atmosphere, etc., [19].

Within EU-27 countries, it is estimated that 1.4 billion tons of manure from farmed animals were produced annually in the period from 2016 to 2019. More than 75% of produced manure originates from cattle, whereas pigs and chickens produce around 12% each. Due to the increasing demand for meat and animal-based products, manure is increasingly generated in highly intensive farming systems [18].

As a result, the livestock sector is considered one of the leading sources of environmental pollution which is the reason why manure management is a central issue in a series of international protocols, EU directives, and national regulations [20]. Since the second half of the 21st century, particular awareness of the effects of manure on the environment has awakened the EU community, as well as national and regional authority bodies, to implement specific regulations and limitations on manure management activities to regulate and mitigate these impacts. Currently, manure is not regulated under one single EU regulation or directive, but various directives, regulations, and laws for its management and quality are implemented in the EU Member States [18]. Among the main documents related to manure issues at the European level are the Nitrates Directive, IPPC Directive, the NEC Directive, the Water Framework Directive, and the Guidance document on ammonia emissions from agricultural sources [21].

The Nitrates Directive is the most critical EU tool for the management of manure and its impact on the environment which aims to protect water quality by designating nutrient vulnerable zones and proposing the Member States adopt Good Agricultural Practices in high-risk zones to prevent eutrophication [22]. A limit of 170 kg ha$^{-1}$ year$^{-1}$ of N from organic manure is set by the Directive, whereas some Member States provide farmers with exemptions if manure disposal does not harm ecosystems [23].

The IPPC (Integrated Pollution Prevention and Control) Directive refers to the minimizing of pollution from various agricultural activities [24] and advises the manure management of large animal farms.

The NEC (National Emissions Ceiling) Directive sets ceilings for every Member State for the whole emissions of the four chemical pollutants ($SO_2$, $NO_x$, VOCs, and $NH_3$) which are the main agents that cause eutrophication, acidification, and ground-level ozone pollution, but leaves it largely to the Member States to set their ceilings [25].

The Water Framework Directive aims to expand the scope of water protection to surface waters and groundwater and to achieve good conditions for all European waters within a certain period of time (Wiering et al., 2020) [26].

Guidance document on the ammonia emissions from agricultural sources is a regulation that specifies the current scientific knowledge and best techniques to reduce ammonia pollution in farms (e.g., chemical scrubbers, bioscrubbers, biofilters, etc.) [27].

France is one of the major livestock-production countries in the EU, it makes the largest contribution to total manures produced in the EU [19], and is also the only member that follows the rule of applying a maximum of 170 kg ha$^{-1}$ year$^{-1}$ N from organic manure [28]. All livestock farms are subject to French and European regulations and, depending on the size of the farm, farmers are subject to either Departmental health regulations, that is the Public Health Code, or Environmental Code (listed for environmental protection). The basic nationally prescribed measures for farm establishment and management may be strengthened by local regulations and depend mainly on the local climate and the vulnerability of the local environment [19].

In Germany, legal requirements have been introduced to reduce N losses in agriculture and ensure long-term food security, as well as to meet national and international environmental goals, i.e., fighting climate change, improving water quality, and reducing ammonia emissions. Due to exceeding the upper limit for ground waters defined in the Nitrates Directive at many monitoring sites, Germany was penalized by the European Law of Justice in 2018. This led to the German Fertilizer Application Ordinance tightening in 2020. Besides, to achieve the target for sustainable N management, Germany introduced a farm-gate balance through the Ordinance on Substance Flow Analysis. The nutrient balance of a farm is a relevant indicator for all inputs and outputs of a farm i.e., a relevant indicator for the analysis of the farm nutrient management, representing the potential threat to the environment and the supply of nutrients to the soil [29]. Because much of Germany's livestock production is located in the Northwest, large amounts of manure are transported between farms within the region. This transport takes place under the legal framework of the Fertilization Ordinance which largely implements the Nitrate Directive and also incorporates measures targeting P and $NH_3$ emissions [30]. In addition to Fertilization Ordinance, Germany has also implemented National Fertilizer Act, both of which aim to reduce nutrient losses from agricultural activities to protect groundwater and surface waters. With these two regulations, Germany aims to comply with the Nitrates Directive [31].

In Netherland, The Manure and Fertilizers Act is the main regulation implementing the Nitrates Directive, which specifies, among other things, the maximum amounts of N and P that may be applied to grassland and arable land, as well as the application methods [32].

In Sweden, Zero Eutrophication is the national regulation that is based on the Nitrates Directive. Out of a total of 16 National Environmental Objectives, Zero Eutrophication is one of the most important [33].

Most of the above-mentioned national regulations state that animal wastes may be applied only during the plant's growth season, while its application close to water streams is limited or forbidden [28].

As an EU Member State, Croatia has adopted the EU Nitrates Directive which is applied within the framework of the Action Programme for the Protection of Waters from Nitrate Pollution of Agricultural Origin. The aim is to achieve good status of surface water and groundwaters and to prevent deterioration of the already reached status of water bodies (NN 60/17). The other two regulations implementing the Nitrates Directive are the

Water Framework Directive (NN 153/09, 63/11, 130/11, 56/13, 14/14) and the Decision determining the vulnerable areas in the Republic of Croatia (NN 130/12).

## 3. Anaerobic Digestion

AD is a biochemical process in an anaerobic digester in which a consortium of microorganisms converts complex OM into biogas and DG under controlled conditions in the absence of oxygen [34]. It is a widely used technology by which the volume of different types of biomass, such as the organic fraction of municipal and industrial waste, energy crops, agricultural wastes, and forestry residues, is effectively reduced while renewable energy is recovered [35–43]. During digestion, three groups of microorganisms have been identified in anaerobic digesters where they grow optimally and survive and function in a wide range of temperature regimes [44]. These include psychrophilic, mesophilic, and thermophilic microorganisms. The psychrophilic microorganisms grow and function in a range of 10 to 25 °C and require a longer retention time of up to 70 to 80 days to convert biomass into biogas. The mesophilic microorganisms grow and operate in a range of 30 to 40 °C and require 30 to 40 days to convert biomass to biogas. The thermophilic organisms grow and function in a range of 45 to 60 °C under which they require a shorter retention time to generate biogas of 15 to 20 days [45]. Although the mesophilic temperature regime is most commonly applied in biogas plants, the thermophilic regime is often considered more useful as it offers several advantages, such as higher microbial diversity, faster and higher methanogenic activity, higher organic loading rate (OLR), accelerated hydrolysis and acidogenesis of the recalcitrant substrate, higher biogas production, higher rates of pathogen inactivation compared to the mesophilic regime. However, the thermophilic regime is a more energy-consuming and less stable process, producing biogas with lower methane ($CH_4$) content [44–46].

The process of biogas production is carried out by the combined action of three physiological groups of microorganisms: hydrolytic-acidogenic bacteria and most likely fungi, syntrophic acetogenic bacteria, and methanogenic archaea. The process is divided into four main steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Figure 1).

The first step (hydrolysis) is performed by the hydrolytic bacteria and possible fungi and in this step, the conversion of polymers into soluble monomers occurs which are further converted to short-chain fatty acids, hydrogen, carbon dioxide ($CO_2$), and alcohols by various fermentation reactions. During the steps of hydrolysis and acidogenesis polymers are converted into soluble monomers while acidogenesis polymers are converted to soluble monomers which are further converted to short-chain fatty acids, hydrogen, and carbon dioxide ($CO_2$), and alcohols by various fermentation reactions. After the hydrolysis and acidogenesis comes acetogenesis in which the acids and alcohols are degraded by acetogens to form $CO_2$, hydrogen, and acetate which are used by methanogens during the last step (methanogenesis) to produce biogas. Methanogenesis is the last step in the anaerobic food chain which is catalyzed by methanogens. In methanogenesis, products that are formed in previous steps are converted into $CH_4$. Acetogens and methanogens are in syntropy, meaning that they cannot operate without one another and when they do operate together they exhibit certain metabolic activities which they could not achieve on their own.

A large number of microorganisms that participate in the process of biogas production have been found but not all of them have been identified (Table 1). Because of requirements for low oxygen concentration and because of a high degree of commensalism and mutualism in microorganism communities the isolation, cultivation, and identification of those microorganisms are rather difficult. It is of essential importance to have knowledge of the anaerobic microbiome including mechanisms of interspecies interaction, metabolic capacities of microorganisms, and the level of functional redundancy within a community, for the optimization and steering of the process of the anaerobic digestion process. Microbial communities undergo large shifts in species diversity over a small period in the biogas production process but show surprising robustness and consistency over the long term [46].
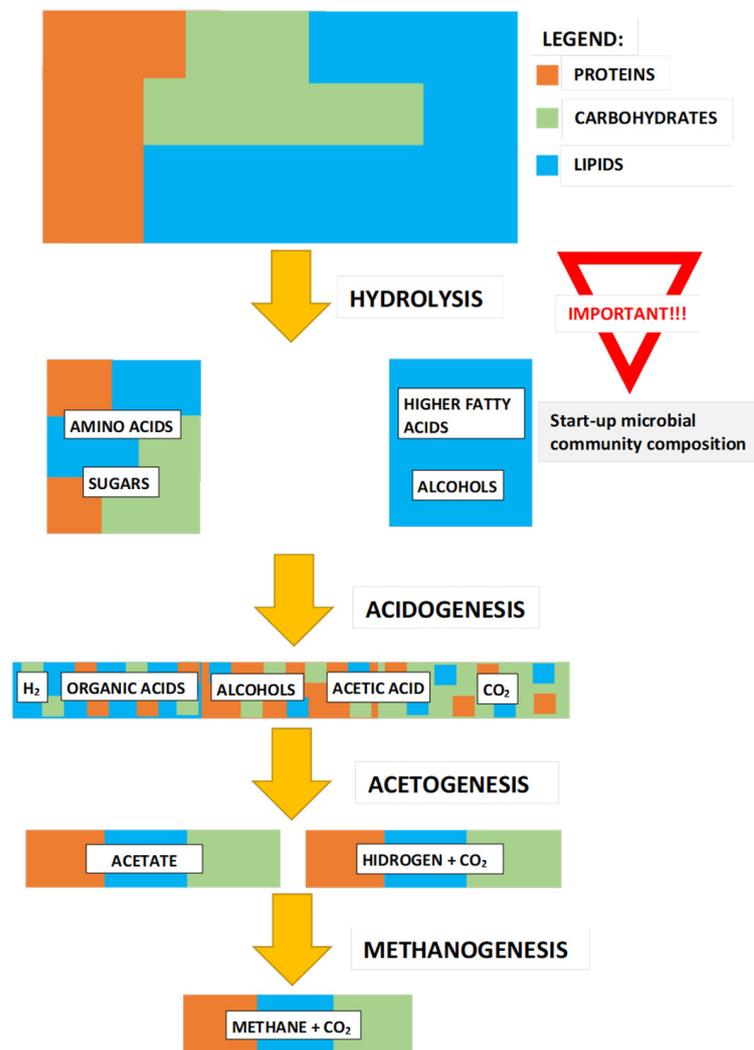
**Figure 1.** Phases of the anaerobic digestion process and their main products.

**Table 1.** Breakdown of organic polymers and microorganisms involved (adapted from [47]).

| Phase of AD | Input | Microorganisms Involved | Output |
|---|---|---|---|
| Hydrolysis & Acidogenesis | Proteins | *Clostridium* sp. *Proteus vulgaris* *Peptococcus* sp. *Bacteriodes* sp. *Bacillus* sp. *Vibrio* sp. | Amino acids Sugars |
| | Carbohydrates | *Clostridium* sp. *Acetovibrio calluliticus* *Staphylococcus* sp. *Bacteriodes* sp. | Amino acids Sugars |
| | Lipids | *Clostridium* sp. *Micrococcus* sp. *Staphylococcus* sp. | Higher fatty acids Alcohols Amino acids Sugars |

**Table 1.** *Cont.*

| Phase of AD | Input | Microorganisms Involved | Output |
|---|---|---|---|
| Acetogenesis | Amino acids Sugars | *Lactobacillus* sp. *Escherichia* sp *Staphylococcus* sp. *Micrococcus* sp. *Bacillus* sp. *Pseudomonas* sp. *Desulfovibrio* sp. *Selenomonas* sp. *Veillonella* sp. *Sarcina* sp. *Streptococcus* sp. *Desulfobacter* sp. *Desulfuromonas* sp. *Clostridium* sp. *Eubacterium* sp. *Streptococcus* sp. *Zymomonas mobilis* | Acetate Hydrogen<br><br>Intermediates<br><br>Alcohols |
| | Higher fatty acids Alcohols | *Clostridium* sp. *Syntrophomonas wolfei* | Hydrogen Acetate Intermediates |
| | Intermediates | *Syntrophomonas wolfei* *Syntrophobacter wolinii* | Acetate Hydrogen |
| Methanogenesis | Acetate (Hydrogen) | *Clostridium aceticum* | Hydrogen (Acetate) |
| | Acetate Hydrogen | *Methanothrix* sp. *Methanosarcina* sp. *Methanospirillum* sp. *Mathanobacterium* sp *Methanobrevibacterium* sp. *Methanoplanus* sp. | Methane |

## 4. Digestate

Although AD is considered one of the most favorable waste treatment technologies, especially from an environmental point of view, it is not able to fully stabilize waste. However, the process parameters can be adjusted to achieve optimal digestion in terms of biogas productivity and DG quality (Table 2). DG, remaining as liquid/solid residue after AD, can be used as soil fertilizer for crop growth [48]. However, DG from agricultural biogas plants does not meet the relevant soil regulations and therefore needs to be further treated by recycling to avoid environmental risks [49]. Nevertheless, unlike digested sludge and compost, there is a lack of knowledge about DG use in agriculture. DG has not been subjected to any scientific study revealing its configuration in agronomic terms, and whether DG might act more as a fertilizer or amendment, or both, is still not clear. DG can be separated into two fractions—the solid fraction, which has a much higher OM and P content, and the liquid fraction which has a higher N and K content. Therefore, the liquid fraction has greater potential as fertilizer while the solid fraction has a greater potential to amend soil composition [50]. Table 3 presents the main DG characteristics obtained after AD of various feedstocks. The table shows that the main DG parameters can vary greatly, depending on both, the type of substrate used in anaerobic fermentation and the AD process conditions.

**Table 2.** AD conducted with the aim to produce quality DG.

| Substrates | AD Process Conditions | The Aim of the Study | Results | Ref. |
|---|---|---|---|---|
| Corn stalks, tomato residues (stalks and leaves), dairy manure. | Batch mesophilic AD; feedstock to inoculum ratio: 4 (based on VS), TS of mixture: 20%. | Influence of digestion time on the performance of subsequent DG composting. | DG composting causes benefits on GI, pH, EC, and reduced GHG emissions compared to composting with raw feedstocks. | [51] |
| Olive wastes and citrus pulp mixed with straw, livestock wastes, and cheese whey. | Two biogas plants: (I) mesophilic regime, pH 7.8, HRT: 60 days. (II) mesophilic regime, pH 8.0, HRT: 60 days. | Influence of mixtures of substrates in order to produce a more stable DG with compatible soil use as fertilizer. | Increased OM content and optimization of nutrient balance positively affected soil fertility. Solid fractions increased soil stability and humification rates. | [52] |
| PM and FVW, dairy sludge effluent (inoculum). | Two semi-continuous stirred tank mesophilic reactors (bench-scale). TS of substrate: 8%. | Influence of PM mono-digestion and PM + FVW co-digestion on DG quality. | EC, COD, Mn, Ca and Zn values were statistically higher in PM than in PM-FVW DG. Both DGs showed high EC values. | [53] |
| MAR & TWAS. R1-untreated MAR; R2-MAR treated with KOH; R3-MAR/TWAS. | Pretreatment: (I) mechanical: knife, vibro, and planetary ball mill; (II) chemical: (a) $H_3PO_4$, (b) KOH; (III) thermal. BMP: mesophilic regime, continuous stirring. | Effect of pretreatment on DG quality. | Nutrient concentrations in R2 DG are lower than in R1, except for K (brought by the KOH). R3 DG contained high concentrations of $NH_4^+$, P, and K compared to R1. R2 was more stabilized and can be more beneficial for soil in the long term. | [54] |
| OFMSW, sludge, cattle slurry. | The mesophilic regime in both reactor types. | Monitoring of fecal indicators, pathogens, HM concentration, and fertilizing performance of DGs. | The presence of *Salmonella* and other pathogens, and high levels of Cu, Ni, and Zn in some DGs. A significant positive effect on plant growth observed with the DG from a lab-scale reactor. | [55] |
| PM, sunflower hulls, and seed sludge (inoculum). | Batch AD in the mesophilic regime. Substrates mixed in 6 different proportions (*w/w*). | Influence of anaerobically digested different substrates mixtures on DG characteristics. | The DG contained low amounts of HM and a high concentration of Zn. | [56] |
| Food and garden waste from the food industry and households. | Ground substrates were heated to 137 °C for 24 min at 2.4 bar and digested (mesophilic regime, full-scale AD). | Composition of separated liquid and solid DG fractions (concentration and seasonal variation of HM, organic pollutants, pesticides, and *E. coli* and *B. cereus*). | According to Norwegian regulation—higher Zn concentration; hazardous organic pollutants, two fungicide types, most frequently found in both fractions. Viable *B. cereus* detected in liquid phase; no DNA or viable cells of *E. coli* detected. | [57] |
| CM, PL, PS, and onion waste | Batch mesophilic digestion, manual agitation, HRT: 60 days. Manure: onion waste ratio 5:1 (*w/w*). | Influence of chemical and spectroscopic characteristics of AD substrates on soil biological activity; growth dynamic of lettuce and digested wastes incorporation into the soil. | Low C/N, high $NH_4^+$-N/N ratio, a greater proportion of short-chain organic acids, and greater stability of DGs if compared to fresh manures. Soils amended with DGs showed less $CO_2$ emission than soils amended with manures. | [58] |

**Table 2.** *Cont.*

| Substrates | AD Process Conditions | The Aim of the Study | Results | Ref. |
|---|---|---|---|---|
| 20 different DGs from different biogas plants-10 PS and 10 COM | Biogas plants operate under mesophilic or thermophilic conditions. | Influence of chemical characteristics of DGs on soil microbial activities, i.e., PAO and soil respiration | DGs contained significantly higher $NH_3$ concentrations, but lower TC and VFA concentrations if compared to PS and COM. The DGs showed both stimulating and inhibiting effects on PAO, while all COM and PS except one showed inhibiting effects on PAO. | [59] |
| APW and DM | Lab batch mesophilic AD. APW/DM wet weight ratios: 1:0, 3:1, 1:1, 1:3, and 0:1. The initial inoculum of each bottle was 30% (*w/w*). | The performance of AD based on the pH, TKN, CODt, and VS removal rate. Evaluation of the stability of DG by the TG and DSC analysis. | High stability of the DG was obtained after AD of APW and DM. Single digestion of the APW and DM was incomplete compared with the mixture thereby leading to the lower stability of DG. | [60] |

**Table 3.** Main DG characteristics obtained after AD of different feedstocks.

| Parameter | Unit | Values | References |
|---|---|---|---|
| EC | $\mu S\ cm^{-1}$ | 100–642 | [54,61] |
| pH | - | 5.6–8.6 | [51,54,61–64] |
| DM | % | 0.7–90 | [51,54,61–64] |
| OM | % DM | 15.6–98.0 | [54,61] |
| Total C | % DM | 10.4–58.7 | [51,54,61,63–65] |
| Total N | % DM | 0.2–20.5 | [51,54,61–65] |
| $NH_4^+$-N | $g\ kg^{-1}$ DM | 2.1–17.9 | [54,61,66] |
| Ca | $g\ kg^{-1}$ DM | 0.6–98.5 | [54,62–65] |
| K | $g\ kg^{-1}$ DM | 0.9–110.5 | [54,61–65] |
| Mg | $g\ kg^{-1}$ DM | 0.1–14.1 | [54,62,63,65] |
| P | $g\ kg^{-1}$ DM | 0.1–54.0 | [54,62–64] |

According to previous studies, DG represents an organic matrix used more for its fertilization properties (high N and P content, low C:N ratio), while amendment properties were only visible at high dosages [50]. In contrast, compost may improve the physical and chemical properties of soils by increasing the nutrient and water holding capacity, organic content, pH, and cation exchange capacity [67]. However, [68] conducted research comparing the properties of liquid undigested and digested animal slurries and DG from dedicated energy crops. The results showed a wide range of nutrient contents: DG had higher $NH_4^+$:total N (TN) ratios, decreased OM contents, decreased total (TOC) and organic carbon (OC) contents, reduced biological oxygen demands (BOD) (factor 5–13), increased pH values, lower C:N ratios, and reduced viscosities than undigested animal manure. Goberna et al. [69] also highlighted the benefits of DG like malodor reduction, pathogen control, a more balanced nutrient mix, and higher nutrient bioavailability but still no increase in nutrient leaching losses. However, the scientific literature regarding the survival of pathogens, HMs, persistent organic pollutants, and inorganic contents of biogas DG is not so well determined and little is known about their fate during DG processing [17].

High-quality DG suitable for soil fertilization is characterized by some essential features related to its properties such as declared content of nutrients, pH value, the content of dry matter and OM, and homogeneity. Equally important are DG features related to health and safety such as purity (free of plastic, stones, glass, non-digestible matter, etc.), hygiene or sanitization (free of pathogenic and other undesired biological content), and safety (safe for living organisms and the environment). These concerns demand strict controls and limitations on the undesirable content of both organic and inorganic chemical pollutants.

Therefore, the only feasible way to ensure the production of high-quality DG is to use high-quality feedstock as a substrate for AD [70].

Pathogenic microbes (*Escherichia coli*, *Salmonella* spp., *Listeria monocytogenes*, *Listeria perfringens*, *Campylobacter jejuni*, *Cryptosporidium parvum*, *Giardia intestinalis*, *Clostridium botulinum*) which are not a major problem in AD of various animal wastes (particularly cattle, pig, poultry and sheep manure) [71], can survive the digestion process and remain in the DG [69]. Since DG can play a role in transporting pathogens from agricultural land through the food chain to humans, proper sanitation is essential. Proper sanitation of DG also depends on the quality of the substrates fed to the reactor, as well as the reactor performance, digestion temperature, slurry retention time, pH, and $NH_3$ concentration. In addition, different pretreatment methods can be used to reduce the number of pathogens in the final DG, such as pasteurization [72], treatment with chlorine, UV-light, ozone, and high internal pressure in the vessel [73]. However, animal by-products that originate from the food industry (various waste from livestock production, slaughterhouse, and food processing) and are not suitable for human usage, that are used for AD, require pasteurization i.e., hygienization before AD. This process is carried out at 70 °C for at least 60 min whereas the maximum size of particles that enter hygienizers should not exceed 12 mm. The objective is to reduce the concentration of *Enterococcus faecalis* or *Salmonella senftenberg* by a factor of $10^5$ and thermal-resistant virus by $10^3$. *Enterococcus faecalis* (Gram-positive bacteria) and *Escherichia coli* (Gram-negative bacteria) are two microorganisms that often serve as indicators characterizing the performance of the hygienization process. *Enterococcus faecalis* is also chosen by EU regulation No. 142/2011 as indicator bacteria [74]. Although the thermal inactivation of pathogens has been widely studied on a laboratory scale, consideration should be paid when applying the results to large-scale systems. Exposure time that is required for the inactivation of pathogens may be affected by uneven heating, fluctuating temperatures, or shielding properties of solids. Therefore, the transfer of the laboratory results to full-scale systems requires further investigation [75]. Besides conventional thermal pasteurization technologies, alternative thermal pasteurization technologies such as electro-technology, microwave, pressurization, ultrasound, and chemical treatments, are capable of considerably reducing the number of bacteria and at the same time increasing the $CH_4$ yield. However, their performance varies greatly and depends on the type of bio-waste, the operational parameters, and energy input [76]. Yet, several spore-formers and therefore less heat-sensitive bacteria (e.g., *Clostridium* spp. and *Bacillus* spp.) cannot be reduced [69,77]. This was confirmed with a study in which the microbiological quality of the DG from three different biogas plants in Sweden was studied. Control of spore-forming species and presence of antibiotic resistance were conducted, and the results confirmed that all formal criteria were met, the amounts of *Escherichia coli*, enterococci, and *Salmonella* were all below the maximum accepted levels at all three locations. However, DGs from all plants had unsanitary levels of the food-borne spore-forming pathogen *Bacillus cereus* [78]. The results are in agreement with a previous study [79] conducted on the hygiene aspects of DGs where high levels of *Bacillus* spp. were detected, and it was concluded that neither the hygienization treatment nor the subsequent AD affected the number of *Bacillus* spp. In another study by Le Maréchal et al. [80] liquid manures and DGs from five biogas plants in France were examined to assess the contamination by sporulating (*Clostridium perfringens*, *Clostridioides difficile*, and *Clostridium botulinum*) and nonsporulating (*Escherichia coli* and enterococci, *Salmonella* spp., *Campylobacter* and *Listeria monocytogenes*) bacterial species. Authors concluded that spore-forming bacteria, as well as *Listeria monocytogenes*, *Salmonella* spp., and enterococci, can persist during AD, but the concentration of the pathogens was similar or lower in DGs than in liquid manures. Therefore, further treatment of the DG is recommended to obtain a more efficient reduction of pathogens. Since the DG is often stored before being spread on agricultural land, the potential regrowth of pathogens during the storage may also occur. Therefore, [81] attempted to find a technical solution to either eliminate or reduce the content of spore-forming pathogen *Clostridium* spp. in the stored solid DG so that it could be safely used as fertilizer or amendment. They converted the

solid part of DG into pellets and after microbiological analysis, the results showed complete elimination of *Clostridium* spp. in pelleted DG samples.

HM contents in DG can vary widely (Table 4). These variations are related to the input materials, which are usually classified as green waste (organic waste from private gardens and public green areas) and bio-waste (green waste and food and kitchen waste from households, restaurants, caterers, retail premises, and waste from food processing plants). In addition, the origin of the input material could be important because the aerial deposition of HMs is usually higher in urban environments than in rural regions, while the season of input material collection might play a role, as the deposition of HMs tends to peak in winter [82].

**Table 4.** HM content in DGs obtained after AD of different substrates.

| HM (mg kg$^{-1}$ DM) | Values | References |
|---|---|---|
| Cd | 0.18–5.0 | [55–57,61,62,65] |
| Pb | 0.02–126 | [55–57,61,62] |
| Cu | 1.4–681.0 | [55–57,61–63] |
| Hg | 0.05–1.34 | [55–57,61] |
| Ni | 0.51–355.9 | [55–57,61] |
| Zn | 0.81–4019 | [55–57,61–63] |
| Cr | 0.06–560.3 | [55–57] |
| Fe | 371–29 837 | [55,62,63,65] |
| Mn | 31.5–96.5 | [65] |

In recent times, the DG composition has been increasingly studied at the molecular level. Such data may be useful in identifying structural changes during the mineralization of OM [83]. For these purposes spectroscopy techniques like nuclear magnetic resonance (NMR) and Fourier transform infrared spectroscopy (FTIR) have been proposed and most commonly used. These methods can selectively identify different types of C and H and therefore enable the comparison of different concentrations of main functional groups [84]. According to [85], during AD most OM is converted into biogas, while the biological stability of remaining OM increases during AD with the increase of more recalcitrant molecules such as lignin, cutin, humic acids, steroids, and complex proteins which are possible humus precursors with high biological stability. This was also confirmed by other studies. Schievano et al. [86] conducted research in which they analyzed twelve DGs sampled from a full-scale biogas plant co-digesting swine manure, various energy crops, organic residues, and the OFMSW. The authors conducted the spectroscopic analysis of DGs. The spectra obtained by NMR showed four regions representing four different types of organic molecules such as carboxyl-C, aromatic-C, O-alkyl-C, and the aliphatic-C. Comparing the spectra of one of the considered anaerobic substrates and its relative DG, the more degradable molecules (the region of the O-alkyl-C) resulted in a net decrease in the DG, while the more recalcitrant OM fraction (other three types of organic molecules) resulted in a relative net increase in the DG. Therefore, the authors confirmed the relative accumulation of molecules containing carboxyl-C, aromatic-C, and aliphatic-C in more recalcitrant fractions such as lignin, cutin, humic acids, steroids, and complex proteins. Gómez et al. [87] co-digested CM with bedding material (straw) for a prolonged period to evaluate the changes in OM content. Degradation of the OM was evaluated using thermal analysis and NMR. Stabilization through AD increased the quality of the OM (characterized by enrichment in thermostable compounds), and an accumulation of long-chain aliphatic materials.

AD feedstocks (mainly sewage sludge, domestic wastewaters, industrial organic waste, household waste, and even food waste) can contain various amounts of unwanted chemical matter of which some are persistent organic pollutants. Feedstocks derived from agriculture in most EU countries where strict legislation bans the use of pesticides from the United Nations list of persistent organic pollutants (e.g., diklorodifeniltrikloroetan or

DDT, heksaklorocikloheksan or HCH, etc.) do not contain such pollutants. However, trace amounts of other pesticides, antibiotics, and chemicals used in agriculture can be present in agricultural feedstock [70].

Nowadays different distribution models can be applied depending on the specific biogas installation, the geographical area, the type of feedstock and DG, and the economics. DG distribution models are not a standard method that can be useful for all biogas plants, where wrong decisions about DG distribution can be critical for the viability of an AD project. Therefore, it is important to analyze the characteristics of the biogas plant and to develop a proper DG management plan which should be integrated into the farm's fertilizing plan in the same way as mineral fertilizers, and it must be applied in a uniform and accurate rate [88]. The most common distribution models are presented in Figure 2.
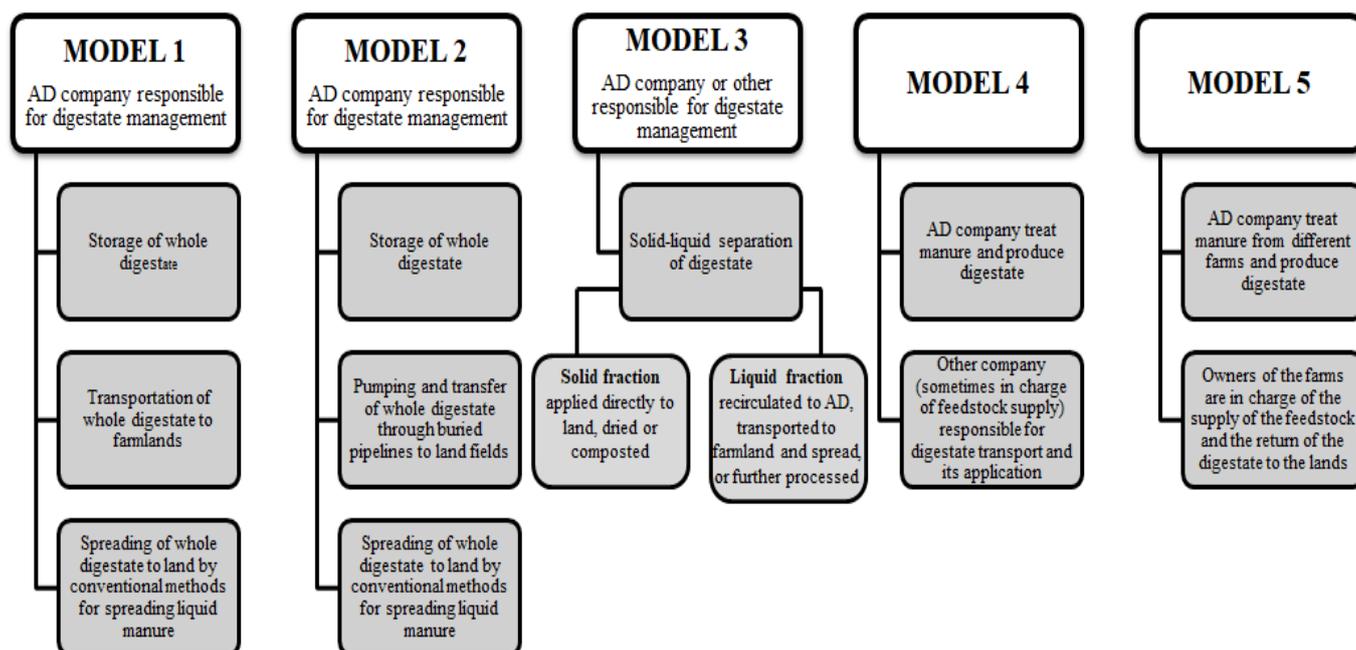


**Figure 2.** Distribution models of DG (according to [88]).

## 5. Digestate Processing

About 180 million tons of DG are produced annually in the EU. Most of the DG produced (120 million tons) is of agricultural origin (typically a mixture of manure and plants, particularly energy crops). About 46 million tons are produced from the organic fraction of mixed municipal solid waste, at least 7 million tons from source-separated biowaste, while the smaller quantities (about 1.7 million tons each) come from sewage sludge and agro/food industry by-products [89]. DG remaining after AD is stored before utilization. Several factors affect the required storage period of DG, such as environmental restrictions for application, DG stabilization, geographic location, soil and crop type, and DG demand. The storage of DG requires a significant amount of cost and land occupation [88]. The most common utilization of DG is a direct application to agricultural land which is a well-known and proven technology. However, to protect groundwater resources, the balance of nutrients in the soil needs to be considered and the legal limits of maximum allowable nutrients loads have to be complied with [90]. In addition, some factors such as non-uniformity (which is determined by properties of the biomass which was used for AD), highly variable nutrient content, high volume of DG, and the impossibility of spreading DG near the biogas plant impact the economics of DG marketing sometimes making its use difficult to realize [88]. For these reasons, there is an increasing focus on adequate DG treatment options.

The major goals of DG treatment are (i) volume reduction to improve the manageability and reduce transportation costs, and (ii) recovery of nutrients in concentrated form. In general, DG treatment processes can be classified into two different approaches: (a) Partial treatment—this aims to reduce the volume or separate it into solid and liquid fractions that can be more easily handled or stored. It is usually the first step in the DG treatment and is less energy demanding and cheaper if compared to (b) complete purification—where the valuable ingredients are separated and concentrated while the remaining liquid fraction is purified, allowing reuse in the AD process or direct discharge to a water body [88,90].

Different processing technologies (Figure 3) result in different physical characteristics and fertilizer values of the final product [90]. Although significant capital costs are required due to adequate machinery, high energy, and reagent consumption [88,90], the lower operating costs derived from the decrease in water, energy, and feedstock consumption make these technologies a profitable investment in the medium and long-term. Since DG treatment has only recently (about the last 10 to 15 years), become a focus of interest, there is no standard procedure and rather a wide variety of treatment schemes exists.
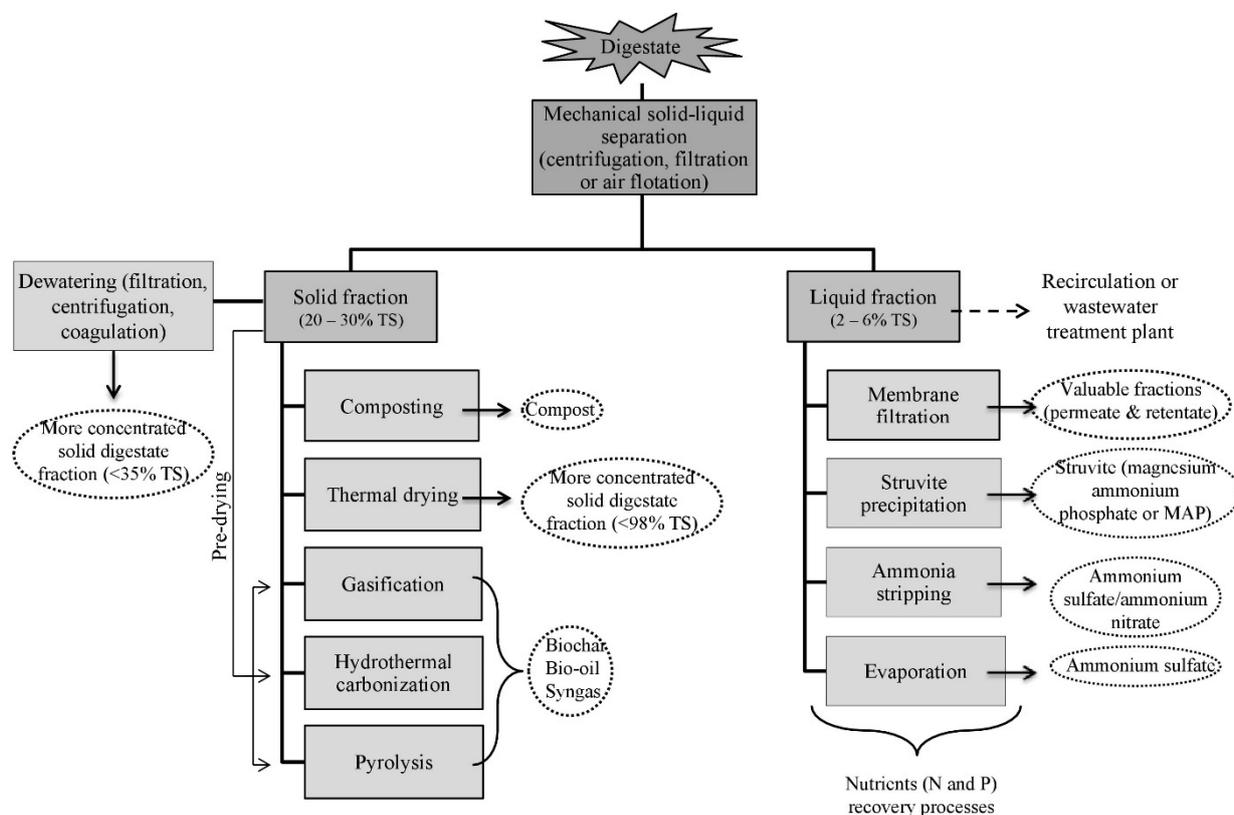


**Figure 3.** Most commonly applied DG valorization processes.

Except for specific cases, such as some advanced technologies and membrane filtration technologies, all processes described below have already been applied at a large scale [91]. Most of the DG treatment technologies that are currently available on the market work on volume reduction and concentration of nutrients [92].

*5.1. Solid-Liquid Separation*

Separation of the DG into a solid and a liquid fraction is a simple and low cost-effective technology [93], which is usually carried out before any further post-treatment of the DG [94]. Solid-liquid separation reduces the volume of the DG and is usually performed by screw press [90,93,95] or by thickening [91,95]. Thickening can be a static (gravity settling) or a dynamic process (filtration, air flotation, or centrifugation) that concentrates DG to as low as up to 5 to 10% suspended solids [91]. Due to the amounts of

undigested OM and extracellular polymeric substance (EPS) from microbial metabolites, DG is hardly dewatered effectively. Therefore, polyelectrolytes can be added to increase the concentration of suspended solids [95]. The dense slurry can be further dewatered to obtain a cake with a solids content of up to 35%. Dewatering can be performed by mechanical methods such as filtration and centrifugation, or by electrochemical and physicochemical methods such as electrocoagulation and chemical coagulation [91].

Solid fraction, often referred to as pressed cake, which concentrates dry matter (between 20 and 30%) and nutrients, mainly organic N and P [96], is generally used as an organic amendment [93]. Liquid fraction, with a dry matter content of around 2 to 6% [96,97] concentrates mineral N above all in the form of ammonia and therefore can be used as a fertilizer in substitution for mineral fertilizers [93]. Due to its high fertilizer and humus value, the solid fraction is regarded as cost-effective to transport, while the liquid fraction has limited market potential due to its high water content and low organic content [96].

### 5.2. Treatments of the Solid Fraction

After solid-liquid separation of the DG, each fraction can be treated to remove or extract nutrients. The solid fraction, which is partially stabilized after liquid fraction separation, can be used directly as a biofertilizer or soil conditioner. Since it still contains some biodegradable materials, microbial activity can still be active and odor emissions can also occur [98]. Therefore, a solid fraction can be chemically or thermally stabilized. Chemical stabilization is usually performed by adding an acid to decrease the pH and prevent the loss of ammonia during storage or land spreading, or by adding alkali to raise the pH, kill pathogens, and neutralize odors [91].

### 5.2.1. Composting

The organic material in the solid fraction of the DG is converted to $CO_2$, biomass, thermal energy (heat), and humus-like end-product [99] by microorganisms under aerobic conditions in the controlled self-heating composting process [98,100,101]. The ability of microorganisms to assimilate organic material depends on their ability to produce the enzymes needed to degrade the composted material. The more complex the composted material, the more comprehensive the enzyme system required. Typically, composting process goes through three phases: mesophilic (usually at 25–40 °C), thermophilic (lasts from a few days to several months, usually at 40–65 °C), and cooling and maturation (lasts for several months usually at 10–40 °C) [99,101]. The length of the composting phases depends on the nature of the OM and the efficiency of the process, which depends largely on the degree of aeration and agitation. At the beginning of composting, the biomass is at ambient temperature and is usually slightly acidic. In the early stages of composting, microorganisms utilize soluble and easily degradable C sources such as monosaccharides, starch, and lipids [99]. This is accompanied by the formation of organic acids formation which causes pH to be lowered (to 5 or less). In the next stage, microorganisms start to degrade proteins, which lead to the release of $NH_3$ and an increase in pH (to about 8 or 8.5) [101]. Then, more complex compounds such as cellulose, hemicellulose, and lignin are partly converted into humus which is the final product of the humification process. Humification is a process in which compounds of natural origin are partially converted into humic substances (humin, humic acids fulvic acids), which are considered the major reservoir of OC in soils and aquatic environments. In general, immature compost contains a high proportion of fulvic acids and a low proportion of humic acids, while as decomposition proceeds, fulvic acids either decrease or remain unchanged, while humic acids are formed. At the beginning of composting, mesophilic bacteria predominate, but after the temperature rises above 40 °C, thermophilic bacteria and fungi take over. When the temperature exceeds 60 °C, microbial activity decreases significantly [99]. Due to the high thermophilic temperatures maintained during the process, pathogens and antibiotics could be effectively removed [102]. After the compost has cooled, mesophilic bacteria and

actinomycetes become dominant. In addition to aerobic microbes, anaerobic bacteria could also be found in compost piles. Since all anaerobic bacteria present in the compost are cellulolytic, they may play a significant role in the degradation of macromolecules [99]. The pH decreases slightly during the cooling phase to a range of 7 to 8 in mature compost. Composting can tolerate a wide pH range, from 5 to 8, with a pH between 7 and 8 generally considered optimal [103].

The process can be carried out in a closed (reactor) or open system (open-air or under a roof). Open system composting that is composting in the open air, is the oldest, the best known, and the cheapest composting method in which composted waste is piled with a triangular or trapezoidal cross-section. The piles are aerated by forcing air through the compost mixture by shifting or using blowers or fans. The main thermophilic phase of composting lasts 6 to 12 weeks, which depends on the moisture and oxygen content, C/N ratio, and air porosity of the composted material. Composting in reactors (containers, chambers, tunnels, and closed halls and towers) is quite similar to composting in piles, although it takes place in a closed reactor which allows better control of process parameters and facilitates the maintenance of low emissions to the environment through the ability to capture and purify polluted air [100].

Recent efforts have been applied to improve composting performance, such as optimizing process parameters (aeration rate, feedstock properties, and matrix structure), adding useful additives (bulking agents), and integrating hybrid systems [102]. Aeration plays an important role in oxygen supply, temperature regime, and moisture control of composting [94].

Optimum aeration rates have been systematically studied for various organic solids and it was concluded that increasing the aeration rate can promote the activity of aerobic microorganisms for the decomposition of the OM. However, increased aeration may increase greenhouse gas and ammonia emissions, and facilitates the release of generated heat and water which can inhibit microbial growth and activity. Therefore, optimal aeration intensities should be determined for the specific composting process [102]. The addition of bulking agent, which helps to construct the composting pile and assures a good distribution of the airflow and hence the free-air space inside the piles [94], improves the physio-chemical properties of organic solid wastes, particularly those with high moisture and density, and consequently advance their composting [102]. Furthermore, the bulking agent can have positive effects such as increasing nutrient concentration, decreasing electrical conductivity, decreasing N concentration in terms of increasing C/N ratio, and diluting HM content in compost [98]. Special attention should be paid to the ratio of bulking agent and DG as it affects the initiation of composting [102]. Commonly used bulking agents are mostly derived from plant material [99] e.g., lignocellulosic waste such as corn stalks, straw, mushroom residues, sawdust, and green wastes. Numerous researchers also suggest materials with high porosity and a large specific surface area such as biochar, ceramsite, and zeolite [104]. Vermicomposting, which uses earthworms to stabilize DG and eliminate pathogens, is also a sustainable approach to DG management that, like composting, is an easy-to-use, eco-friendly and cost-effective technology [91].

Besides all the advantages, composting DG also has some disadvantages [94]. During AD, organic N is transformed through a series of reactions like ammonization, anaerobic ammonia oxidation, and denitrification. Most of these N substances result in high $NH_3$-N content in DG which can be easily volatilized in the form of smelly and toxic $NH_3$ in the thermophilic period of composting [104]. Once released into the atmosphere, $NH_3$ emissions may lead to acid rain and eutrophication of local systems. Furthermore, the nitrifying microorganisms can develop during composting and oxidize $NH_3$-N to nitrites ($NO_2^-$) and nitrates ($NO_3^-$) and can further reduce $NO_x^-$ to $N_2$. Both nitrification and denitrification can emit $N_2O$ which can be known for its high global-warming potential and for causing ozone depletion. Other disadvantages include high moisture content, which affects very low composting efficiency, low C/N ratio, which requires a long composting process, and

low DG degradability, which results in a low-temperature rise during composting that cannot ensure the required disinfection of the compost [94].

In literature as well as in industry, there is insufficient information to optimize the operational parameters of DG composting [94].

Table 5 summarizes studies related to DG processing via composting.

**Table 5.** The studies related to DG processing via composting.

| Substrate | Process Conditions of Composting | The Aim of the Study | Results | Ref. |
|---|---|---|---|---|
| DG (household wastes) | Mixing ratios WC:DG = 1:1, 2:1, 3:1, 4:1, 5:1 in volume; aeration rate: 7, 15 and 30 $Lh^{-1}$ kg $OM_0$ | Influence of different sizes of BA and different mixing ratios of DG and BA on compost quality. | Higher mixing ratios of substrates increased $O_2$ utilization and self-heating potential, and reduced gas emissions. 15 $Lh^{-1}$ kg $OM_0$ assured $O_2$ supply, self-heating, and limits $NH_3$ emission. | [94] |
| DG | Concentrations of OS in DG: 0, 10, 20 and 30; C/N ratio: 25–30; aeration rate: 0.15 $Lmin^{-1}$ $kg^{-1}$ TS | Influence of OS as BA on composting and different mixing ratios of DG and BA on compost quality. | Improved OM degradation promoted the transformation of $NH_4^+$-N to $NH_3^-$-N and enhanced composting performance. GI revealed improvement in compost quality. | [104] |
| Solid residue DG | DG was mixed with equal parts of peat and composted for 80 days | Evaluation of composting parameters of DG from 3 depths: T of composting pile, TOC, TN, TK, TP, pH, ECs, $NO_3^-$-N, and $NH_4^+$-N. | $NH_4^+$-N, TOC, and C/N decreased with the composting process, while TP, TK, and $NO_3^-$-N increased. GI and SGI showed that raw DGs were toxic to plants, but the GI and SGI increased during the composting process. | [105] |
| DG fraction (agricultural waste and distillery stillage) | DG was composted for 51 days in 165 L composting bioreactors. Aeration was performed on days 16 and 34 by manual mixing. | Composting parameters: dry matter, OM, pH, ECs, and T; daily measurements of gaseous emissions. | DG shows a very good structure and proper C/N ratio for composting. Production of compost from DG could be a good solution for managing digested waste. | [106] |
| The solid phase of DG (maize silage, peach juice pulp, cattle slurry) | Lab-batch experiment which lasted 96 h. Moisture = 50 and 70%$_{DM}$ (*w/w*); C/N ratio: 28, 31, 33 and 36; OM = 88.07%; T measured every 15 min; aeration for 2 min by opening the Dewar jars | Optimization of pH, C/N ratio, and moisture values to maximize self-heating activity (Dewar tests) to establish the startup conditions to transfer the procedure to an industrial scale. | The optimal conditions (pH = 7.7, moisture = 50%) obtained experimentally were used to develop a mathematical model which for process optimization. The conclusions should be validated on an industrial scale to check reproducibility and compliance with standards of stabilization, sterilization and compost quality. | [103] |
| Fresh, air-dried, and oven-dried DG (municipal organic waste) | A part of solid DG was taken for air-drying (20–30 °C), a part was treated in open heaps for 6 weeks, and the third part was dried at 70 °C in a laboratory oven until the weight of DG remained constant. | Influence of drying, composting, and sieving on final DG properties, nutrient availability, HM, and C elution. | Sieving of composted DG showed that HM concentration increases with decreasing mesh sizes. The element concentration is higher in composted batches, while the water-extractability of nutrients, HM, and C is significantly lower in composted over dried DGs. A significant correlation was found between the dissolution of Zn, Ni, Ca, and Mg, pH of eluate, and DOC release (R > 0.7, $p < 0.05$). | [107] |

**Table 5.** *Cont.*

| Substrate | Process Conditions of Composting | The Aim of the Study | Results | Ref. |
|---|---|---|---|---|
| A solid fraction obtained by mechanical separation of DG produced by AD of PS, ECs, and AIR | DG and LBA mixture ratio 4:1 (*w/w*), lab-scale adiabatic reactor (90 days). Aeration: 14–16% $O_2$ during the bio-oxidative phase, (during 6 to 12 days) after which the material was placed in a plastic container (curing phase; wetting and turning weekly). | Evaluation of compost and composting quality of solid fraction of DG—chemical and biological characterization. | DG produced by AD had high biological stability with a PDRI close to 1000 mg$O_2$ kgVS$^{-1}$h$^{-1}$. Subsequent composting of a mixture of DG and LBA did not give remarkably different results and led only to a slight modification of the characteristics of the initial non-composted mixtures. The composts obtained fully respected the legal limits for high-quality compost. | [108] |
| A solid fraction obtained by mechanical separation of DG produced by AD of PS | Different mixtures of DG and BA: WSD for P1 and P2, EGM for P3, VSP for P4, and PPP for P5; thermo-composters, natural ventilation. Aeration and T control were maintained by turning. Moisture = 40–70%. | The feasibility of the treatment of the solid fraction of a PS DG by co-composting with different BA, and determination of the final characteristics of the produced composts. | The composts showed suitable physical properties, and a degree of stability and maturity for their potential use as growing media. Also, the type of BA strongly influenced the development of composting and the final properties of the composts, showing the mixtures with WSD and VP the most suitable characteristics. | [109] |
| SD from a WTP, and an DG from a biogas plant treating CM | SD and DG mixed with WSD as BA, turned 3 times a day to homogenize the mixture and maintain adequate $O_2$ levels; moisture = 55%. | OM degradation and microbial community dynamics during the thermophilic phase of composting. | Variations in T, pH, moisture, and bacterial profiles were similar in both processes. SD constituted more than 20 bacterial phyla, DG was represented by 7 phyla. | [110] |
| Ten SW and five DGs (AW, MSW, biowastes, SS, and GW) | Aerobic treatment for 31 days. The mixing ratios of BA (oak wood chips) to substrates ranged from 0.4 to 1.1 (fresh mass basis). Mixtures were turned twice (after 10 and 20 days of the process) by emptying the reactors, mixing their load, and refilling. | Determination of volatile compounds (chemical composition) and odor emissions (concentrations) upon composting of different DGs and SWs. | A total of 60 chemical compounds were identified and quantified. Terpenes, oxygenated compounds, and ammonia exhibited the largest cumulative mass emission. The composting process of SWs accounted for OEFs ranging from 65 to 3089 OU$_E$ g$^{-1}$ OM$_0$; DGs showed a lower odor emission potential with OEF ranging from 8.6 to 30.5 OU$_E$ g$^{-1}$ OM$_0$. Volatile S compounds were the main odorants (POi = 54–99%). | [111] |

Integrating compost into a farm's nutrient management plan should aim to maximize the use of nutrients supplied. Adequate application of compost help farmers achieve good crop performance and avoid wasting money, and also avoid environmental harm. Compost is best suited for soils requiring OM and/or P and potash. Soil condition and condition of equipment prior to compost application should be considered, as well as calculating the nutrients supplied by the compost and subtracting them from the crop's need.

Since the nutrient content and liming value of compost can vary from manufacturer to manufacturer, it is recommended that users get an up-to-date laboratory analysis of the compost that is planned to be applied to the soil. Furthermore, when handling compost as with all biological materials, users should wear gloves, and avoid consuming any of the material or inhaling any airborne dust, water vapor, or microscopic particles that may be generated when handling [112].

Costs of the composting processes may vary considerably which mainly depends on local conditions, the quality of the material to be composted, pollution control equipment, front-end separation technologies, and techniques to reduce odors, as well as the costs for marketing. Though, the most important variable is whether the process is carried out in-vessel, or in open-air windrows. According to an economic analysis conducted in 2009 by Eunomia [113], an independent consultancy company, open-air windrow composting can cost less than EUR 20 per tonne. However, after modeling best practice technologies in their report, Eunomia suggested that EUR 45 per tonne (excluding revenue) may be a price for a plant of 20,000 tonnes capacity. However, production prices may differ between countries. For instance, in some countries like Germany (EUR 80–160 per tonne), Denmark (EUR 106 per tonne), and Luxemburg (EUR 70 per tonne) these estimates are too low.

Generally, the greater the size of the system, the more economically viable it became. The profits generated from compost sale came primarily from gate fees, although compost sales also made a modest contribution to the economic viability of the facilities. The choice of composting technology, management practices, market access, and availability of carbon credits also impact the price of compost production [114].

### 5.2.2. Thermal Drying

Drying of the solid fraction of the DG aims to stabilize and dry the DG in about 7 to 10 days [91] and reduce its total mass, as well as increase the nutrient concentration [98]. Therefore, drying facilitates sanitation, storage, and transportation [115]. Wet DG showed higher cumulative ammonia emissions than dewatered DG. In many cases, electric power is produced at biogas plants, and surplus heat can be exploited for drying [98]. The substrate is dried by air convection which evaporates the water. This process is similar to composting although drying aims to eliminate humidity and conserve the highest amounts of C (up to 45%) in the dried solids. Hundreds of DG drying systems exist on European farms, but the most prevalent are belt dryers, drum dryers, and solar dryers [116]. Exhaust gasses from DG dryers contain dust, ammonia, and other volatiles, so exhaust gas cleaning systems (e.g., scrubbers and washers) should be used to reduce emissions [117].

### 5.2.3. Thermochemical Treatment

In a typical AD process, the energy conversion efficiency is about 33 to 50% which means that more than half of the energy remains in the DG [118]. Therefore, thermochemical treatments of DG could be coupled with AD to improve energy efficiency and biomass utilization [119]. However, the application of thermal decomposition treatments of DGs is relatively limited [116]. The three most commonly applied treatments are gasification, hydrothermal carbonization, and pyrolysis [119]. The main advantage of thermochemical processing is the production of value-added products (such as biochar, bio-oil, and syngas) [120] in a short period without worrying about fluctuations in the microbial community. The key limiting factor in these processes is the moisture content, which should be less than 30%.

Gasification is the partial oxidation of OM that occurs in a temperature range from 800 to 1200 °C [121]. The main product of the process is syngas, while other products are solid carbonaceous biochar and bio-oil (a mixture of different polycyclic aromatic hydrocarbons). Several authors have shown that gasification of the dried solid fraction of the DG could be a promising way to produce a gaseous product that can be used as fuel in an internal combustion engine, while the by-products (biochar, bio-oil, and ash) can be further converted into value-added products and used for different purposes [118,121].

Hydrothermal carbonization (HTC) is a process that converts OM into high C content under varying temperatures (190–250 °C) and pressure (2 to 10 MPa) for several hours. Through relevant studies conducted over the last decade, HTC has emerged as a promising technology due to its many advantages such as the conversion of biomass into numerous products, e.g., solid fuel, bio-oil, soil amendment, activated C material that can be used as an adsorbent, C catalyst [122]. The HTC process may be classified as either a direct or

catalytic HTC process. In the direct HTC process, only water and feed are heated in a reactor at different temperature ranges, while the catalytic HTC process uses a catalyst [123].

Pyrolysis is a process that converts high solids content substrates into value-added products such as biochar, bio-oil, and syngas by heating in the absence or low concentration of oxygen [119]. It is usually conducted in an inert gas environment at atmospheric or slightly high pressure, although vacuum conditions or pressurized hydrogen (H) are sometimes employed [124].

Biochar is a C-rich solid produced by the decomposition of biomass in the presence of little or no oxygen [125]. Biochar exhibits various properties such as highly-porous structure, functional groups, large specific surface area [119], high cation exchange capacity, and stable structure. Therefore, it has attracted increasing attention, which is evident from the increasing number of published studies related to biochar [126]. Most of the attention on biochar applications has focused on its use to increase crop yields [127,128], improve nutrient availability in soil [129,130], as a soil amendment [131,132], and on environment protection application, such as wastewater treatment [133,134], water purification [135,136], C sequestration [137,138], detoxification [139,140], etc.

Bio-oil is considered to be of great importance due to its high content (up to 50% or more) in thermochemical treatment products [141]. Therefore, researchers are increasingly focusing on recovering bio-oil for purposes such as clean and renewable fuel [142] and various chemicals [143]. However, currently, bio-oil is considered an unsuitable drop-in fuel due to its poor properties, such as oxygen content, low C and H content, acidic pH, high instability, and low higher heating value (HHV) [141].

Syngas, or synthesis gas, is a mixture of gases (mainly $CO$, $CO_2$, and $H_2$). The proportion of each gas depends on the type of biomass used as a feedstock, the configuration of the gasifier, and the process parameters of the thermochemical process. Syngas is important from an environmental point of view as it is an important by-product of several industrial processes such as steel milling, petroleum refining, steam reforming, etc. [144], and can be used as a substitute for natural gas to facilitate demand [145].

*5.3. Treatments of the Liquid Fraction*

After solid-liquid separation, some nutrients and suspended solids remain in the liquid fraction. Due to regulatory requirements, it cannot be discharged directly to a receiving water body [98] but can be sent to a wastewater treatment plant. There are several technologies recommended for the extraction and valorization of nutrients from the liquid fraction, the application of which depends on economic viability and environmental impact [91]. Besides further processing, the liquid fraction can be reused as a nutrient-rich medium for algae cultivation [146], or again in AD [120]. The recirculation of the liquid fraction of the DG in the biogas digester is an interesting option to reduce $CH_4$ emissions and produce more biogas from feedstock [147]. Several studies have confirmed the residual $CH_4$ potential of recirculated DG, e.g., [148] conducted mesophilic AD in continuously stirred tank reactors where they reused the liquid fraction of DG in AD of wheat straw and compared it to monodigestion of wheat straw. The methane yields achieved with reused liquid fraction showed an improvement of 21% compared to the process without a liquid fraction of DG. Furthermore, [149] investigated the potential benefits of recirculation of liquid fraction of DG to biogas digesters by determining the BMP of the DG and comparing it to the BMP of untreated cattle slurry. The results indicated much higher BMP from DG (up to about 45%) than from untreated cattle slurry and highlighted the potential of recirculating DG to reduce the hydraulic retention time in the biogas digester while maintaining a long solid retention time to ensure process efficiency and stability. A comprehensive study by [150] investigated the effect of the liquid fraction of DG recirculation under different ratios of corn straw and pig manure on semi-continuous AD. Additionally, bacterial and Archaeal community structure was investigated while quantifying the benefits of the liquid fraction of DG recirculation. The authors concluded that liquid DG recirculation could be successfully used in most biogas plants by appropriately adjusting feedstocks and

fermentation parameters to reduce waste, recycle materials, water, and energy, and make biomethane production cleaner and more efficient. Furthermore, the liquid fraction can also be used to moisturize compost heaps or as a source of microorganisms to facilitate the composting process [98].

When the nutrients in the liquid fraction are not utilized, it is discharged to wastewater treatment plants to remove N and P before the aqueous effluent is discharged to water bodies [151]. Liquid DG contains high contents of nutrients in the available form with the potential to promote plant growth and increase the tolerance to biotic and abiotic stress. Therefore, it can be applied to soil as a liquid fertilizer via seed soaking, foliar spraying, soil amendment, and fertigation [152]. However, the liquid fraction of DG can cause environmental problems such as N leaching and infiltration into the groundwater, polluting nearby waters, ammonia, and greenhouse gas emissions. To overcome such problems, recovery and concentration of nutrients from the liquid fraction may be a desirable option [153]. In the literature, nutrient recovery technologies for the liquid fraction of DG have been the subject of numerous studies with a particular interest in N and P [152].

### 5.3.1. Membrane Technology

Membrane technology separates the liquid fraction of the DG into a solid rich fraction (retentate or concentrate) and an aqueous solution that passes through the membrane (permeate). Both fractions (retentate and permeate) contain valuable chemical building blocks that can be used for various purposes. The main disadvantages are mainly the significant upfront costs [154] and the tendency to membrane fouling and clogging which lead to loss of performance and significant operational costs [155]. Almost all types of membrane processes have been investigated for the treatment of anaerobic DG: microfiltration [154,156], ultrafiltration [157,158], nanofiltration [159,160], reverse osmosis [159,160], forward osmosis [155]. However, the introduction of membrane technology in farming environments has proven to be quite challenging. Among membrane process technologies, microfiltration and ultrafiltration are very broadly used. They concentrate molecules and particles above 0.01 and up to 1 μm, e.g., pathogens (bacteria, viruses, etc.), organic macromolecules (proteins, carbohydrates, etc.), and minerals (clays, latex, etc.) can be well separated by microporous membranes. Their main advantage is the relatively low operating pressure (from 0.1 to 5 bar) and therefore limited energy costs. High-pressure membrane processes, such as reverse osmosis, retain the smallest organics (tannins, organic acids, polyphenols, pesticides, pharmaceuticals, etc.), HMs, and salts. In comparison with thermal processes, reverse osmosis proves to be less energy-intensive, requires fewer investment costs, and has a smaller footprint. As an alternative to microfiltration, ultrafiltration, and reverse osmosis, nanofiltration with intermediate properties (operating pressure, molecular weight cut-off), which can split compounds into divalent ions, may be a more suitable choice [161]. In addition, forward osmosis is considered to be very energy efficient and has a low fouling tendency, so purification is rarely required. In forward osmosis, a semipermeable membrane (ideally allowing only water molecules to pass) is placed between a feed (a solution to be treated whose osmotic pressure is low compared to the draw) and a draw solution (which has high osmotic pressure and in which pure water is extracted). The osmotic gradient arises from the difference in osmotic pressures of the feed and the draw solution [162] which means that the process does not require pressure vessels and expensive high-pressure pumps. Forward osmosis allows reaching high-concentrated [161] and high-quality products while the applied filters show an extended lifetime if compared to filters used in pressure-driven processes. However, forward osmosis has several limitations such as relatively low water flux, back salt diffusion, the necessity to recover the draw solution, the internal concentration polarization phenomenon, and fouling [162]. Despite significant advances in membrane design and operation, applications of osmotic processes remain mostly pilot scale to date [161].

### 5.3.2. Struvite Precipitation

Struvite precipitation has been studied for the recovery of solubilized phosphate and ammonia N which is performed by the addition of magnesium salts that form a complex insoluble compound called magnesium ammonium phosphate or struvite ($MgNH_4PO_4.6H_2O$) [91]. Struvite is a white crystalline slightly alkaline substance composed of Mg, $NH_4^+$, and P in a molar ratio of 1:1:1. Struvite is an excellent fertilizer in which the nutrients have low water solubility and give a slow release in the soil. Since the availability of the free ions $NH_4^+$, $Mg^{2+}$, and $PO_4^{3-}$ is strongly dependent on the $H^+$ concentration, pH is used as a parameter to control struvite formation. The minimum solubility of struvite is at pH 10, but crystallization can also occur at pH values below 8. The main limiting factors for struvite precipitation are the cost of magnesium salts and of alkalis which are added for pH control [163] which make the cost of this process too high to be economically attractive [164]. However, since the pH is an essential parameter that promotes struvite precipitation, many of the studies are focused on increasing pH by adding alkalis NaOH, $Mg(OH)_2$, MgO, $MgCl_2$, and $Ca(OH)_2$ [165,166] and through stripping the $CO_2$ from the media being treated [167,168]. Additionally, the use of low-cost sources of magnesium can be the solution to the high cost of the process. For this purpose, various substrates have been investigated, such as salt obtained by evaporation of seawater [169,170], desalination waste such as brine [169,171], and natural brucite [172,173], etc. The results of the aforementioned studies emphasized that the application of the low-cost magnesium sources in struvite precipitation could achieve high ammonia removal efficiency, similar to the use of pure magnesium reagents [174].

Struvite is known to be appropriate for use as fertilizer on turf, tree seedlings, ornamentals, vegetables, and flower boards [175] and would be also effective in grasslands and forests, where fertilizers are applied once every several years. However, up to now the agronomic value of struvite has not been fully examined [176].

### 5.3.3. Ammonia Stripping

In ammonia stripping, air or steam (or possibly biogas) is introduced into stripping towers equipped with compressors, and the DG flows in the reverse direction, changing $NH_3$ from the liquid to the gas phase [177,178]. The gas is then transferred to an air scrubber where mass transfer and absorption of the $NH_3$ from the gas to a liquid phase (usually sulfuric or sometimes nitric acid) takes place, followed by the formation and recovery of a concentrated solution of ammonium sulfate (or ammonium nitrate) as an end-product [179,180]. The process is typically conducted at a pH above 9 and temperatures above 20 °C [177]. Ammonium sulfate is an inorganic salt, which can be reused as a marketable fertilizer rich in directly available macronutrients, N and S. It can be a valuable substitute for chemical fertilizers based on fossil resources. Alternatively, ammonium nitrate, a concentrated ammonia solution (by adding liquid ammonia), or other ammonia salts can be produced, depending on local legislation and land application options [179].

The efficiency of the process is dominated by several parameters, such as $NH_4^+$ concentration, pH, temperature, retention time, and the flow rates of gas and liquid in the stripping towers. However, pH improves the stripping rate more efficiently than the other parameters which are the reason why alkali addition is adopted in large-scale production. Due to its low cost, lime is often used for that purpose. However, due to the high dosage requirements, the cost may be unexpectedly high [178]. In addition, high dosages of alkali can lead to scaling and fouling of the packing material, which requires periodic cleaning [179].

This process is widely applied on a full-scale around the world [178] and is the most commonly used method for N recovery [152,177].

### 5.3.4. Vacuum Evaporation

Vacuum evaporation is an established technology used for the concentration of various types of substrates. The main advantages of the technology are operational reliability and

robustness, while among the main disadvantages is its high energy consumption, especially thermal energy. Because there is usually a surplus of heat in biogas plants, this disadvantage then becomes an advantage. Many studies conducted proven that vacuum evaporation is a viable technological solution for the concentration of the liquid fraction of DG and is already used in many biogas plants [97]. However, each evaporator has its specific arrangement, integration within the biogas plant, and particular operating conditions while each DG has its specific characteristics. Therefore, the mass and energy balance of the particular biogas plant equipped with a vacuum evaporator must be established, as it is crucial for the economic evaluation and cost-effectiveness of the project.

Vacuum evaporation is carried out at a reduced pressure that is lower than atmospheric pressure. As a result, the boiling temperature of the substrate is lower, leading to energy savings and the possibility of evaporation of otherwise thermally sensitive substances. In the first stage, as many $NH_3$ ions ($NH_4^+$) as possible should be concentrated and then neutralized with sulfuric acid. A second stage is required to reduce the liquid volume and concentrate the salt to an acceptable level. Ammonium sulfate, which is a product of neutralization, is an inorganic salt that can be used as a commercial fertilizer [181].

## 6. Regulations and Standards for Digestate Management

In the longer term, the European Union (EU) has set an enthusiastic target of building a low C economy and achieving an 80–95% reduction in GHG emissions by 2050, with renewables accounting for between 55% and 75% of gross final energy consumption [182]. However, only a limited amount of waste produced in the EU is recycled (43%), while the rest ends up in landfills (31%) or is incinerated (26%). According to European Commission, it has been estimated that 600 million tons more of waste could be recycled or reused in the EU [183]. In light of this insight, EU energy, and climate policies, especially in the last decade, are focused on promoting and developing a circular and innovative, resource-efficient, and competitive bioeconomy that combines food security with the sustainable use of renewable resources for industrial purposes. The bio-based economy plays a key role in replacing fossil fuels for energy applications, as well as for chemicals and material applications, through a circular economy, concerning recycling and reuse [184,185]. This policy has stimulated a rapid emergence of new AD plants in the EU [186]. The number of AD plants in the EU increased from 6227 [187] to 18202 [188] between 2010 and 2018. While biogas is the main product of AD, millions of tons of DG are produced annually as a by-product. DG requires proper management and/or disposal and is typically mechanically separated into liquid and solid fractions [186] and can be used for various purposes such as fertilizer, animal feed, bedding, raw material for construction, energy source, etc. [189].

The first European regulation to address the issues of DG was the Waste Directive from 1991, which referred to the protection of surface water and groundwater from pathogens affecting compromise the quality of water. Since then, EU political authorities have passed further legislation. According to the many EU Member States, DG was considered waste. In 2010, the European Commission highlighted the excessive production of waste, mainly due to common practices and inadequate waste management systems. Therefore, the Commission established that DG and compost obtained from bio-waste (forestry and agricultural residues, manure and sewage sludge, and other biodegradable materials such as natural textiles, paper, or processed wood) are considered used materials [89,183]. The recycling of bio-waste consists of the appropriate treatment by composting to produce organic fertilizers that can replace mineral fertilizers and be used on the land. The final use of the DG on land represents the essential stage for the effective closure of the loop consistent with the zero waste goals [89]. The problem with DG is that there is a lack of confidence among end-users, which means that most farmers are poorly (or even incorrectly) informed about the benefits of DG, which often makes them reluctant to apply it to their land [190,191]. This problem could be solved by regulating the application of DG in a way that does not have a negative impact on the soil. Thanks to the Implementing Regulation from 2014, DG from biogas produced via AD of by-products of animal origin mixed with materials of

plant origin, has been recognized as fertilizer ready for market. Pending the adoption of the regulation on fertilizers from organic waste, already proposed in 2016, DG could be considered a marketable organic fertilizer [183].

However, by now, there is no EU regulation on DG, and only local and volunteer basis guidelines have been proposed by some EU Member States [50,88,183]. On the other hand, the European Commission is considering proposing minimum standards and guidelines for use of DG in agriculture via revision of the Sewage Sludge Directive.

## 7. Fertilization Value of the Digestate

Modern agricultural production is becoming increasingly intensive while the demand for the development of new fertilizers, that can help overcome obstacles in global agricultural production, is constantly increasing. The increasing intensity of agricultural production, along with the expansion and development in the food industry, leads to an increase in the amount of organic waste produced globally. To produce a high-quality organic fertilizer sustainably, organic waste needs to be managed as a valuable resource that could significantly support agricultural production. The most appropriate and valuable way to use or reuse organic waste is through fertilization. Some of the potential benefits of using organic wastes are the possible improvement of soil fertility, provision of plant nutrients in agricultural production, and increase in soil organic content [192]. Considering climate change and fossil fuel constraints, DG is considered an environmentally friendly fertilizer that can be sustainably used for food production [193]. It can be used in various types of agricultural productions and can reduce dependence on inorganic fertilizers. However, its application can sometimes cause nitrate and phosphate pollution of groundwater. Therefore, the selection of the method of DG application is crucial and it determines whether DG is a solution or a problem for the environment and agricultural production. When applied adequately, DG can maintain grassland productivity, reduce environmental impact and increase biomass yields [64]. Ref. [194] conducted six-year field experiments at two challenging sites in southwestern Germany in which they evaluated the impact of (a) mineral fertilizer, (b) combined solid DG fraction and mineral fertilizer, (c) solid DG fraction, (d) combined liquid DG fraction and mineral fertilizer, and (e) liquid DG fraction on silage maize biomass yield, perennial grassland and in intercropping of clover grass and triticale. The objective of the study was to determine whether separated DG can supplement or replace mineral fertilizers and what influence it has on long-term yield performance in different biomass cropping and fertilizer systems. The results showed that the application of mineral fertilizer combined with the liquid fraction of DG resulted in the highest biomass yields in all cropping systems. In contrast, fertilization using only the solid fraction of the DG resulted in the lowest yields in all plots. Yields in plots fertilized with the solid fraction of DG were not significantly different from the control. The authors concluded that the use of separate biogas DG gave similar results to mineral fertilizers and had comparable results. Although in some systems (intercropping) it is possible to completely replace mineral fertilizers with DG, the best results are obtained with the application of mineral fertilizers combined with DG, which can reduce the use of mineral fertilizers by up to 66%. Mineral N from DG is generally poorly immobilized in the soil, due not only to the low C/N ratio but also to the content of highly stable OM. When the DG is incorporated into the soil, the $NH_3$ ions undergo an immediate nitrification process. When comparing different types of DGs, the DG produced after AD of sewage sludge has a high rate of nitrification and mineralization of OM and its capacity to supply the plants with mineral N is comparable to the urea. Because of its characteristics, it can at least partially, substitute or complement synthetic N fertilizers and reduce their use in agricultural production [195].

Application of DG can have a stimulating effect on soil C matter decomposition supplying the soil with an additional pool of readily available mineral N. However, it also can cause excess $NH_3$ volatilization and dispersal of oxidized forms of N through nitrate ($NO_3^-$) leaching or nitrous oxide ($N_2O$) emissions. To achieve significant positive effects, DGs need to be directly and immediately incorporated into the soil after field spreading. If

the DGs are handled in that way, the available N will correspond to its $NH_4^+$-N content plus a small part of the organic N fractions (10–20%) [68,196].

The high fertilizing potential of DG is also closely related to the high content of plant-available P, K, and other nutrients. P is present in both, the solid fraction of the DG (organic and inorganic forms), and in the liquid fraction in which the inorganic form prevails. DG can influence the levels of plant-available P in two ways—by direct uptake of inorganic P or by stimulating microorganisms to undergo different activities. The transformation of organic P depends on the C/P ratio, while the transformation of inorganic P depends on the soil pH and the presence of metal cations. Although DG usually contains less organic C than the parent from which the DG is made, it can make up for the losses after the DG is incorporated into the soil. Fractionation or composting of DG could improve the sequestration of C in the soil. According to [197], DG applied together with cattle slurry and straw in the field experiment significantly changed the content of plant-available P, K, and mineral N. The content of plant-available K in the topsoil increased when straw was incorporated before DG application. After a certain period, the DG had a positive effect on soil $NO_3^-$ content, especially in spring.

Table 6 represents studies in which DG was applied on land instead commercial fertilizers and the results of DG application (effect on the soil properties and yield and nutritional values of different crops).

**Table 6.** Effect of DG fertilization on the soil properties and yield and nutritional value of different crops.

| Fertilization Parameters | The Aim of the Study | Results | Ref. |
|---|---|---|---|
| Three-year application of 30 and 60 $m^3$ $ha^{-1}$ DG. | Determination of physicochemical properties of highly acidic, silty loam soils with low macronutrient content, the yield and nutritional value of switchgrass. | The 60 $m^3$ $ha^{-1}$ DG application significantly reduced soil acidity, improved its sorption properties, increased the soil OM, K, and Zn content, significantly increased switchgrass yield, the number of panicles per plant, panicle height, crude ash, and protein content from the 1st cut, and the content of protein, P, and Mg in biomass from the second cut. | [65] |
| Three-year application of (a) 5.1 t DM $ha^{-1}$ DG, and (b) 155 t DM $ha^{-1}$ MS + 5.1 t DM $ha^{-1}$ DG. | Influence of DG and MS fertilization on wheat yield and the level of major nutrients in grain, and tracking of bioaccumulation of HM in wheat grains during 3 growing seasons (2013–2016). | In all years fertilization with MS+DG significantly increased the grain yield compared to controls, in 2015 compared to NPK, and the content of TPt, wet gluten, and phenols in grain compared to NPK. MS fertilization had a positive effect on the total ACI of grain in the 1st year. HM concentration in soil and grains was lowest in the DG treatments. | [198] |
| The experiment consisted of 4 treatments: CT, BS, CBS, and CMm. | Influence of treatments on soil properties, tomato fruit quality, and composition of microflora in both nonrhizosphere and rhizosphere soils. | In comparison to CT and CMm, treatments with BS and CBS significantly improved the content of soil available N, P, K, and EC. OM increased by different degrees, while pH values declined from 5.43 to 5.22. In the application of BS, total concentrations of N and P decreased by 4.82% and 3.45%, respectively. | [199] |
| Five different treatments: B0-no BS; B1-10 kg of BS/plant/year; B2-20 kg of BS/plant/year; B3-30 kg of BS/plant/year; B4-40 kg of BS/plant/year. | Influence of BS applications on the soil nutrients, the fruit yield, and fruit quality of *C. oleifera*. | Fertilization with BS significantly improved available N, P, and K concentrations in soils, and significantly improved the plant yield. The oil yield also showed a correlation to the promotion of available N, P, and K in rhizosphere soils. Fertilization with 30 kg/plant/year above (treatments B3 and B4) had the highest fresh fruit yield, fresh seed rate, and dry seed rate, and resulted in a higher oil yield per plant. | [200] |

**Table 6.** *Cont.*

| Fertilization Parameters | The Aim of the Study | Results | Ref. |
|---|---|---|---|
| Three-year application of (a) carbocalk, (b) filter dust, (c) wood ash, (d) blast furnace slag; at each site, the field trial was divided into two sides, with and without solid DG. | Evaluation and comparison of the effectiveness of four liming materials in combination with and without solid DG as organic fertilizer as a measure to raise the soil pH to the optimum (pH = 6–7). Alfalfa was planted as a test crop. | All four liming materials raised the pH of the soil, whereas wood ash showed to be the best while blast furnace slag was the worst. The yield of alfalfa increased with the application of all four lime materials. The highest yields were achieved with the application of wood ash. Application of liming materials with solid DG increased soil OM and had slightly higher yields compared to liming materials without solid DG. | [201] |

## 8. Conclusions

Animal manure is a valuable source of nutrients and OM which can serve as organic fertilizer for crops and pasture growth. However, nutrients contained in animal manure can degrade air, water, and soil quality, and cause threats to public health when manure management is poorly handled.

So far, knowledge about manure management practices is poor, and existing manure management practices variate widely on a global scale. The problems are commonly associated with the disposal of urine and liquid manure, particularly in non-mechanized and smaller farms. Proper management and utilization of manure require investments in infrastructure which can be provided through policy intervention by the provision of subsidies.

In the EU, regulations, directives, or laws have been introduced in almost all Member States, but so far, manure is not regulated under one single EU regulation or directive. Only a few tools regarding manure management and some directives that are indirectly related to manure management exist in EU legislation which indicates that there are many open questions related to this issue.

Since manure may contain pathogens and/or components that can cause adverse environmental impacts and compromise food safety, its direct use as a fertilizer is limited. The solution lies in processes such as recycling and recovery of manure. Anaerobic digestion is a biochemical process that is used to convert organic material (manure) into biogas, whereas DG remains as a residual rich in nutrients that can be extracted and concentrated through the application of a range of technologies and processes. Nutrient recovery technologies or DG processing technologies are those that result in a valuable end-product with higher concentrations of nutrients if compared to unprocessed DG or technologies that are capable of separating nutrients in mineral form, or of creating another marketable end product, suitable for recycling as organic fertilizer, and closing the nutrient cycle in which waste becomes a valuable product. Some of these processing methods are commercially available but some remain on the research scale.

The implementation of sustainable agro-energy systems that integrate the production of crops, livestock farming, and bioenergy is attracting increasing attention to farmers. However, storage, transportation, processing, handling, and application of processed DG as fertilizer involve significant costs for farmers. For that reason, measures that have to be taken to strengthen knowledge and awareness about the benefits and usefulness of DG, particularly processed DG, are the establishment of stronger policy for better regulation systems and incentives, raising of knowledge and awareness among farmers about the benefits of processed DG and further thorough research related to vast possibilities of DG processing and processed DG applications.

## Abbreviations

| | |
|---|---|
| ACI | antioxidant capacity index |
| AD | anaerobic digestion |
| AIR | agro-industrial residues |
| APW | aloe peel waste |
| ASP | almond shell powder |
| AW | agricultural wastes |
| BA | bulking agent |
| BMP | biochemical methane potential |
| BOD | biological oxygen demands |
| BS | biogas slurry |
| C | carbon |
| CBS | concentrated biogas slurry |
| $CH_4$ | methane |
| CM | cattle manure |
| CMm | conventional management |
| COM | cow manure |
| $CO_2$ | carbon dioxide |
| COD | chemical oxygen demand |
| CODt | total chemical oxygen demand |
| CT | blank control |
| DG | digestate |
| DM | dairy manure |
| DOC | dissolved organic carbon |
| DSC | differential scanning calorimetry |
| DWC | dry wood chips |
| EC | electric conductivity |
| ECs | energy crops |
| EGM | exhausted grape marc |
| EPS | extracellular polymeric substance |
| FVW | fruit and vegetable waste |
| GI | germination index |
| GHG | greenhouse gasses |
| GW | green wastes |
| H | hydrogen |
| HHV | higher heating value |
| HM | heavy metal |
| HRT | hydraulic retention time |
| HTC | hydrothermal carbonization |
| K | potassium |
| LBA | lignocellulosic bulking agent |
| MAR | macroalgal residue |

| | |
|---|---|
| MS | mudstones |
| MSW | municipal solid wastes |
| N | nitrogen |
| $NH_3$ | ammonium |
| OC | organic carbon |
| OFMSW | organic fraction of municipal solid waste |
| OLR | organic loading rate |
| OM | organic matter |
| $OM_0$ | organic matter of digestate |
| OS | oyster shells |
| P | phosphorus |
| PAO | potential ammonia oxidation rate |
| PDRI | potential dynamic respiration index |
| PL | poultry litter |
| PM | poultry manure |
| PPP | pepper plant pruning |
| PS | pig slurry |
| S | sulfur |
| SD | sewage sludge digestate |
| SGI | seedling growth index |
| SS | sewage sludge |
| SW | solid wastes |
| T | temperature |
| TC | total carbon |
| TG | thermogravimetry |
| TK | total potassium |
| TKN | total Kjeldahl nitrogen |
| TN | total nitrogen |
| TOC | total organic carbon |
| TP | total phosphorus |
| TPt | total proteins |
| TS | total solids |
| TWAS | thickened waste activated sludge |
| VFA | volatile fatty acids |
| VS | volatile solids |
| VSP | vine shoot pruning |
| WS | wheat straw |
| WSC | water-soluble carbon |
| WSD | wood sawdust |
| WTP | wastewater treatment plant |

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