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Review

Manure management in EU for biosecurity increase and livestock farming footprints reduction

George Attard[1], Antonio Comparetti[2,*], Eglė Jotautienė[3], Antanas Juostas[3] and Francesco Mira[2]

[1] University of Malta, Department of Rural Sciences and Food Systems, Msida MSD 2080, La Valletta, Malta
[2] University of Palermo, Department of Agricultural, Food and Forest Sciences, Viale delle Scienze, Building 4, 90128 Palermo, Italy
[3] Vytautas Magnus University, Agriculture Academy, Faculty of Engineering, Studentų str. 15, LT-53361, Akademija, Kaunas, Lithuania

* **Correspondence:** Email: antonio.comparetti@unipa.it; Tel: +3909123897057.

Abstract: The spread of livestock diseases, such as African swine fever (ASF) or the highly pathogenic avian influenza (HPAI), caused by viruses and/or bacteria such as *Salmonella* spp. and *Escherichia coli*, are currently reducing biosecurity; as such, EU regulations avoid the use of derived manure for biofertilisation. This is happening in a global context, where the price of food, fertilisers, and energy have a strong correlation. In fact, surges in the cost of these commodities contribute to strong tensions in food-insecure countries, very often resulting in food riots. This review paper addresses the current technologies available in the EU for the treatment of manure, including that derived from livestock affected by the above diseases. Additionally, within the agricultural sector, livestock farming is the major source of greenhouse gas (GHG) emissions, such as methane, nitrogen monoxide, and carbon dioxide, which contribute to global warming and, therefore, climate change. Thus, this paper also discusses manure management technologies aimed at reducing GHG emissions, considered as livestock farming footprints according to EU regulations. The literature review followed a widely implemented method divided into three phases: planning (theoretical background), execution (search strategy), and result analysis. The current technologies available in the EU for manure management are aerobic treatment, composting, anaerobic digestion (AD), decanter centrifuge, VP-HoBe, BENAS AD, Geamix housing system, belt press sieve–reverse osmosis, vibrating reverse osmosis, granulation, gasification, and pyrolysis. RENURE (REcovered Nitrogen from manure), i.e., an organic fertiliser that is partially or totally derived from manure, can replace synthetic chemical/mineral fertilisers,

thereby building up a resilient food production chain capable of using locally available resources. This review indicates that pyrolysis and AD are the best suited technologies for processing manure that may be affected by the above diseases, as they have been proven to effectively avoid the spread of those specific pathogens. Moreover, these two technologies can reduce livestock footprints. However, further research will need to assess the selected manure management technologies through the computation of energy balance, in order to maximise energy efficiency.

Keywords: fertilisers; nitrates; pathogens; diseases; anaerobic digestion; pyrolysis; circular bioeconomy

1. Introduction

The emission of greenhouse gases (GHGs), such as methane, nitrogen monoxide, and carbon dioxide, produced by livestock farming, can contribute to global warming and, therefore, climate change. According to IPCC (Intergovernmental Panel on Climate Change) classifications, 323 Mt CO_2 eq. (49%) of total GHG emissions are created in the agricultural sector, 136 Mt CO_2 eq. (21%) in the energy sector, and 11 Mt CO_2 eq. (2%) in the industrial sector [1]. Within the agricultural sector, livestock farming is the major source of GHG emissions (i.e., methane, nitrogen monoxide, and carbon dioxide): through LCA (Life Cycle Assessment) methodology, the IPCC x estimated that 57% of total GHG emissions of EU-27 agricultural sector is caused by livestock production up to the farm gate, including land use and land-use change emissions [1].

On December 11, 2019, the European Union adopted the European Green Deal (EGD), aimed at reducing GHG emissions by 55% with reference to 1990, so that Europe would become the first climate-neutral continent by 2050 [2]. A key EGD objective is to promote healthier food production systems that are more environmentally friendly, since agricultural GHG emissions in the EU were almost constant between 2005 and 2019 [3]. This transition is additionally emphasised due to the existing environmental, climatic, and geopolitical instability, which has a direct negative effect on the European food supply chain, with damaging consequences for the EU member states and, at a higher level, for food-insecure countries. Such a shift needs a dedicated strategy aimed at minimising the potential negative effects of EU agricultural policy on extra-EU countries (e.g., African ones) [4,5].

In order to decrease the negative environmental impact caused by intensive agriculture and reduce carbon leakage, the EU has embarked on a GHG net-zero food production chain, in anticipation of providing healthy food to the European 2050 predicted population. Several options were identified that can potentially facilitate the achievement of these objectives. One of the most tangible options is the adoption of circular bioeconomy (CBE) principles and agro-ecological practices, while maintaining high crop yields with a significantly lower nitrogen pollution impact. In this transition, the smart use of fertilisers as crop inputs is not only key for food production but has also environmental impact throughout the agri-food production chain.

After the 2nd World War, the evolution of major agri-food-producing countries, including the EU member states, witnessed the increase of agricultural product amounts. This surge in production was achieved through the increased use of several agrochemicals, including synthetic chemical/mineral fertilisers, together with territorial specialisation and integration within the global markets. The concept of a "food regime" was first formulated by Harriet Friedmann in 1987 [6]; it stemmed from previous research on the international food order after the 2nd World War, when Friedmann, in 1982,

charted the rise and demise of the US food aid programme, as a geopolitical weapon in the Cold War [7]. Then, a more systematic formulation of "food regime" by Friedmann and McMichael appeared in the European journal Sociologia Ruralis in 1989 [8]. It is estimated that the amount of fertilisers used on a global level has quadrupled since the 1960s and currently stand at an estimated yearly use of 200 million tonnes, most of which are used for the production of cash crops such as cereals and pulses. The amount of chemical/mineral fertilisers used in European agriculture became constant over the past decades, reaching 11.2 million tonnes in 2020, i.e., 8.3% higher than in 2010. Yet, the amount of nitrogen (N) fertilisers remained almost the same in 2017 when compared to 2000, i.e., 10.64 million tonnes [9].

Although N fertilisers represent 89% of the total synthetic fertilisers used in the EU, phosphorus (P) is important as a nutrient required by crops. In fact, the EU agri-food sector is highly dependent on imported P fertilisers. Raw phosphorus is a non-renewable resource and is found as phosphate rock in just a few geographic locations outside the EU, thus making P a strategical material, included in the EU list of Critical Raw Materials (CRM) [9,10].

In an attempt to contain domestic food-related inflation, Russia, a global supply leader of fertilisers, imposed export restriction measures of N fertilisers in 2021, in order to try to prevent shortages on its local market. The onset of the Russia–Ukraine war in February 2022, followed by a further extension of the export quotas, caused havoc in the European fertiliser markets, with higher prices and lower supply. This geopolitical and economic turmoil not only caused a significant supply reduction of Russian fertilisers on the international markets but also highly affected the price of gas, the energy source selected by most non-Russian industries for manufacturing fertilisers. This symbiotic relationship makes the prices of both fertilisers and gas highly correlated, catapulting the fertiliser costs at par with the 2008 crises that triggered food-related riots in several countries of Sub-Saharan Africa. The process of transition from an economy based on fossil fuels to a bio-based one requires the retrieval of potential plant nutrients that exist in the various organic waste streams for the eventual replacement of chemical/mineral fertilisers with bio-based ones [11].

In the past, several geopolitical circumstances in Middle East (Gulf war in 1990–1991 in Kuwait and Iraq) and Northern Africa (riots of Arab Spring in early 2010s, including Libyan war in 2011), as well as the Russia–Ukraine war from 2022 and the USA–Iran war from 2026, not only increased the price of fertilisers but also that of natural gas. Therefore, biogas gained remarkable attention as a local resource for both biomethane as bioenergy source and digestate as biofertiliser for agriculture [12]. Moreover, climate change–related damage incentivises all sectors to decarbonise and integrate environmentally friendly technologies, such as anaerobic digestion (AD), which allows both decarbonisation and optimal biowaste management [12]. If AD plants are built up in each country, global warming could be limited to 2 °C [12]. Moreover, if suitable policies are implemented, AD plants could reduce global GHG emissions by 10–13% (3.29–4.36 Gt CO_2-eq) [12]. In fact, the AD process is able to capture methane and mitigate CO_2 emissions associated with the produced biogas [12]. As biogas impurities (i.e., H_2S, CO_2) can cause severe practical difficulties in biogas storage and biomethane delivery to the natural gas grid, upgrading technologies must be implemented for removing H_2S and eliminating or consuming CO_2 inside biogas, thus achieving a minimum biomethane content of 95% [12]. Hydrogen-assisted biogas is able to sequestrate carbon by converting CO_2 into biomethane by using the hydrogen generated mainly through other renewable energy sources (RES), namely water electrolysis and photovoltaic solar facilities or wind turbines (CO_2 and H_2 are converted into CH_4 and H_2O) [12]. This biogas upgrading allows to store and use the excess extracted biomethane

in the natural gas grid [12]. If CO_2 produced during AD is converted into additional biomethane, biogas could satisfy 53% of the demand for fossil natural gas [12]. Moreover, the digestate co-produced during the AD process can be used for generating biochar, which can be used directly as a biofertiliser or indirectly as a biomethanation improver, as well as an upgrading and cleaning material [12].

In fact, bio-based or organic fertilisers or biofertilisers such as manure and digestate, compared to chemical/mineral ones, produce the following benefits:

1) Biofertilisers release the nutrients over a longer time, so that they better meet the crop needs;

2) Biofertilisers include not only macronutrients (e.g., N, P and K) but also micronutrients and, above all, organic matter, which binds with mineral compounds of soil, thereby improving not only its chemical fertility but also its physical one, i.e., its structure; therefore, organic fertilisers are also used for soil amendment;

3) Biofertilisers can be of animal origin and are not produced through a process using energy.

The potential production of RES from livestock waste that is commonly found in the Mediterranean islands was evaluated by Attard et al. [13], using the island of Malta as a case study [14], together with other scientists [15]. They demonstrated that the production of RES, i.e. biomethane, electrical, and thermal energy, from organic waste can also have a high added value, because the potential additional income would include that derived from the sale of biomethane or electrical and thermal energy. Moreover, the income obtained by replacing chemical/mineral fertilisers with organic digestate should be quantified.

Specific examples of AD plants in the Mediterranean region and the conditions under which these plants operate (i.e., dominant feedstocks, pathways of biogas valorisation, national policies, and regulatory frameworks for biomethane) are reported in a review of biomethane production in this region [16].

Regulation (EU) 2019/1009 of the European Parliament and Council of June 5, 2019, lays down rules on the market of EU fertilising products and amends Regulations (EC) No 1069/2009 and (EC) No 1107/2009 while repealing Regulation (EC) No 2003/2003, establishing the rules for marketing livestock manure [17]. However, the marketing and movement of livestock manure and other animal by-products are also subject to specific requirements under animal health legislation. In particular, Regulation (EU) 2016/429 (Animal Health Law) establishes a framework for the prevention and control of listed animal diseases, including African swine fever (ASF) and highly pathogenic avian influenza (HPAI); additionally, it provides biosecurity measures aimed at preventing their introduction and spread [18]. These measures are particularly relevant in the context of animal-derived materials, including manure, whose movement and use may require specific conditions, depending on the epidemiological situation and the concerned disease. Despite the implementation of these control measures, several EU member states have recently reported outbreaks of ASF and HPAI, thus posing a significant threat to livestock production on local and regional levels and potentially facilitating further geographical spreading. The epidemiological relevance of these diseases is further increased by their ability to affect both susceptible domestic livestock and wildlife populations, which may contribute to the persistence and spread of infections in affected areas.

According to data reported through the Animal Disease Information System (ADIS), as of September 9, 2026, ASF outbreaks have been reported in 18 European countries, including Italy, predominantly affecting wild boar and, on a lesser extent, domestic pigs. According to the official notifications submitted to the World Organisation for Animal Health (WOAH), ASF has been reported across Northern, Central, and Southern Italy, including Piedmont, Liguria, Lombardy, Emilia-

Romagna, Tuscany, and Lazio, while previous outbreaks had been reported in Calabria and Campania. In 2026, Tuscany experienced a particularly marked increase in ASF cases, especially among wild boars. This highlights the ongoing epidemiological concern posed by ASF in Italy, thus prompting the implementation of movement restrictions and strengthening on-farm biosecurity measures aimed at limiting the spread of this disease. In addition, a plan to reduce the wild boar population by half (equivalent to an estimated 750,000 wild boars) by 2025 was activated [19].

Similarly, during 2026, 33 outbreaks of HPAI H5N1 have been reported in poultry, wild, and captive birds in the EU. Since 2021, H5N1 viruses belonging to clade 2.3.4.4b have spread across Europe, Northern and Southern America, Antarctica and, more recently, Australia, thus causing successive waves of outbreaks affecting several wild and domestic bird species and, of particular concern, a growing number of terrestrial and marine mammal species. In response, strict biosecurity measures have been implemented to reduce the risk of virus introduction and transmission, particularly in poultry production systems, thereby limiting the impact of HPAI on animal health, poultry production, and food security [19].

Bacterial pathogens also represent an important concern in animal production systems, as livestock manure and wastewater may act as potential vehicles for their environmental dissemination. Pathogens such as *Salmonella* spp., *Escherichia coli*, and *Campylobacter* spp. can be brought by infected animals and, subsequently, enter manure, slurry, and wastewater streams. Whether inadequately treated or managed, these materials may contaminate soil and water bodies and facilitate pathogen transmission to other animals and, potentially, humans. This concern is not limited to the transmission of pathogens and the associated clinical risks but also includes the potential dissemination of antimicrobial-resistant pathogens and antimicrobial traits, which may contribute to their spread and reduce the effectiveness of available antimicrobial treatments. Consequently, effective treatment and management of manure and wastewater are essential to reduce pathogen loads and limit their environmental dissemination, thus highlighting the importance of treatment technologies capable of achieving effective pathogen inactivation. In order to avoid these situations, proper manure management protocols have to be implemented, to prevent the potential crossing of diseases from infected farms onto the surrounding wild animals.

Therefore, the final scope of this review paper is to analyse the literature, in order to identify manure management technologies suitable for addressing food biosecurity and the reduction of livestock farming footprints, i.e., lowering GHG emissions from this sector, in the EU.

2. Review methodology

This review followed the method by Torraco [20] to analyse the available literature and legislative archives. According to this widely implemented method, the review search was divided into three stages: 1) planning phase (theoretical background); 2) execution phase (search strategy); and 3) analysis of results.

The first stage, i.e., the planning phase, implies the identification of research questions. This review focused on the research question "Which practices help to achieve sustainable manure management in the EU?" with the ultimate aim to "recommend best farming practices for sustainable manure management to enhance benefits of manure for soil structure and fertility". In addition, from the question "Which shortcomings in regulations and practices, if any, currently prevent sustainable manure management in the EU?" the aim was "to determine knowledge gaps and limitations in current

manure management practices and regulations, to recommend a sustainable manure management in the EU".

In the second stage, i.e., the execution phase, a systematic literature review on the technologies employed for manure management in the EU was conducted. Web of Science and Scopus indexes, as well as Google search engine, were used to source studies published from January 1, 2000, to September 30, 2026, using keywords describing technologies for manure management and the Boolean operator AND, such as "aerobic AND treatment"; "aerobic AND composting"; "anaerobic AND digestion"; "decanter AND centrifuge"; "vp AND hobe"; "benas AND system"; "Geamix AND housing AND system"; "belt AND press AND sieve AND reverse AND osmosis"; "vibrating AND reverse AND osmosis"; "granulation"; "pelletising"; "pelletisation"; and "pyrolysis". In this phase, 237 documents were retrieved. Retrieved documents were selected based on source quality; only peer-reviewed papers were chosen. These documents responded to the above questions because they included some information allowing to answer them. Only the above documents were read, while all others were excluded.

The third stage, i.e., the analysis of results, implies that once relevant information was extracted, it was summarised and discussed, so that recommendations were deduced and reported in the discussion section. In this phase, 99 documents were selected.

3. Results

The results indicate the following technologies available for manure management: 1) aerobic treatment (10 selected documents); 2) composting (6 selected documents); 3) anaerobic digestion (AD) (16 selected documents); 4) decanter centrifuge (3 selected documents); 5) VP-HoBe (2 selected documents); 6) BENAS system (5 selected documents); 7) Geamix housing system (5 selected documents); 8) belt press sieve–reverse osmosis (2 selected documents); 9) vibrating reverse osmosis (10 selected documents); 10) granulation (8 selected documents); 11) gasification (4 selected documents); and 12) pyrolysis (12 selected documents).

3.1. Aerobic treatment

The aerobic treatment alters nitrogen through the processes of nitrification and denitrification, which are implemented through (spatially or temporally) alternating anaerobic and aerobic phases or under low aeration levels [21] (Figure 1). These processes emit nitrogen (N_2) but, under unfavourable conditions, can also occasionally generates GHGs, i.e., nitrous oxides [22,23].

A variety of aerobic treatment plants include the option of separation technology [25]. The products of this treatment process usually contain less N, compared to the raw slurry input, making them ideal for increasing soil organic matter and nutrient contents in areas classified as nitrate vulnerable zones (NVZ). This technology is quite popular in France. The separated products can be composted on-farm or at a collective platform and then exported [23].

Aerobic treatment, applied to livestock manure, has been shown to enhance the inactivation of several bacterial or viral pathogens, including *Salmonella* spp., *Listeria monocytogenes*, enteroviruses, and adenoviruses. Under thermophilic conditions, the increased temperature can further enhance pathogen inactivation and overall manure sanitation [26–29]. Therefore, this technology is considered as a biosecurity measure.

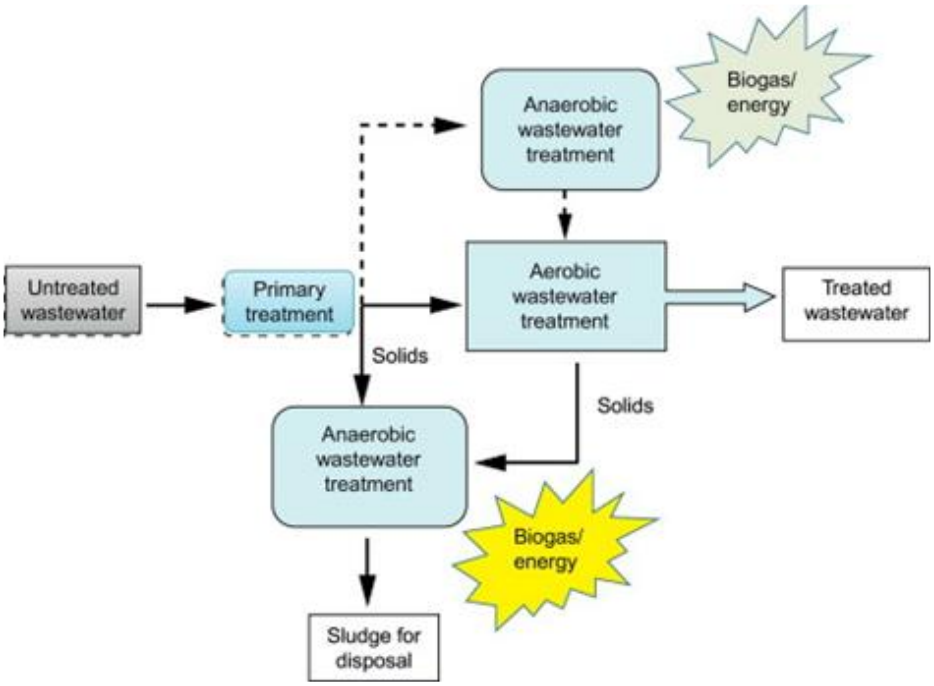


Figure 1. Combined aerobic/anaerobic process for the treatment of wastewater [24].

Moreover, it contributes to reduced livestock farming footprints. In fact, He et al. [30] monitored the carbon footprints, expressed as GHG emissions, of a conventional domestic wastewater treatment plant (WWTP) with different working loads by means of water–energy nexus and LCA. The CH_4 emission rates were significantly reduced during the treatment processes, and the CH_4 dissolved in wastewater mainly originated from the sewage. The N_2O emission rates and the change rate of N_2O dissolved in wastewater were higher in the biological treatment. Due to significant oxidation and inadequate glucose dosage, the WWTP showed a net reduction of CH_4 but a net source of N_2O. Indirect GHG emissions from electrical energy use in the operation and maintenance phase accounted for 86.4% of GHG emissions, thus causing the highest carbon footprint in the life cycle of the WWTP. The optimum direct GHG emission, glucose dosage, and electrical energy use obtained by the conceptual model of the water-energy nexus were 0.0095 kg CO_2 eq. m^{-3}, 0.0039 kg m^{-3}, and 0.1081 kWh m^{-3}, respectively.

3.2. Composting

The natural process of decomposition of organic matter by microorganisms under controlled conditions is called composting and produces a biofertilizer, called compost [31].

This technology can be divided into anaerobic composting, occurring under the absence or in the presence of limited oxygen (O_2), and aerobic composting, happening under the presence of abundant O_2. During anaerobic composting, anaerobic microorganisms generate intermediate compounds, e.g., methane, organic acids, and hydrogen sulphide. As anaerobic composting occurs at low temperatures, it does not eliminate bacterial and fungal pathogens or weed seeds, so it is not a biosecurity measure [31].

Instead, during aerobic composting (Figure 2), aerobic microorganisms convert the organic matter into carbon dioxide (CO_2), ammonia (NH_3), water, and a relatively stable organic product known as

humus. This process also generates thermal energy, thereby accelerating the digestion of proteins, fats, and complex carbohydrates, i.e., cellulose and hemi-cellulose, and reducing the process time. This technology is capable of eliminating bacterial and viral pathogens (for humans or plants) and weed seeds. Even if aerobic composting tends to reduce the nutrients contained in the raw materials, it is considered as more efficient than anaerobic composting [31].

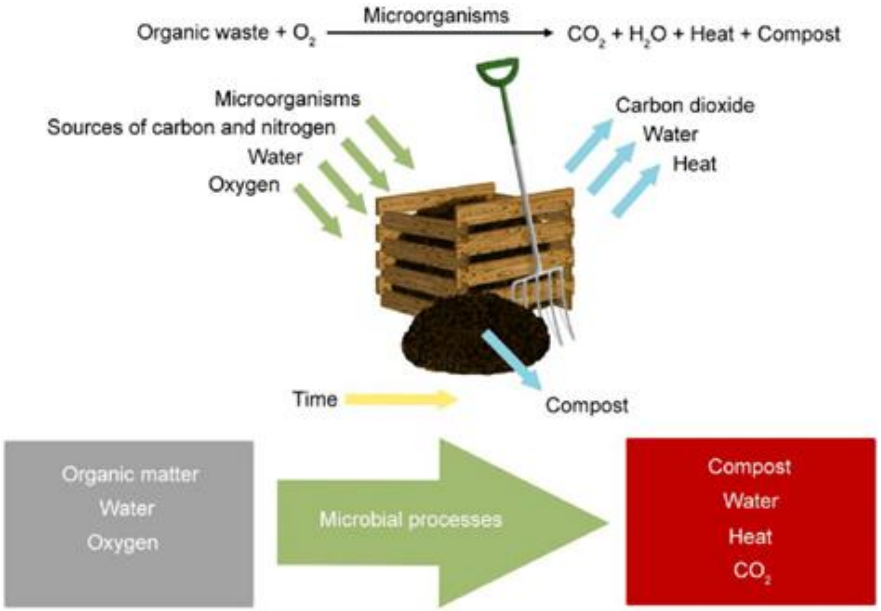


Figure 2. Principles of aerobic composting [33].

During the active stage of aerobic composting, mesophilic microorganisms (whose optimal temperature for growth is 20–45 °C) use carbohydrates and amino acids for their rapid cell division and growth. Yet, this metabolic activity generates thermal energy, thus increasing the temperature to a level that inhibits their own activity. Then, thermophilic fungi and bacteria (whose optimal temperature for growth is 50–70 °C) complete composting, thereby raising the temperature to 65 °C, which eliminates pathogen microorganisms and weed seeds [31].

During the next curing phase, another group of thermophilic fungi starts to prolificate and further breakdowns plant cell wall materials, i.e., cellulose and hemicellulose. The obtained mature compost contains nitrogen (N) and oxygen but not organic acids that are toxic for plants. Moreover, the mature compost usually has a colour from dark brown to black and is constituted by particles whose size is reduced until it becomes similar to soil texture. Compared to the raw materials, the mature compost has higher humus amount and exchange capacity, as well as a lower carbon to nitrogen ratio (C:N) and an almost neutral pH [31].

Composting can also be carried out through the enzymatic degradation of organic raw materials, as they pass through the digestive system of earthworms [31]. This process is called vermicomposting [31,32].

The high organic matter content of compost plays an important role in maintaining soil fertility and allowing environmentally friendly crop operations. It is not only a source of plant nutrients but also improves the soil physical, chemical, and biological parameters. In fact, as a result, the soil 1) becomes resistant to stresses due to drought, diseases, and toxicity, 2) increases the uptake of plant nutrients, thereby increasing crop yield, and 3) increases soil nutrient cycling capacity and microbial activity [34].

Composting can substantially reduce bacterial pathogens in livestock manure through the combined effects of thermophilic temperatures, microbial competition, and long treatment time, with evidence for the inactivation of bacteria such as *Salmonella* spp., *Escherichia coli*, and *Listeria monocytogenes*, as well as a marked reduction of some viral pathogens such as bovine enterovirus and parvovirus or detectable RNA hepatitis E virus (HEV) [35–37].

Compost can be used for soil fertilisation and amendment, by replacing chemical/mineral fertilisers, thus contributing to reduced livestock farming footprints. Manure composting has a significant mitigation potential toward GHG emissions. According to Brown et al. [38], the main advantage of composting, compared to anaerobic manure storage, is the reduction of the emissions of methane (CH_4), i.e., a GHG with Global Warming Potential (GWP), expressed as CO_2 eq., 25 times higher than carbon dioxide. Specifically, if the same amount of manure is composted, this could save 3.1 Mg CO_2 eq. per mg of dry feedstock, compared to anaerobic storage. However, composting produces and emits other GHGs, i.e., nitrous oxide gases and CO_2. The emissions of nitrous oxides are generally higher during thermophilic composting, when the oxygen presence is limited, as observed by using heaped manure [39], as well as during the curing and storage phases, when ammonium nitrogen is converted into nitrate. However, Brown et al. [38] concluded that the emissions of nitrous oxide gases and CO_2 during composting are minimal, compared to the reduction in methane emissions and bad smell. Therefore, compared to anaerobic manure storage, composting is a recommended GHG-mitigating process.

3.3. Anaerobic digestion

The anaerobic digestion (AD) technology (Figure 3) is well established in Northern Europe. This process uses biomass and biowaste, e.g., livestock manure and food industry by-products, to generate biogas, i.e., bioenergy or environmentally friendly RES (green energy), and digestate, i.e., a by-product rich in macro- and micronutrients, which can be used as a biofertiliser [11]. The operational efficiency of AD technology depends on the chemical composition and pH of raw materials, environmental temperature, and microbial composition, all of which influence the biogas and digestate yields and the process reliability [40].

A combined heat and power (CHP) plant can use biogas for the co-generation of electrical and thermal energy [41], while biomethane (CH_4) can be injected directly into the natural gas grid and/or be used as biofuel for vehicles [42]. The application of digestate produced from the AD of livestock manure as biofertiliser reduces the veterinary health risks that are usually associated with the soil application of raw livestock manure and slurry. However, in order to become suitable for being used as biofertiliser, the digestate must undergo a controlled sanitation procedure [43]. Depending on the type and quality of the used raw materials, the AD process itself is capable of providing adequate sanitation through a minimum hydraulic retention time (HRT) of 1 h at thermophilic temperature (45–70 °C). Instead, if the AD process is carried out at a mesophilic temperature (25–45 °C), sanitation must be performed through pasteurisation or pressure sterilisation [40].

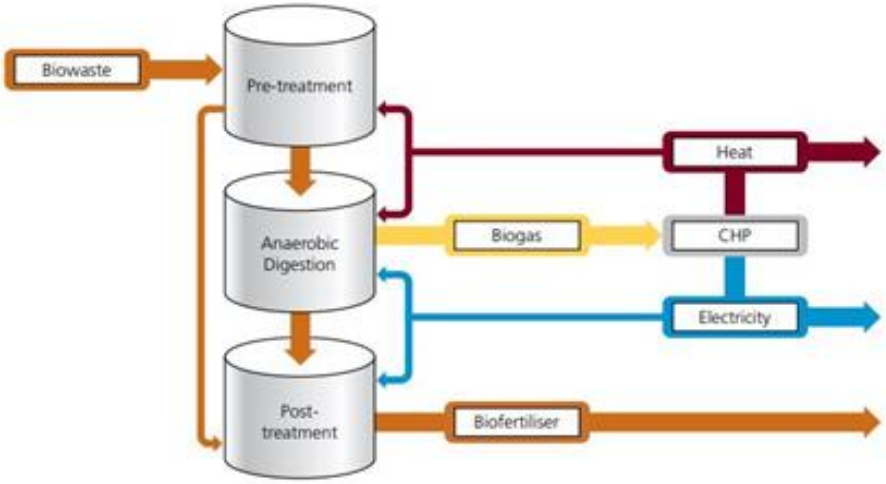


Figure 3. Flow chart of an anaerobic digestion plant (Powersystems, UK).

As an alternative to chemical/mineral fertilisers, the digestate can be used to achieve the following main benefits:

1) During the AD process, bio-chemical reactions transform the organically bound plant nutrients into inorganic forms; this mineralisation makes plant nutrients more available for uptake by plants, as substitutes of chemical fertilisers;

2) While chemical fertilisers supply only the nutrients, the digestate will also provide a significant source of humus-effective carbon, which will contribute to improved soil structure, while providing a platform on which soil microorganisms can thrive; moreover, the effective organic carbon (EOC), related to stable organic material found inside the digestate, will contribute to carbon sequestration;

3) Digestate can undergo a granulation process for producing pellets or granules (see section 3.10), which can also be integrated with biochar;

4) When using digestate instead of chemical/mineral fertilisers, GHG emissions and the use of fossil fuels, required for producing the latter fertilisers, are avoided; applying digestate to soil allows for the recycling of nitrogen (N), phosphorus (P), and potassium (K) in the soil according to CBE principles; in the EU, GHG emissions as a direct result of the production of chemical nitrogen fertilisers represented 19.9 Mt of CO_2 eq. in 2018; on the assumption that digestate use can replace 10–11% of chemical nitrogen fertilisers use by 2030, the resulting reductions in GHG emissions could represent at least 21 Mt of CO_2 eq. per year; furthermore, a corresponding average consumption of 1.1 billion m^3 of natural gas could also be saved per year by 2030 [34].

The AD technology contributes to reduce livestock farming footprints, while also having good biosecurity potential. In fact, a study carried out in Northern Spain indicated that methane emissions from slurry management (including its storage and use as biofertiliser) were between 34 and 66 kg CH_4/cow/year for dairy cows, and between 13 and 25 kg CH_4/calf/year for suckler calves, so that total emissions ranged from 22,223 to 107,949 kg CO_2 eq./year. Instead, livestock farms can potentially save between 978 and 1776 kg CO_2 eq./year if AD is used, because this process prevents methane emissions during slurry management [44]. Even if pig production is the second contributor to GHG emissions derived from livestock farming [45], it has been proved that pig manure is biodegradable and a good base for AD [46,47], which can substantially contribute to mitigate GHG emissions. In a

study in Finland, Kaparaju and Rintala [48] found that the adoption of AD in sow and finishing pig farms can avoid 87.7 and 125.6 Mg of CO_2 eq. per year, respectively. Finally, a report from Mexico indicated that using the biogas produced from the AD of pig manure for generating electrical energy, together with composting, resulted in the lowest net GHG emissions of 272 kg CO_2 eq. [49].

Regarding the biosecurity potential of AD, this process eliminates viral and bacterial pathogens, even if thermophilic conditions result in the highest pathogen reductions. However, the results of a comprehensive meta-analysis indicate that, among microbial groups, *Clostridiaceae* are highly affected by AD, and their reduction may be favoured by some pre-treatments. This meta-analysis demonstrated the effectiveness of AD for efficiently reducing some pathogenic species, such as faecal coliforms, i.e., *Escherichia coli* or *Salmonella* spp. Regarding the impact of operational parameters on pathogen reduction and the coupling of pre- and post-treatments with the AD process, the HRT in (semi)continuous digesters did not affect the overall pathogen reduction, implying that HRT values can be set according to the desired biomethane production rates. Heat-based post-treatments coupled with thermophilic AD resulted in the highest pathogen reductions, so that the pathogen amounts at the end of AD were lower than the legislation thresholds. The results of this review confirmed that temperature is the most relevant parameter: thermophilic conditions (45–70 °C) resulted in the highest pathogen reductions, while psychrophilic (lower than 25 °C) and mesophilic (25–45 °C) temperatures showed similar performances. The impact of pH on pathogen removal was confirmed, as acidic and basic values enhanced pathogen reductions. This is probably due to a combination of the effect of pH and of the concentrations of inhibitory compounds also affecting pH itself (e.g., VFAs or NH_3/NH_4^+) [50].

3.4. Decanter centrifuge

This process recovers nitrogen and phosphorous as a liquid or solid organic fertiliser when manure or digestate from the AD process is used as input material (Figure 4).



Figure 4. Decanter centrifuge for the recovery of nitrogen and phosphorus from manure or digestate (GEA Westfalia Separator Group GmbH, Germany).

This technology has been successfully applied for decades by farmers worldwide to recover nutrients from manure or digestate [51]. The centrifugal force leads the thinnest suspended solids to

precipitate, thus increasing the nutrient contents inside the liquid fraction. This process operates with or without chemical flocculants. However, due to their high cost, separation is usually performed without these additives.

This separation technology can remove 70–90% of phosphate compounds and 30–40% of nitrogen compounds. After separation, the crumbly solid fraction facilitates the storage and transportation of the product for further transformation [51]. The liquid fraction can be applied to local fields or further processed through a biological or physical-chemical treatment. It is even possible to further polish the liquid fraction by means of a disc stack centrifuge. Decanter centrifuges are the separation machines with the best separation performance per livestock farming footprint: they can separate more particles, compared to other filtration technologies.

Slurry or liquid digestate can be separated into a compact precipitate and a clarified liquid. Both still have high amounts of nitrogen and phosphorous, so that they are suitable for being used as solid and liquid organic fertilisers, respectively.

Full-scale studies have reported limited reduction of bacterial indicators in the liquid fraction, whereas higher centrifugal forces can achieve higher reductions under laboratory conditions. Therefore, centrifugation may redistribute microorganisms between solid and liquid fractions rather than substantially reduce the overall pathogen load [52].

Therefore, even if this technology is not a biosecurity measure, as it does not eliminate pathogen microorganisms and weed seeds, it contributes to reduce livestock farming footprints. In fact, when the separation between the solid and liquid fractions of manure or digestate is implemented by means of a decanter centrifuge, the net GHG emissions from manure management can be reduced by 19%. In fact, even if this separation can be carried out by consuming electrical energy obtained from fossil fuels (e.g., coal), the increase of GHG emissions is negligible compared to the reduction of GHG emissions from manure [53].

3.5. VP-HoBe valorisation system

This process recovers nitrogen in the form of a mineral concentrate or ammonia water or ammonium sulphate from livestock slurry or digestate or wastewater (Figure 5). This technology is associated with low operational costs (in terms of energy and additives), while it produces several biofertilisers, as well as clean dischargeable water.

Flocculants are added to manure, which undergoes separation inside a flotation device equipped with a belt filter press, in order to generate liquid and solid fractions. Inside the flotation device, small air bubbles bring particles to the tank surface, where they form a sludge layer. This floating layer, which typically presents 30% dry matter (DM) content, is scraped-off and pressed dry up to 90% DM in order to form the solid fraction. The liquid fraction, that typically still has 1.7% of suspended solids, can be subjected to a reverse osmosis (RO) treatment, in order to produce a retentate concentrate of nitrogen/potassium oxide (K_2O) and a permeate. The retentate can be further processed by means of an evaporator in order to remove water and, therefore, concentrate the suspended solids. The liquid fraction passes through a film evaporator that evaporates the water. Under vacuum, the boiling point of liquids is lowered, so that this efficient technology reduces the energy needed to boil off liquids, when compared to evaporation under atmospheric pressure. The ammonia contained in the incoming liquid fraction is concentrated into ammonia-water (14% N). Scrubbing of the vapour emerging from the evaporator captures a K concentrate (25% DM) and a solution of ammonium sulphate [51].

The working capacity of this plant is scalable: 50,000, 125,000, or 250,000 tonnes of input per year.



Figure 5. Plant using the VP-HoBe manure and digestate valorisation system (VP-HoBe B.V., the Netherlands).

Slurry or digestate or wastewater can be converted into mineral concentrate, ammonia water, and ammonium sulphate, including nitrogen, as well as clean dischargeable water [34]. Ammonium sulphate is produced by scrubbing the vapour coming out from the evaporator with sulphuric acid, thus converting ammonia into ammonium sulphate (7% N) [51].

The key features of the ammonium sulphate obtained through this technology are the following:

- It is a liquid nitrogen biofertilizer;
- It contains 70 g kg^{-1} of N (NH_4), i.e., 7%;
- It contains 76 g kg^{-1} of sulphur (S);
- It has a high level of purity with low amounts of phosphate;
- It is free from *Salmonella* spp. and *Escherichia coli* [51].

The spatially variable rate application of the above biofertiliser can be implemented, according to precision agriculture principles, in order to reduce agriculture footprints.

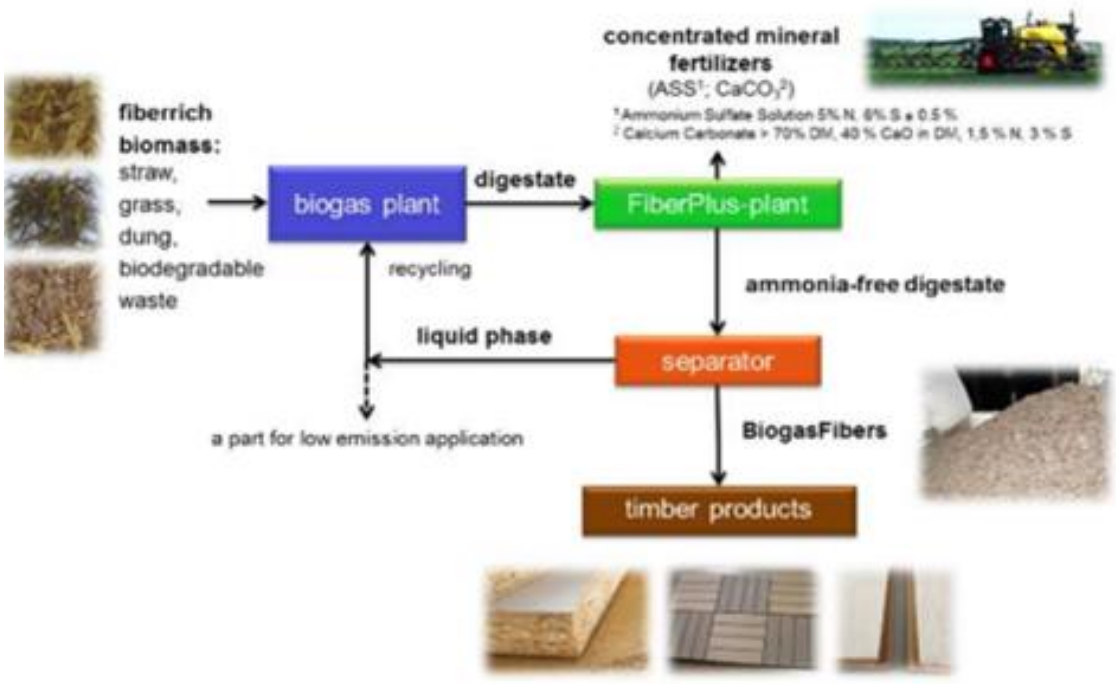
This biofertiliser can be applied by means of a spreader equipped with an injection device, in line with the best available technology guidelines for low emission application techniques, in order to minimise ammonia losses through volatilisation [51]. This technology is a partially good biosecurity measure as it eliminates bacterial pathogens but not viral ones, besides contributing to reduce livestock farming footprints. However, specific peer-reviewed evidence quantifying bacterial or viral pathogen reduction during the VP-HoBe treatment chain remains limited.

3.6. BENAS anaerobic digestion

This process recovers ammonium sulphate as a biofertiliser from the anaerobic co-digestion of corn silage, poultry manure, and food biowaste (or wastewater) (Figure 6) [51].



(a)



(b)

Figure 6. Layout (a) and flowchart (b) of the BENAS anaerobic digestion plant for the co-digestion of corn silage/poultry manure/food biowaste (or wastewater) mix, integrated with the FiberPlus system to generate ammonium sulphate, lime, phosphorous, and potassium (as fibres) (GNS: Gesellschaft für Nachhalige Stoffnutzung mbH, Germany).

The BENAS AD plant has a yearly capacity to convert 80,000 tonnes of corn silage/poultry manure/food biowaste mix into biogas, biofertilisers, mineral nitrogen, and calcium carbonate. The scrubbing process inside a BENAS AD plant recovers 80% (equivalent to 200 t/year) of the ammonia contained in the digestate. This AD plant can produce two different types of biofertilisers, following the addition of flue gas desulphurisation-gypsum (FGD-gypsum): 25% ammonium sulphate (AmS) solution, with a yield of 5–40 t/day; and solid calcium carbonate (lime, having 70% DM content), with a yield of 1.5–14 t/day. The added gypsum increases soil pH, thereby enhancing nutrient availability without causing alkalinisation (in acidic soils), while providing calcium (important plant macronutrient). This additional process does not require a supplementary source of thermal energy, as it uses the exhaust heat coming from the CHP plant that would otherwise be lost [51].

A unique feature of this plant is that, by adding a nitrogen stripper (FiberPlus), it is possible to produce ammonia-free fibres, which can be used in the fibre and timber industries (fibreboard). This system has low GHG emissions and, therefore, minimises the loss of nitrogen, so that it can recover the following macronutrients: 67% of ammonium-N as AmS; 6% of ammonium-N as lime; 6% of P; and 5% of K as fibres [51].

The technology employed in the BENAS AD plant can operate as a closed system according to CBE principles. This process achieves the following benefits:

- Recovery of up to 80% of the ammonia contained in the digestate;
- Lower incidence of GHG emissions, by reducing the CO_2 emissions from the digestate transportation;
- Reduction of soil water contamination by nitrate and GHG emissions, i.e., ammonia and nitrous oxide [51];
- Decreased storage and transportation costs by integrating the nitrogen stripper;
- Production of two marketable biofertilisers, i.e., ammonium sulphate (AmS) solution and solid calcium carbonate.

The cost of this technology is €5.7 per tonne of produced digestate.

The BENAS AD plant, integrated with the FiberPlus system, can supply ammonium sulphate, lime, phosphorous, and potassium (as fibres), which can replace chemical/mineral fertilisers [34].

Inside the BENAS plant, thermophilic AD is carried out, so that this plant has a substantial potential for pathogen reduction through temperature-mediated inactivation. However, while thermophilic AD has been shown to effectively inactivate several bacterial and viral pathogens, technology-specific quantitative evidence for pathogen reduction during the complete BENAS process remains limited [54–56].

Therefore, even if this technology is not a biosecurity measure, it contributes to reduce livestock farming footprints.

3.7. Geamix housing system

The "Geamix" (Groei En Anvaulling Mix) housing system (Figure 7) was designed to separate livestock urine from faeces, facilitating the recovery of nitrogen and phosphorous from urine and the production of a solid soil improver from the dry manure.



Figure 7. "Geamix" housing system for nitrogen and phosphorous recovery from urine and solid soil improver from calves manure (Geamix, calf breeder Stefan Thelosen, the Netherlands).

In a barn, livestock are reared on a suspended steel slatted coated floor, where approximately 50% of manure passes through a grid. Due to the unsticked coating, the manure hardly adheres to this floor, reducing GHG emissions. The faeces and urine are moved onto a punctured belt located under the grid; this belt unloads the semidry manure fraction several times a day onto an air-tight collection vat, located outside the barn.

Urine is collected onto a coated sub-floor reservoir with a sloping floor, channelling urine itself to flow away to a closed reservoir, also located outside the barn. The coated sloping sub-floor is washed with water once a day, in order to prevent sedimentation [34].

By using this system, the solid manure retains a 40% DM content. Currently, a device is under development to incorporate quicklime into the manure, in order to dry it further, before crumbling it into an 85% DM matrix. This product can be sold both on the regional and international levels because it is pathogen-free [51]. This biofertiliser and soil improver can replace chemical/mineral fertilisers and dry manure pellets, according to CBE principles.

In order to capture the ammonia emissions from the solid fraction during drying, this final step is carried out in an existing air scrubber [51].

The Geamix housing system primarily aims at reducing cross-contamination between faecal and urinary fractions through source separation, rather than direct pathogen inactivation. Although subsequent drying or other sanitation steps may reduce microbial hazards, specific evidence quantifying bacterial or viral pathogen reduction attributable to this system remains limited.

3.8. Belt press sieve–reverse osmosis

This process allows to convert the liquid fraction of pig and/or cattle slurry into a solid fraction containing phosphorous and a liquid fraction containing nitrogen and potassium, by means of a belt press sieve and a reverse osmosis technique (Figure 8).



Figure 8. Process for the recovery of nitrogen and phosphorous from manure, by means of belt press sieve and reverse osmosis (Vlako B.V., the Netherlands).

This technology is used, for example, by Vlako company (the Netherlands); here, slurry from pigs, cattle, and mink operations is discharged into the reactor tank, and sulphuric acid and iron sulphate are added [51]. On mixing, the acidified slurry is carried onto a sieve belt press, where the liquid fraction, with soluble minerals, is separated.

Following pasteurisation, the solid fraction is sold as a phosphate biofertiliser. The estimated production capacity of the Vlako processing plant is 135,000 m^3/year of phosphate biofertiliser.

The liquid fraction undergoes a further process of filtration and reverse osmosis to produce a liquid N/K fertiliser. Moreover, reverse osmosis is highly viewed as being the best available technique to generate clean water [51] from the liquid fraction of slurry.

The benefits of this process include:

- Reduction of GHG emissions by separation at source, because both solid and liquid fractions are used as biofertilisers, instead of the input materials (pig and/or cattle slurry) that can emit methane, i.e., a GHG with a GWP 25 times higher than carbon dioxide;
- Generation of high-quality biofertilisers that can be applied to soils according to CBE principles [34].

The combination of mechanical solid–liquid separation and reverse osmosis can enhance the microbiological safety of the liquid fraction, by coupling particulate removal with membrane-based retention of microorganisms. However, the biosafety benefit of this technology is mainly associated with the membrane-based filtration step, while pathogens retained in the solid fraction or in the reverse osmosis concentrate may require an additional treatment before soil application as biofertiliser or further use [57,58].

3.9. Vibrating reverse osmosis (vibratory shear enhanced processing, VSEP)

Dr. Jennifer Bilbao (Stuttgard, Germany), after carrying out a project on VSEP, proposed it as a mobile or no-spot solution for farms having little available land. VSEP is a vibrating membrane-separation technology that takes advantage of intense shear waves: When they act on the membrane surface, a reduction in membrane fouling is achieved, thereby allowing a high separation efficiency of

the membrane. The "plate and frame" membrane design undergoes torsional vibration, while the membrane surface experiences shear forces that are higher than those applied in belt press sieve–reverse osmosis technology [59–62]. Macronutrients (N, P, K) are removed by using the VSEP technology; high nitrogen removal efficiency, i.e., 96%, and lower phosphorus removal efficiency, i.e., 60% maximum, are obtained from livestock waste [63–65].

Most VSEP technology applications are based on its capability to treat different waste and recover nutrients. Vaneeckhaute et al. [66] evaluated the performance of VSEP technology in recovering plant nutrients from liquid digestate. Yoon et al. [67] investigated the fertiliser potential of the concentrate obtained through the VSEP process by applying it on rice. The authors stated that the concentrate obtained from the treatment of piggery wastewater by VSEP technology resulted in the same crop yield as that obtained using a chemical/mineral fertiliser.

The VSEP technique, operating by means of reverse osmosis membranes and tested at a pilot scale, was proved to have potential to recover nutrients from the liquid fractions of pig slurry and digestate, in order to obtain concentrated biofertilisers (Figure 9). The use of the VSEP plant allowed for reductions in the water content of the pig slurry and digestate, i.e., 77% and 67%, respectively. Both VSEP concentrates were characterised by significant macronutrient (N, P, K) contents and showed a nitrogen fertiliser replacement value similar to that of mineral fertilisers. This was demonstrated in a test on barley crop cultivated in pots, although the salinity of the digestate concentrate limited its application rate, in order not to reduce the crop yield [68].

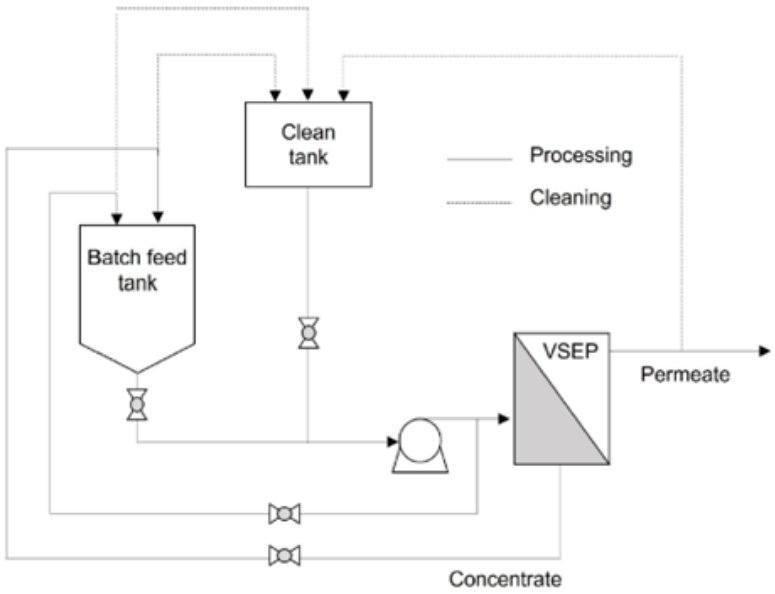


Figure 9. Flowchart of VSEP (vibratory shear enhanced processing) batch mode pilot testing process, integrated with a reverse osmosis membrane [68].

Vibrating reverse osmosis can provide an effective physical barrier for microorganisms during the treatment of liquid manure fraction, with microbial retention expected to occur through membrane filtration. However, available studies on vibrating reverse osmosis applied to pig slurry and digestate have primarily focused on nutrient recovery, whereas direct quantitative evidence on bacterial or viral pathogen removal remains limited [68].

3.10. Granulation

Granulation, pelletising, or pelletisation is a technique that transforms a material into small and spherical particles, by applying high pressure and temperature. The material to be pelletised is usually dried slurry or manure that is fed into a pellet mill. The pellet mill consists of a matrix having holes of a specific shape and size, through which the material is forced. Then, the resulting pellets are cut and cooled, thus forming the final product. Pellets present several advantages compared to the raw materials, such as ease of handling, storage, and transportation, as well as preservation of the nutrients contents. Pellets are widely used for fertilisation, as they provide a uniform and controlled release of nutrients to the soil [69,70].

There are five standard methods for the granulation of organic waste, including manure: mixer-dryer granulation (Figure 10); disc pelletising; drum granulation; extrusion; and pipe reactor granulation.

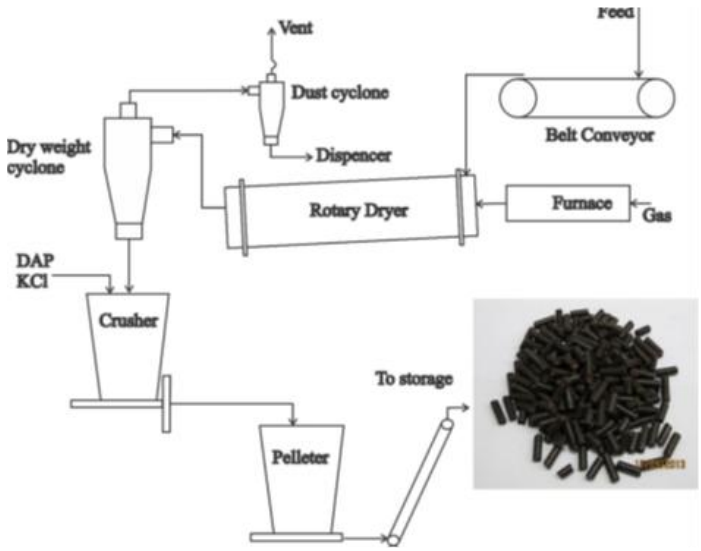


Figure 10. Flowchart of the mixer-dryer granulation method, applied to poultry litter [72].

In mixer-dryer granulation, the mixer receives pre-treated manure. The type of mixer depends on the feedstock characteristics and can be either a pin mixer or a pug mill. A pin mixer is suitable for drier and thinner raw materials, e.g., compost and chicken litter. A pug mill works better with wetter and thicker raw materials, e.g., liquid manure that has been dewatered. The mixer evenly blends the feedstocks, the binder, and any other additive. The materials start to form round pellets while they are in the mixer. Then, the mixer releases the pellets, which are transported by a conveyor to the rotary drum dryer for drying. After drying, the pellets are usually cooled to enhance their storage quality and reduce clumping [70,71].

In the method of disc pelletising, a disc pelletiser is added after the mixer and before the dryer, unlike in mixer-dryer granulation. This machine enhances the process output and allows for more adjustment and control over the final product. Generally, a disc pelletiser improves the overall working capacity and the product quality. Pelletisers can also work by using different binders. Disc pelletising is a method of agglomeration without pressure (tumble growth) that converts thin materials into round—not cylindrical—pellets. The pellets from disc pelletising are denser and more spherical than

those from only mixing.

The method of drum granulation is similar to disc pelletising in terms of process flow, but it uses a granulation drum instead of a disc pelletiser. A granulation drum is usually preferable, due to its higher working capacity and ability to operate in a closed system. Granulation drums are generally used when the product does not need to be premium quality or when the raw materials are dusty [70,71].

The extrusion method incorporates a dry pellet mill followed by a crumbler. This method is different from the first three, as they are methods of agglomeration without pressure. Extrusion is an agglomeration method that uses pressure to push thin raw materials against a mold and make them to stick together as pellets. The extrusion process is simple and cheaper than the other methods. However, the cylindrical granules obtained through the extrusion process have lower quality than the round pellets from tumble growth methods. This is because round granules have much less dust and friction and can be more customised.

In the pipe reactor granulation method, the pipe reactor is a vessel where acids and bases react to obtain products of a specific quality. The hot melt from the reaction can be either rolled in a granulator or mixed in a pug mill to produce rough agglomerates. The pipe reactor granulation method presents two main benefits when working with organic materials like manure: the reaction reduces the material smell and, primarily, the heat from the reaction can be used to dry the product, thus saving significant energy that would be consumed by the dryer. Pipe reactors can also change the nutrient content of the product according to the input materials [70,71].

Several research works have suggested how to speed up the composting process of solid manure, the reduction of its moisture content (as mass), and the granulation process. One of the granulation methods, i.e., mixer-dryer granulation, applied to poultry litter, is shown in Figure 10 [72].

The granulation process can be aimed at spatially variable rate application of granular biofertiliser obtained from manure, according to precision agriculture principles, in order to reduce both livestock farming and agriculture footprints. In fact, when manure is converted into granular biofertiliser, GHG emissions from manure stored in stockpiles are avoided, so that livestock farming footprints are reduced. Specifically, data from manure management projects show that systems combining solids removal and subsequent treatment emit 0.2 t of CO_2 eq. per ton of treated total solids, while granulation process can save 31,785 t of CO_2 eq. over five years [73]. Moreover, when this granular biofertiliser is applied to soils, by replacing chemical/mineral fertilisers, GHG emissions from the Haber-Bosch process, needed for manufacturing the nitrogen chemical fertilisers, are avoided. Furthermore, when this granular biofertiliser is applied only where it is needed and only by using the required amount, GHG emissions from the internal combustion engine of the tractor connected to the centrifugal spreader are reduced. For the last two reasons, agriculture footprints are reduced.

Through the granulation process, digestate from plant biomass, fruit pomace, or cereal silage is converted into solid biofertiliser pellets, including macronutrients, i.e., N (1.5%), P (0.2%), and K (0.6%), as well as organic matter (DM content higher than 80%, e.g., 88%).

The price of this biofertiliser, certified as fully organic, is variable among countries (€8/5 kg for retail customers in some countries), while its suggested application rate is 1 kg m^{-2} in conventional agriculture. This biofertiliser, having a pellet form, must be stored in a dry and covered place, protected from direct sunlight, in its original packaging.

The Planteo pelleted biofertiliser (marketed by Zielone Suszarnie Ltd, Poland) is a carbon-rich biofertiliser that is effective in conventional, organic, low input, and precision agriculture [51]. This environmentally friendly biofertiliser can be applied in open fields, gardens, greenhouses, and at home.

It is recommended to be applied to the soil before sowing or transplanting and should be mixed with topsoil. It is obtained from the digestate produced, together with biogas, through the AD process by using only plant materials, inside a modern agricultural AD plant located in Kożanówka, Poland [51]. Due to its plant origin, it is free of antibiotics and includes very low amounts of contaminants, so that its use is safe for children, animals, and bees, and does not cause allergies. Therefore, this technology is also a good biosecurity measure.

The biofertiliser pellets can improve soil structure and increase soil organic content (SOC), chemical fertility, and water holding capacity. Therefore, it is recommended for soils having low SOC, as well as crops and soils sensitive to drought events. Moreover, this biofertiliser slowly releases macro- and micronutrients, thus implying no water pollution risk. This biofertiliser includes also endophytic bacteria, i.e., *Bacillus subtilis* and *Pseudomonas fluorescens*, originating from the digestate and producing phytohormones, that stimulate plant growth, protect plants against fungal pathogens and pests, and increase plant resistance to weather stress [51].

Granulation can contribute to pathogen reduction when the process involves sufficient thermal exposure, drying, and mechanical treatment. Even if *Enterobacteriaceae* were reduced to below the detection limit after pellet production from digestate, and *Salmonella* was not detected from AD onward, complete sterilisation was not demonstrated [74]. Moreover, no direct evidence is available on viral pathogens.

3.11. Gasification

Gasification is an innovative technology that uses carbon-based organic matter to generate energy without combustion. This process involves the chemical transformation of waste (solid or liquid) into syngas (Figure 11). This process involves small amounts of oxygen to react with the carbon-based organic matter (without burning), breaking it down into syngas, i.e., a mixture of hydrogen (H_2) and carbon monoxide (CO). The syngas produced can be used to power a CHP plant. The gasification process transforms the chemical energy stored in the waste into another chemical energy in the form of syngas.

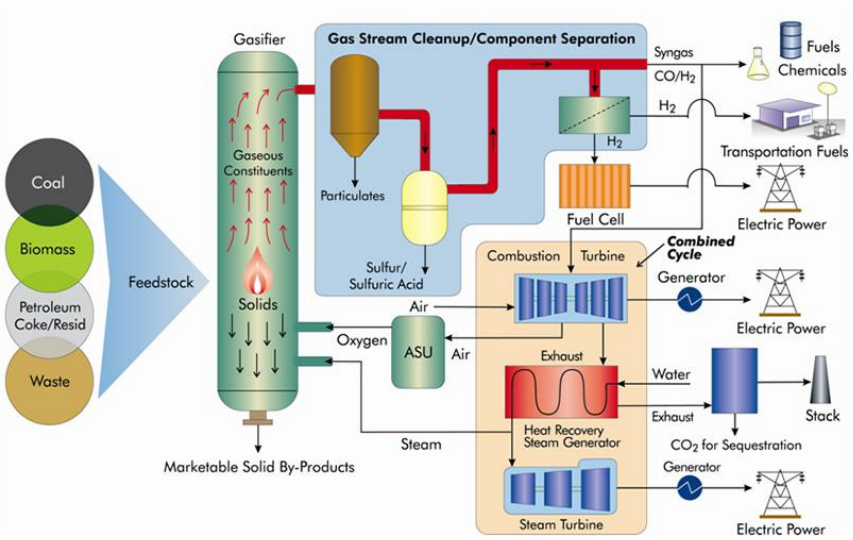


Figure 11. Flowchart of the gasification process [76].

Temperatures from 900 to 1100 °C for air and from 1000 to 1400 °C for oxygen are normally reached inside the gasification reactors. The most commonly used method is air gasification, since it is cost-effective, but this process generates low energy dense syngas. The production of an energy dense syngas (oxygen gasification) requires an abundant oxygen supply, thereby significantly increasing the cost of process. Gasification occurring at temperatures above 1600 °C has the advantage of converting ash into inert slag [75].

Gasification can provide effective pathogen elimination through exposure to high temperatures under limited oxygen or partially oxidising conditions. An industrial-scale study of chicken manure gasification demonstrated a substantial reduction of microbial hazards, as quantitative microbial risk assessment indicated removal of the potential pathogenic risks associated with the manure and proved the microbiological safety of the resulting product [77,78].

3.12. Pyrolysis

Regions having a high livestock density generally do not have sufficient land areas on which to apply the manure without exceeding the legal permissible limits as established by the EU Nitrates Directive and the EU Water Framework Directive. Furthermore, these regions usually lack manure processing plants, thereby aggravating the manure management challenge, especially in the case of EU islands. Consequently, manure becomes a liability that needs to be addressed rather than a valuable resource that would benefit agriculture.

Research indicates that pyrolysis may be a beneficial option. The pyrolysis technology differs from gasification, as the former produces more ash, while the latter produces more biochar. Depending on the process conditions and on the characteristics of the manure, highly influenced by the digestive physiology of the livestock species and manure treatment protocol, different yields of biochar (pyrolysis solid phase), bio-oil (pyrolysis liquid phase), and syngas (pyrolysis gas phase) are obtained. All pyrolysis products can be potentially used as biofuels in a combustion chamber.

The ratio of biochar:bio-oil:syngas released by poultry, cow, and sheep manure is 1:1:1, 1:0.5:1.5, and 1:4:1.7, respectively. This confirms that the different feedstocks are constituted by different compounds having different boiling points. Hence, depending on the specific boiling points, the released volatile compounds segregate according to the corresponding molecular properties into syngas or condense into bio-oil. Research results indicate that a mixture of cow and poultry manure will complement each other and release syngas at a steady rate [79].

However, a disadvantage of the pyrolysis process is that the feedstock has to be dried. This is a challenging situation when dealing with manure that can have a water content higher than 50%, requiring the expensive pre-treatment of drying (Figure 12). In fact, this high water content compromises the pyrolysis process, as it causes a reduction of operating temperature and energy extraction efficiency [79]. When poultry manure samples were tested for heating values, the energy content on a DM basis was, on average, 4.8 times higher than that obtained from the wet manure [80].

Thus, the total amount of energy required for the pyrolysis of manure includes an amount required for drying and the sensible heat to raise the dried biomass to the correct temperature, e.g., 570 °C. The energy required to dry the feedstock is equal to the amount of heat required to raise the temperature of the wet biomass to 100 °C, plus the latent heat of vaporisation to remove the water and, therefore, dry the substrate. Generally, a proper pyrolysis process requires a feedstock with a water content between 5% and 15%, thus needing pre-treatment [79].

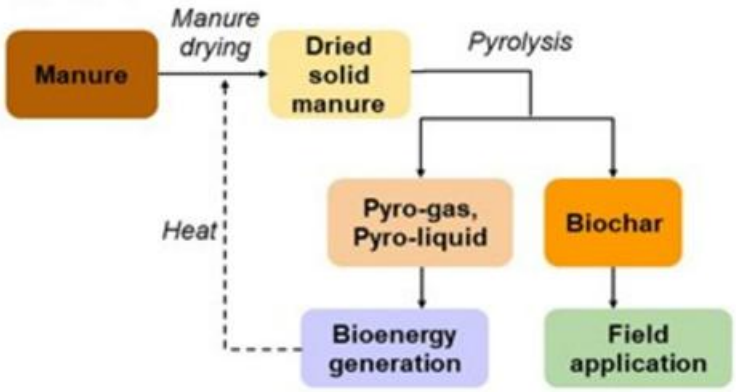


Figure 12. Drying approach to integrate livestock manure in a pyrolysis process: excess heat generated during the pyrolysis is used to dry manure prior to pyrolysis [86].

Yet, manure drying could be carried out through contact with the sawdust from wood vessels used for transporting water, and must be followed by pyrolysis together with waste water (sewage sludge). Thus, it will be possible to avoid a two-days stop and, therefore, save energy.

Another disadvantage of pyrolysis is that biochar was only recently included by the EU for fertilisation/amendment, while the market of this pyrolysis product is still under development. A further disadvantage is that the pyrolyser includes a chimney and, therefore, emits smoke in the atmosphere. Thus, this plant is considered to be a source of air pollution.

However, this technology has the benefits of a shorter conversion time compared to aerobic composting, the absence of non-biodegradable and toxic compounds, high processing temperatures that are adequate to neutralise all pathogens potentially found inside manure, and conversion into added-value products [81]. Thus, the thermo-chemical conversion of livestock manure into biofuels through pyrolysis contributes to the development of a bio-based economy, thus improving the sustainability of rural communities and the health of humans, wildlife, and the environment [82].

According to CBE principles, the pyrolysis technology can be implemented for recycling the solid digestate produced through the AD process, instead of using it as biofertiliser. In fact, the solid digestate cannot be applied in nitrate vulnerable zones (NVZ), where it could contribute to water eutrophication. Instead, though isothermal pyrolysis, solid digestate can be used as a biofuel source. Akor et al. [83] used the Advanced Kinetics and Technology Solutions (AKTS) thermokinetics software to model and calculate the activation energy (Ea) and other kinetic parameters. They used the differential isoconversional (model-free) method, compared to ASTM-E698 and Ozawa–Flynn–Wall models. Ea values were 85–190.0, 169.8, and 75–175.0 kJ mol^{-1}, respectively. The kinetic prediction of isothermal pyrolysis of solid digestate indicated that a temperature higher than 210 °C is required for triggering its decomposition. Moreover, the solid digestate has the potential to produce an additional 27.9 MJ per day in a 500 kW AD plant. Thus, solid digestate can be recycled into biochar, i.e., a biofuel, that is a further revenue of AD technology. Moreover, this conversion can connect AD plants with pyrolysers, thus building up a more environmentally friendly circular system, compared to the only digester, producing digestate to be applied to soils.

Furthermore, in the study carried out in Chile by Ginebra et al. [84], two manure-derived biochar types and their feedstocks were used as soil amendments to evaluate the effect of pyrolysis on CO_2 and N_2O (GHGs) emissions, carbon stability, and GWP for one year. The experiment included five

treatments: unamended soil (control), pig manure, biochar from pig manure, manure of dairy cattle, and biochar from dairy cattle manure. The negative values obtained in both biochar treatments indicate the mitigation potential of pyrolysed manure types (−4.4 t CO_2 eq. ha^{-1}, on average) compared to their feedstocks (14.63 t CO_2 eq. ha^{-1}, on average). The increase in soil carbon content produced a negative GWP for all treatments, even if this effect was 59.8% higher by using biochar types rather than unpyrolysed manure types. However, pig and dairy cattle manure increased the GWP in terms of both N_2O and CO_2 emissions, compared to the control. In a later experiment, poultry litter, dairy cattle manure, biochar from poultry litter, and biochar from dairy cattle manure were applied at rates of 8 t ha^{-1} in a red clover (*Trifolium pratense* L.) field. Manure biochar types proved useful at a low rate for increasing crop yield and soil carbon sequestration [85]. Therefore, the application of manure biochar is a promising option to reduce the manure volume and the carbon footprints of poultry, pig, and dairy cattle farms, thus promoting an increase in soil carbon sequestration and reducing soil N_2O emissions [84,85].

Pyrolysis offers a high sanitation potential for livestock manure through exposure to high temperatures under limited-oxygen conditions. Available evidence indicates a substantial or complete elimination of pathogenic microorganisms at sufficiently high pyrolysis temperatures, while recent studies and reviews also suggest marked reductions in antibiotic resistance genes, although the extent of microbial and genetic inactivation depends on temperature, process time, and pyrolyser type [86–88].

3. Discussion

Originally, the Nitrates and Water Framework EU Directives considered the use of fertilisers only as a soil pollution issue, i.e., a factor contributing to losses of nitrates and phosphates from agricultural soils into ground and surface water bodies.

In fact, the EU Nitrates Directive, i.e., the Council Directive of December 12, 1991, concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC) in vulnerable zones (all known land areas in their territories that drain into the waters and contribute to pollution), establishes measures for preventing this pollution [89]. These measures ensure that, for each farm or livestock unit, the amount of manure applied to the land each year shall not exceed a specified amount per hectare, i.e., the amount of manure containing 170 kg N [89]. This limit was established to prevent the negative environmental impact caused by the spreading of unprocessed manure.

Instead, in 2010s, the EU addressed fertilisers as strategic crop inputs, whose access should be secured, either through domestic production or imports, as proved by a 2019 initiative aimed at ensuring the availability of fertilisers on the EU market.

In this context, EU member states should be able to use biofertilisers, partially or totally produced from livestock manure through processing, called as REcovered Nitrogen from manURE (RENURE) in not vulnerable zones. RENURE can replace chemical/mineral fertilisers and make food production chains resilient, as they can depend on these locally available resources [90].

Moreover, the European Biogas Association (EBA) proposes two main recommendations to European Commission: 1) to apply the RENURE criteria developed by the Joint Research Centre (JRC), in order to allow the use of sustainable crop inputs above the limit established by EU Nitrates Directive; and 2) to complete the RENURE criteria with a guidance on agronomic practices, in order to ensure the efficient and safe use of RENURE.

The guidance on agronomic practices should be addressed to EU member states, even if exemptions must be granted for the safe use of RENURE and/or chemical/mineral fertilisers by

farmers. These agronomic practices, flexible enough to be adapted to the different local conditions in the EU, should imply crop rotations, including species belonging to *Leguminosae* family (able to provide soil with N) and remote sensing of plant nutrient contents from UAVs (unmanned aerial vehicles) and/or satellites, according to precision agriculture principles.

Among the manure management technologies available at EU level, pyrolysis and AD can be considered as particularly relevant for treating manure potentially contaminated by bacterial or viral pathogens, including *Salmonella* spp., *Escherichia coli*, African swine fever virus (ASFV), and highly pathogenic avian influenza viruses (HPAIV). Their main advantage, from a biosecurity perspective, is that pathogen reduction is associated with defined and controllable treatment conditions (i.e., temperature and time), providing a barrier between contaminated manure and its subsequent use, storage, or disposal [91,92].

Pyrolysis represents a particularly strong thermal treatment. The high temperatures reached under limited oxygen conditions can effectively inactivate microorganisms, provided that adequate temperature and residence time are achieved throughout the treated materials. Experimental studies have demonstrated the thermal sensitivity of ASFV in pig slurry, with complete inactivation reported at 53 °C under defined experimental conditions [93]. Similarly, such a thermal treatment, followed by a properly managed composting, has been shown to effectively reduce or eliminate infectious HPAIV in poultry manure and litter [94,95]. In addition, pyrolysis converts manure into biochar, thus substantially changing the characteristics of the raw materials and reducing the risks associated with the subsequent treatment and application [96].

Moreover, AD is another process able to reduce pathogen load, although under conditions different from those featuring pyrolysis. Anaerobic conditions, microbial competition, organic acids and ammonia contents, temperature, and HRT can contribute to inactivate bacterial and viral pathogens. Significant reductions in *Escherichia coli* and *Salmonella* have been reported, although the efficacy of this process strongly depends on operating conditions [97]. Animal viruses can also be inactivated during thermal treatment of slurry, thus significantly reducing the pathogen load observed under thermophilic conditions [93,98]. For ASFV, however, direct validation under actual AD conditions remains limited, so that thermophilic AD should be considered as a potential rather than universally demonstrated viral inactivation barrier [99]. More generally, recent evidence confirms that temperature is a major factor of pathogen reduction during AD [50]. However, the prevention of post-treatment recontamination remains essential, in accordance with EU requirements for sanitation and treatment of animal by-products.

The relevance of both pyrolysis and AD is particularly evident during outbreaks of high-impact animal diseases. In fact, ASFV can persist in contaminated materials, while HPAIV can remain in poultry faeces and litter under ordinary farm environmental conditions [92]. Studies on ASFV-infected materials have shown a rapid loss of infectious virus at sufficiently high temperatures, although viral DNA may remain detectable [100]. This distinction is also relevant for HPAIV and highlights the importance of assessing treatment efficacy in terms of infectivity loss rather than simply disappearance of viral nucleic acids. Therefore, compared to manure storage, pyrolysis and AD offer the advantage of integrating pathogen reduction into controlled treatment systems, rather than predominantly relying on natural pathogens decay.

Even if other manure management technologies, i.e., composting, can also provide effective pathogen reduction, their efficacy depends on the achievement of adequate and homogeneous time-temperature conditions [94,100].

4. Conclusions

Among the 17 Sustainable Development Goals (SDGs) of the United Nations, the results of this work, i.e., the possible available technologies proposed, on EU level, for managing the manure produced by livestock affected by diseases, are linked with the following:

- Zero Hunger (end hunger, achieve food security and improved nutrition, and promote sustainable agriculture, no 2);
- Good Health and Well-Being (ensure healthy lives and promote well-being for all at all ages, no 3);
- Clean Water and Sanitation (ensure availability and sustainable management of water and sanitation for all, no 6);
- Affordable and Clean Energy (ensure access to affordable, reliable, sustainable, and modern energy for all, no 7);
- Climate Action (take urgent action to combat climate change and its impacts, no 13);
- Life on Land (protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss, no 15).

Based on the results and discussion of this review paper, among the possible technologies for manure management available on EU level, it is possible to suggest pyrolysis and anaerobic digestion (AD) as the best methods for treating the manure produced by animals potentially contaminated by viruses and/or bacteria, in order to improve biosecurity measures, i.e., obtain safe livestock manure and avoid the spreading of these pathogens.

Pyrolysis is the best management technology for manure produced by animals affected by pathogens or suspected to be. Yet, if this process is implemented, a priori manure drying needs to be carried out, until reaching a water content of 5–15%, as a wetter substrate reduces the operating temperature and the energy extraction efficiency. This pre-treatment is time- and cost-consuming, so that its economic viability must be evaluated case by case.

AD is the second-best biosecurity technology, after pyrolysis. If AD is implemented, the digestate produced during this process must be subjected to pasteurisation or pressure sterilisation, unless a thermophilic temperature (45–70 °C) for a minimum hydraulic retention time (HRT) of 1 h was used in the digester. Moreover, the following recommendations on the use of digestate originating from the AD of manure should be implemented:

- Synchronise digestate application with crop growth phase, in order to reduce the possibility of nitrogen leaching or ammonia volatilisation;
- Promote the use of highly efficient agricultural machines for spatially variable rate biofertiliser application (according to precision agriculture principles), in order to compliment conservation techniques, during the crop life cycle;
- Avoid nozzle application, as this technique promotes ammonia volatilisation, and, instead, prefer the use of agricultural implements able to bury the digestate, such as mouldboard ploughs (able to deeply bury manure into the soil, effectively mixing it with the soil profile), disc harrows (able to break up clumps of manure and mix it with the soil surface, promoting faster decomposition and nutrients release), cultivators or tillage equipment (able to incorporate manure into the soil while minimising soil disturbance), or injection equipment (able to directly place slurry into the soil at a controlled depth, reducing surface runoff and odour emissions) [101];
- Store digestate in covered storage tanks or in commercially available above-ground flexible

storage bags, in order to minimise biomethane and ammonia losses [90].

Overall, all the technologies considered in this review paper, i.e., aerobic treatment, composting, AD, decanter centrifuge, VP-HoBe, BENAS system, Geamix housing system, belt press sieve–reverse osmosis, vibrating reverse osmosis, granulation, gasification, and pyrolysis, produce biofertilisers that can replace mineral/chemical/synthetic ones, so that they can contribute to reduce footprints from livestock farming. Moreover, if spatially variable rate biofertilisation is implemented, it is possible to also reduce agricultural footprints.

However, further research will also need to assess the selected manure management technologies through the computation of energy balance. In fact, in a previously performed survey, the energy balance was computed for four considered scenarios. Within the implementation of the integrated solid waste management (ISWM) method, AD resulted in an energy balance much higher than that of aerobic composting. In fact, differently from composting, AD can significantly contribute to energy recovery, while retaining the nutrients in the digestate produced and reducing GHG emissions [102].

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

Antonio Comparetti is an editorial board member for AIMS Agriculture and Food and was not involved in the editorial review or the decision to publish this article The authors declare no conflict of interest.

Author contributions

George Attard: Conceptualization, methodology, writing—original draft; Antonio Comparetti: Supervision, investigation, methodology, writing—original draft; Eglė Jotautienė: Investigation, writing—original draft, writing—review and editing; Antanas Juostas: Investigation, writing—original draft; Francesco Mira: Investigation, writing—original draft, writing—review and editing.

References

1. Leip A, Weiss F, Wassenaar T, et al. (2010) Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS)—final report. European Commission, Joint Research Centre.
2. Crippa M, Solazzo E, Guizzardi D, et al. (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat Food* 2: 198–209. https://doi.org/10.1038/s43016-021-00225-9
3. EEA-European Environment Agency (2021) Greenhouse gas emissions from agriculture in Europe.
4. Fuchs R, Calum B, Rounsevell M (2020) Europe's Green Deal offshores environmental damage to other nations. *Nature* 586: 671–673. https://doi.org/10.1038/d41586-020-02991-1
5. Europe Sustainable Development Report 2021 (2021) Transforming the European Union to achieve the Sustainable Development Goals. SDSN & IEEP.

6. Friedmann H (1987) International regimes of food and agriculture since 1870. In: Shanin T (ed.), *Peasants and peasant societies,* Oxford: Basil Blackwell, 258–276.
7. Friedmann H (1982) The political economy of food: The rise and fall of the postwar international food order. *Am J Soc* 88S: 248–286.
8. Friedmann H, McMichael P (1989) Agriculture and the state system: The rise and fall of national agricultures, 1870 to the present. *Sociologia Ruralis* 29: 93–117. https://doi.org/10.1111/j.1467-9523.1989.tb00360.x
9. Sutton M, Howard C, Erisman JW, et al. (2011) *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives,* Cambridge University Press, 1–601. https://doi.org/10.1017/CBO9780511976988
10. Oger A (2022) The fertiliser transition. Addressing social and environmental spillovers in the fertiliser sector. Institute for European Environmental Policy, 1–19.
11. Vaneeckhaute C, Belia E, Meers E, et al. (2018) Nutrient recovery from digested waste: Towards a generic roadmap for setting up an optimal treatment train. *Waste Manage* 78: 385–392. https://doi.org/10.1016/j.wasman.2018.05.047
12. Farghali M, Osman AI, Umetsu K, et al. (2022) Integration of biogas systems into a carbon zero and hydrogen economy: A review. *Environ Chem Lett* 20: 2853–2927. https://doi.org/10.1007/s10311-022-01468-z
13. Attard G, Comparetti A, Febo P, et al. (2017) Case study of potential production of Renewable Energy Sources (RES) from livestock wastes in Mediterranean islands. *Chem Eng Trans* 58: 553–558. https://doi.org/10.3303/CET1758093
14. Billen G, Aguilera E, Einarsson R, et al. (2021) Reshaping the European agro-food system and closing its nitrogen cycle: The potential of combining dietary change, agroecology, and circularity. *One Earth* 4: 839–850. https://doi.org/10.1016/j.oneear.2021.05.008
15. Aguilera E, Díaz-Gaona C, García-Laureano R, et al. (2020) Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review. *Agric Syst* 181: 102809. https://doi.org/10.1016/j.agsy.2020.102809
16. Comparetti A, Ciulla S, Greco C, et al. (2025) State of the art of biomethane production in the Mediterranean Region. *Agronomy* 15: 1702. https://doi.org/10.3390/agronomy15071702
17. Regulation (EU) (2019) 2019/1009 of the European Parliament and Council of the 5th June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 while repealing Regulation (EC) No 2003/2003 establishing the rules for marketing livestock manure.
18. Regulation (EU) (2016) 2016/429 of the European Parliament and of the Council of 9 March 2016 on transmissible animal diseases and amending and repealing certain acts in the area of animal health ("Animal Health Law").
19. European Commission (2026) ADIS current year notification: 01/01/2026–23/09/2026–created on 24/09/2026. Available from: https://webgate.ec.europa.eu/tracesnt/adis/public/notification/outbreaks-current-year-report
20. Torraco RJ (2005) Writing integrative literature reviews: Guidelines and examples. *Hum Resour Dev Rev* 4: 356–367. http://dx.doi.org/10.1177/1534484305278283
21. Beline F, Martinez J (2002) Nitrogen transformations during biological aerobic treatment of pig slurry: effect of intermittent aeration on nitrous oxide emissions. *Bioresour Technol* 83: 225–228. http://dx.doi.org/10.1016/S0960-8524(01)00219-X

22. Loyon L, Guiziou F, Beline F, et al. (2007) Gaseous emissions (NH_3, N_2O, CH_4 and CO_2) from the aerobic treatment of piggery slurry—Comparison with a conventional storage system. *Biosyst Eng* 97: 472–480. https://doi.org/10.1016/j.biosystemseng.2007.03.030
23. Loyon L (2017) Overview of manure treatment in France. *Waste Manage* 61: 516–520. http://dx.doi.org/10.1016/j.wasman.2016.11.040
24. Ranade VV, Bhandari VM (2014) Chapter 1—Industrial wastewater treatment, recycling, and reuse: An overview. In: Ranade VV, Bhandari VM (eds.), *Industrial Wastewater Treatment, Recycling and Reuse,* Butterworth-Heinemann, 1–80. https://doi.org/10.1016/B978-0-08-099968-5.00001-5
25. Béline F, Daumer ML, Loyon L, et al. (2008) The efficiency of biological aerobic treatment of piggery wastewater to control nitrogen, phosphorus, pathogen and gas emissions. *Water Sci Technol* 57: 1909–1914. https://doi.org/10.2166/wst.2008.316
26. Derbyshire JB, Brown EG (1979) The inactivation of viruses in cattle and pig slurry by aeration or treatment with calcium hydroxide. *J Hygiene* 82: 293–299. https://doi.org/10.1017/S0022172400025705
27. Lund E, Nissen B (1983) The survival of enteroviruses in aerated and unaerated cattle and pig slurry. *Agric Wastes* 7: 221–233. https://doi.org/10.1016/0141-4607(83)90044-6
28. Heinonen-Tanski H, Niskanen EM, Salmela P, Lanki E (1998) Salmonella in animal slurry can be destroyed by aeration at low temperatures. *J Appl Microbiol* Aug 85: 277–81. https://doi.org/10.1046/j.1365-2672.1998.00487.x
29. Juteau P, Tremblay D, Ould-Moulaye C-B, et al. (2004) Swine waste treatment by self-heating aerobic thermophilic bioreactors *Water Res* 38: 539–546. https://doi.org/10.1016/j.watres.2003.11.001
30. He X, Li Z, Xing C, et al. (2023) Carbon footprint of a conventional wastewater treatment plant: An analysis of water-energy nexus from life cycle perspective for emission reduction. *J Cleaner Prod* 429: 139562. https://doi.org/10.1016/j.jclepro.2023.139562
31. Misra RV, Roy RN, Hiraoka H (2023) Land and Water Discussion Paper 2, On-Farm Composting Methods, Food and Agriculture Organization of the United Nations, Rome, 2003. Available from: https://www.fao.org/3/y5104e/y5104e05.htm#TopOfPage.
32. Greco C, Comparetti A, Fascella G, et al. (2021) Effects of vermicompost, compost and digestate as commercial alternative peat-based substrates on qualitative parameters of Salvia officinalis. *Agronomy* 11: 98. https://doi.org/10.3390/agronomy11010098
33. Verweij PE, Lucas JA, Arendrup MC, et al. (2020) The one health problem of azole resistance in Aspergillus fumigatus: current insights and future research agenda. *Fungal Biol Rev* 34: 202–214. https://doi.org/10.1016/j.fbr.2020.10.003
34. NUTRIMAN—NUTRIent MANagement and Nutrient Recovery Thematic Network. Available from: https://nutriman.net/farmer-platform/product.
35. Monteith HD, Shannon EE, Derbyshire JB (1986) The inactivation of a bovine enterovirus and a bovine parvovirus in cattle manure by anaerobic digestion, heat treatment, gamma irradiation, ensilage and composting. *J Hyg* (Lond). Aug 97: 175–84. https://doi.org/10.1017/s0022172400064457
36. García M, Fernández-Barredo S, Pérez-Gracia MT (2014) Detection of hepatitis E virus (HEV) through the different stages of pig manure composting plants. *Microb Biotechnol* 7: 26–31. https://doi.org/10.1111/1751-7915.12064
37. Gurtler JB, Doyle MP, Erickson MC, et al. (2018) Composting to inactivate foodborne pathogens for crop soil application: A review. *J Food Prot* 81: 1821–1837. https://doi.org/10.4315/0362-028X.JFP-18-217

38. Brown S, Kruger C, Subler S (2008) Greenhouse gas balance for composting operations. *J Environ Qual* 37: 1396–1410. https://doi.org/10.2134/jeq2007.0453
39. Martins O, Dewes T (1992) Loss of nitrogenous compounds during composting of animal wastes. *Bioresour Technol* 42: 103–111. https://doi.org/10.1016/0960-8524(92)90068-9
40. Comparetti A, Febo P, Greco C, et al. (2013) Current state and future of biogas and digestate production. *Bulg J Agric Sci* 19: 1–14
41. Ward AJ, Hobbs PJ, Holliman PJ, et al. (2008) Optimisation of the anaerobic digestion of agricultural resources. *Bioresour Technol* 99: 7928–7940. https://doi.org/10.1016/j.biortech.2008.02.044
42. Weiland P (2010) Biogas production: current state and perspectives. *Appl Microbiol Biotechnol* 85: 849–860. https://doi.org/10.1007/s00253-009-2246-7
43. Al Seadi T, Rutz D, Prassl H, et al. (2008) Biogas Handbook: 9–10. Published by University of Southern Denmark Esbjerg, Niels Bohrs Vej, DK-6700 Esbjerg, Denmark.
44. Marañón E, Salter AM, Castrillón L, et al. (2011) Reducing the environmental impact of methane emissions from dairy farms by anaerobic digestion of cattle waste. *Waste Manag* 31: 1745–1751. https://doi.org/10.1016/j.wasman.2011.03.015
45. Philippe F-X, Nicks B (2015) Review on greenhouse gas emissions from pig houses: Production of carbon dioxide, methane and nitrous oxide by animals and manure. *Agric Ecosyst Environ* 199: 10–25. https://doi.org/10.1016/j.agee.2014.08.015
46. Andreadakis AD (1992) Anaerobic digestion of piggery wastes. *Water Sci Technol* 25: 9–16. https://doi.org/10.2166/wst.1992.0003
47. Rodríguez DC, Belmonte M, Peñuela G, et al. (2011) Behaviour of molecular weight distribution for the liquid fraction of pig slurry treated by anaerobic digestion. *Environ Technol* 32: 419–425. https://doi.org/10.1080/09593330.2010.501821
48. Kaparaju P, Rintala J (2011) Mitigation of greenhouse gas emissions by adopting anaerobic digestion technology on dairy, sow and pig farms in Finland. *Renew Energy* 36: 31–41. https://doi.org/10.1016/j.renene.2010.05.016
49. Ramírez-Islas ME, Güereca LP, Sosa-Rodriguez FS, et al. (2020) Environmental assessment of energy production from anaerobic digestion of pig manure at medium-scale using life cycle assessment. *Waste Manag* 102: 85–96. https://doi.org/10.1016/j.wasman.2019.10.012
50. Álvarez-Fraga L, Capson-Tojo G, Sanglier M, et al. (2025) A meta-analysis of pathogen reduction data in anaerobic digestion. *Renew Sustainable Energy Rev* 207: 114982. https://doi.org/10.1016/j.rser.2024.114982
51. EIP-AGRI Project Database. Available from: https://eu-cap-network.ec.europa.eu/projects_en.
52. Liu Z, Carroll ZS, Long SC, et al. (2017) Centrifuge separation effect on bacterial indicator reduction in dairy manure. *J Environ Manage* 15 191: 268–274. https://doi.org/10.1016/j.jenvman.2017.01.022
53. Aguirre-Villegas H, Larson RA, Ruark MD (2017) Solid-liquid separation of manure and effects on greenhouse gas and ammonia emissions. Sustainable Dairy Fact Sheet Series. University of Wisconsin - Extension. Available from: sustainabledairy.org.
54. Monteith HD, Shannon EE, Derbyshire JB (1986) The inactivation of a bovine enterovirus and a bovine parvovirus in cattle manure by anaerobic digestion, heat treatment, gamma irradiation, ensilage and composting. *J Hyg* 97: 175–184. https://doi.org/10.1017/S0022172400064457
55. Lund B, Jensen VF, Have P, et al. (1996) Inactivation of virus during anaerobic digestion of manure in laboratory scale biogas reactors. *Vet Microbiol* 52: 137–143. https://doi.org/10.1016/0378-1135(96)00014-2

56. Lin M, Wang A, Ren L, et al. (2022) Challenges of pathogen inactivation in animal manure through anaerobic digestion: A short review. *Bioengineered* 13: 1149–1161. https://doi.org/10.1080/21655979.2021.2017717
57. Camilleri-Rumbau MS, Briceño K, Fjerbæk Søtoft L, et al. (2021) Treatment of manure and digestate liquid fractions using membranes: Opportunities and challenges. *Int J Environ Res Public Health* 18: 3107. https://doi.org/10.3390/ijerph18063107
58. EFSA Panel on Biological Hazards (BIOHAZ), Ricci A, Allende A, et al. (2017) Public health risks associated with hepatitis E virus (HEV) as a food-borne pathogen. *EFSA J* 15: 4886. https://doi.org/10.2903/j.efsa.2017.4886
59. Pabby A, Rizvi A, Sastre A (2008) Handbook of Membrane Separation: Chemical, Pharmaceutical and Biotechnological Application; CRC Press: Boca Raton, FL, USA.
60. Shi Wei Benjamin MM (2009) Fouling of RO membranes in a vibratory shear enhanced filtration process (VSEP) system. *J Membr Sci* 331: 11–20. https://doi.org/10.1016/j.memsci.2008.12.027
61. Johnson G, Culkin B, Monroe M (2003) Vibratory shear guards against mineral scale membrane fouling. *Filtr Sep* 40: 24–29. https://doi.org/10.1016/S0015-1882(03)80095-2
62. Rizzioli F, Bertasini D, Bolzonella D, et al. (2023) A critical review on the techno-economic feasibility of nutrients recovery from anaerobic digestate in the agricultural sector. *Sep Purif Technol* 306: 122690. https://doi.org/10.1016/j.seppur.2022.122690
63. Lee J, Kim S, Choi J, et al. (2004) Tertiary treatment of biologically treated piggery wastewater using vibratory shear-enhanced RO membrane. *Water Sci Technol* 49: 435–442. https://doi.org/10.2166/wst.2004.0785
64. Atkinson S (2005) VSEP vibratory membrane filtration system treats hog manure. *Membr Technol* 1: 10–11. https://doi.org/10.1016/S0958-2118(05)00301-0
65. Vaneeckhaute C, Meers E, Michels E, et al. (2012) Fate of macronutrients in water treatment of digestate using vibrating reverse osmosis. *Water Air Soil Pollut* 223: 1593.
66. Vaneeckhaute C, Darveau O, Meers E (2019) Fate of micronutrients and heavy metals in digestate processing using vibrating reversed osmosis as resource recovery technology. *Sep Purif Technol* 1603: 81–87. https://doi.org/10.1016/j.seppur.2019.04.055
67. Yoon Y, Ok Y-S, Kim D-Y, et al. (2004) Agricultural recycling of the by-product concentrate of livestock wastewater treatment plant processed with VSEP RO and bio-ceramic SBR. *Water Sci Technol* 49: 405–412. https://doi.org/10.2166/wst.2004.0781
68. Vega E, Paredes L, Marks EAN, et al. (2022) Application of vibrating reverse osmosis technology for nutrient recovery from pig slurry in a circular economy model. *Membranes* 12: 848. https://doi.org/10.3390/membranes12090848
69. Gaudutis A, Jotautienė E, Mieldažys R, et al. (2023) Sustainable use of biochar, poultry and cattle manure for the production of organic granular fertilizers. *Agronomy* 13: 1426. https://doi.org/10.3390/agronomy13051426
70. Mieldažys R (2020) Technological and environmental evaluation of manure management and its processing into granular fertilizer using additives. Doctoral dissertation, Vytauto Didžiojo Universitetas.
71. FEECO (2018) The manure granulation handbook. Available from: https://feeco.com/literature.
72. Mazeika R, Staugaitis G, Baltrusaitis J (2016) Engineered pelletized organo-mineral fertilizers (OMF) from poultry manure, diammonium phosphate and potassium chloride. *ACS Sustainable Chem Eng* 4: 2279–2285. https://doi.org/10.1021/acssuschemeng.5b01748

73. Zhang R (2024) University of California, Davis, California Department of Food and Agriculture (CDFA)—Alternative Manure Management Program (AMMP): Demonstration Project—Final Report. Project: "Demonstration of an Advanced Manure Management System for Reducing Greenhouse Gas Emissions and Producing Valuable Products" (Grant Agreement No. 19-0963-000-SO). Available from: https://www.cdfa.ca.gov/oars/ammp/docs/AMMP_DemoNTP2019_FinalReport.pdf.
74. Cathcart A, Smyth BM, Forbes C, et al. (2022) Effect of anaerobic digestate fuel pellet production on Enterobacteriaceae and Salmonella persistence. *GCB Bioenergy-Bioprod Sustainable Bioecon* 14: 1055–1064. https://doi.org/10.1111/gcbb.12986
75. Singh D (2023) Chapter 17—Advances in industrial waste management. In: Singh P, Verma P, Singh R (Eds.), *Waste Management and Resource Recycling in the Developing World*, Elsevier, 385–416. https://doi.org/10.1016/B978-0-323-90463-6.00027-0
76. NETL—National Energy Technology Laboratory. Available from: https://netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/intro-to-gasification.
77. He X, Hu Q, Chen J, et al. (2022) Energy and environmental risk assessments of poultry manure sustainable solution: An industrial case study in Singapore. *J Cleaner Prod* 339: 130787. https://doi.org/10.1016/j.jclepro.2022.130787
78. Rout PR, Pandey DS, Haynes-Parry M, et al. (2023) Sustainable valorisation of animal manures via thermochemical conversion technologies: An inclusive review on recent trends. *Waste Biomass Valor* 14: 553–582. https://doi.org/10.1007/s12649-022-01916-5
79. Attard G, Agnello A, Comparetti A, et al. (2019) Manure as a potential source of renewable energy: The behaviour and characterisation of biofuels generated from three animal manure types when subjected to pyrolysis. *Rivista di Studi sulla Sostenibilità* 2: 331–344. 10.3280/RISS2019-002-S1021
80. Quiroga G, Castrillón L, Fernández Y, et al. (2010) Physico-chemical analysis and calorific values of poultry manure. *Waste Manage* 30: 880–884. https://doi.org/10.1016/j.wasman.2009.12.016
81. Ro KS, Cantrell KB, Hunt PG (2010) High-temperature pyrolysis of blended animal manures for producing renewable energy and value-added biochar. *Ind Eng Chem Res* 49: 10125–10131. https://doi.org/10.1021/ie101155m
82. Schnitzer MI, Monreal CM, Facey GA, et al. (2007) The conversion of chicken manure to biooil by fast pyrolysis I. Analyses of chicken manure, biooils and char by C-13 and H-1 NMR and FTIR spectrophotometry. *J Environ Sci Health, Part B* 42: 71–7. https://doi.org/10.1080/03601230601020894
83. Akor CI, Osman AI, Farrell C, et al. (2021) Thermokinetic study of residual solid digestate from anaerobic digestion. *Chem Eng J* 406: 127039. https://doi.org/10.1016/j.cej.2020.127039
84. Ginebra M, Muñoz C, Zagal E (2022) Carbon stability and soil N_2O emissions. Pyrolyzed or unpyrolyzed manure?. *J Environ Manage* 322: 116095. https://doi.org/10.1016/j.jenvman.2022.116095
85. Muñoz C, Ginebra M, Zagal E (2024) Impact of pyrolyzed and unpyrolyzed animal manures on soil properties, carbon sequestration, and clover productivity in Andisol. *Agronomy* 14: 592. https://doi.org/10.3390/agronomy14030592
86. Rathnayake D, Schmidt HP, Leifeld J, et al. (2023) Biochar from animal manure: A critical assessment on technical feasibility, economic viability, and ecological impact. *GCB-Bioenergy-Bioprod Sustainable Bioecon* 15: 1078–1104. https://doi.org/10.1111/gcbb.13082
87. Su G, Ong HC, Zulkifli NWM, et al. (2022) Valorization of animal manure via pyrolysis for bioenergy: A review. *J Cleaner Prod* 343: 130965. https://doi.org/10.1016/j.jclepro.2022.130965
88. Wang A, Zou D, Zhang L, et al. (2019) Environmental risk assessment in livestock manure derived biochars. *RSC Adv* 9: 40536–40545. https://doi.org/10.1039/c9ra08186k

89. EUR-lex. Document 31991L0676. Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC). Available from: https://eur-lex.europa.eu/legal-content/IT/TXT/?uri=CELEX%3A31991L0676.
90. EBA-European Biogas Association (2023). Recommendations. Publication of the Integrated Nutrient Management Action Plan. 28th March, 2023. Integrated Nutrient Management Action Plan: an opportunity for an holistic approach to nutrient flows and losses. The Role of RENURE. Transparency Register: 18191445640-83: 1–3.
91. Venglovsky J, Sasakova N, Placha I (2009). Pathogens and antibiotic residues in animal manures and hygienic and ecological risks related to subsequent land application. *Bioresour Technol* 100: 5386–5391. https://doi.org/10.1016/j.biortech.2009.03.068
92. Figueroa A, Derksen T, Biswas S, et al. (2021). Persistence of low and highly pathogenic avian influenza virus in reused poultry litter, effects of litter amendment use, and composting temperatures. *J App Poultry Res* 30:100096. https://doi.org/10.1016/j.japr.2020.09.011
93. Turner C, Williams SM, Burton CH, et al. (1999). Pilot scale thermal treatment of pig slurry for the inactivation of animal virus pathogens. *J Environ Sci Health, Part B* 34: 989–1007. https://doi.org/10.1080/03601239909373241
94. Elving J, Emmoth E, Albihn A, et al. (2012) Composting for avian influenza virus elimination. *Appl Environ Microbiol* 78: 3280–3285. https://doi.org/10.1128/AEM.07947-11
95. Stephens CB, Spackman E (2017) Thermal Inactivation of avian influenza virus in poultry litter as a method to decontaminate poultry houses. *Prev Vet Med* 15 145: 73–77. https://doi.org/10.1016/j.prevetmed.2017.06.012
96. Rathnayake D, Schmidt HP, Leifeld J, et al. (2023). Biochar from animal manure: A critical assessment on technical feasibility, economic viability, and ecological impact. *GCB Bioenergy-Bioprod Sustainable Bioecon* 15: 1110–1131. https://doi.org/10.1111/gcbb.13082
97. Lin M, Wang A, Ren L, et al. (2022). Challenges of pathogen inactivation in animal manure through anaerobic digestion: A short review. *Bioengineered* 13: 1149–1161. https://doi.org/10.1080/21655979.2021.2017717
98. Haas B, Ahl R, Böhm R, et al. (1995) Inactivation of viruses in liquid manure. *Rev Sci Tech* 14: 435–445. https://doi.org/10.20506/rst.14.2.844
99. Macdonald A, Omoaka N, Juarez M, et al. (2026). Manure management during African swine fever outbreak: identifying gaps through a narrative review. *Front Vet Sci* 13: 1760996. https://doi.org/10.3389/fvets.2026.1760996
100. Duc HM, Ngan PH, Son HM, et al. (2022) The use of composting for the disposal of African swine fever virus-infected swine carcasses. *Transbound Emerg Dis* 69: e3036–e3044. https://doi.org/10.1111/tbed.14659
101. Symeon GK, Akamati K, Dotas V, et al. (2025) Manure management as a potential mitigation tool to eliminate greenhouse gas emissions in livestock systems. *Sustainability* 17: 586. https://doi.org/10.3390/su17020586
102. Comparetti A, Febo P, Greco C, et al. (2014) Assessment of organic waste management methods through energy balance. *Am J Appl Sci* 11: 1631–1644. https://doi.org/10.3844/ajassp.2014.1631.1644



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