applied sciences

Review

Pig Slurry Anaerobic Digestion: The Role of Biochar as an Additive Towards Biogas and Digestate Improvement

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Abstract: Biowaste from livestock production is increasing globally because of the intensification of livestock farming and inefficient waste management practices. If mismanaged, biowaste can result in environmental problems, including increased greenhouse gas (GHG) emissions. Anaerobic digestion (AD) stands as an effective approach for managing livestock biowaste, simultaneously generating biogas for energy recovery and digestate for agronomic application, following the principles of the circular economy. Considered a biowaste-to-energy approach, AD mitigates GHG emissions, facilitates nutrient recovery, and reduces dependence on fossil fuels. Despite its acknowledged benefits and status as a mature technology, further research is required to identify the best route for optimising the process in terms of stability and performance. This review examines new research that explores innovative ways to enhance the mesophilic AD process in continuous-stirred tank reactors, including the use of additives, especially carbon-based ones like biochar. From this perspective, the key challenges are exploring new insights into future research routes to implement AD units at a real scale, and pursuing goals towards a circular economy model. Finally, new opportunities have arisen for farmers to create synergies across agro-industrial sectors, enabling them to minimise their environmental footprint and simultaneously earn additional revenue.

Keywords: additives; biogas production; biowaste management; CSTR; digestate valorisation; mesophilic conditions

Academic Editors: Luca Fiori and María Ángeles Cancela Carral

Received: 14 November 2024
Revised: 7 January 2025
Accepted: 17 January 2025
Published: 21 January 2025

Citation: Silva, I.; Lapa, N.; Ribeiro, H.; Duarte, E. Pig Slurry Anaerobic Digestion: The Role of Biochar as an Additive Towards Biogas and Digestate Improvement. *Appl. Sci.* **2025**, *15*, 1037. https://doi.org/10.3390/app15031037

1. Introduction

Livestock farming is increasing worldwide, and intensive farming is under pressure to ensure food security given the growing world population [1]. However, an increase in livestock production brings large volumes of biowaste streams that need appropriate management; otherwise, severe environmental problems can occur, such as an increase in greenhouse gas (GHG) emissions [2]. Furthermore, the world's energy demand is rising along with the human population, which heightens the need for innovative renewable energy sources [3].

Several routes can be taken into consideration regarding livestock management, but anaerobic digestion (AD) stands out as one of the most promising [4]. Due to its ability to simultaneously recover energy (biogas or biomethane) and create a digestate that may be used for agronomic valorisation, AD technology aligns with the circular economy framework [1] and contributes to the search for new alternative energy sources. Being a biowaste-to-energy technology, it contributes to biowaste management and nutrient recovery, reduces GHG emissions, and decreases dependency on fossil fuels. Therefore, it is a step forward in the energy transition the European Union aims to achieve [5], while also meeting the UN Sustainable Development Goals (SDGs), particularly "Affordable and Clean Energy", "Industry, Innovation and Infrastructure", and "Responsible Consumption and Production".

Even though AD has been a well-known and well-established technology for several years and its advantages for biowaste treatment (especially livestock management) are well recognised as a bio-valorisation pathway [2,6], its implementation at a real scale still has potential for improvement. For this reason, this literature review covers twenty years of research in this area, from 2004 to 2024, to reinforce the potential role of biowaste-to-energy technology in meeting the EU's goals for energy transition towards GHG reduction and renewable energy production. Adding to that, due to its innovative and flexible approach, AD can be widely applied. Though the 20 years of literature in this review article highlight that the problems with biowaste management have been known for several years, it seems now that addressing the issue requires a more realistic approach to face the future challenges, as it continues to be a key topic on the current agendas of many countries, especially as part of efforts to address climate change, waste management, and renewable energy [7,8].

For a few years now, new strategies for upgrading AD have been studied. Among them, there is the use of additives, which can improve process stability, reduce the impact of inhibitors, and increase methane yield [9–11]. According to Paritosh et al. [10], several additives can be considered for improving the AD process, depending on the purpose of the additive's incorporation, for example biological additives for enzymatic action [12]; zeolite application for introducing cation exchange properties in anaerobic digestion [13]; trace metal application for metabolic activities [14]; nanoparticle application for catalytic activity, metabolism, and symbiosis during AD [15,16]; and carbon-based materials application for syntrophic activity improvement [17,18].

Carbon-based additives can promote syntrophic relationships in the AD reactor and strengthen direct interspecies electron transfer (DIET) in the system [19]. Materials like activated carbon, granular activated carbon, biochar, or hydrochar facilitate the consumption of volatile fatty acids (VFAs) more quickly and provide substrates to methanogens [10]. One of the most promising is biochar, a carbonaceous material that can also be obtained from by-products of other industries (agro-industrial biomass, digestate from AD process, slurries, etc.) and thus contribute to the pursued economic circularity, adding value to wastes [4]. However, the study of biochar as an additive for the AD process only began to be more widely discussed in 2015 onwards, with most of the research focusing on batch trials [20].

Therefore, there is a scientific gap that could be further explored, which is the investigation of the effect of biochar on the AD process under mesophilic conditions of pig slurry in continuous-stirred tank reactors (CSTR), at lab and real scales, on both biogas and digestate. As a viable path to closing the circular economic loop and fostering synergies across agro-industrial sectors, attention should be given to both AD technology and its final products (biogas/biomethane and digestate).

1.1. Livestock Trends: Production and Consumption

Before delving into the subject, it is important to provide an overview of the current trends in meat production and consumption patterns. As mentioned before, livestock production has intensified and grown in response to the increased demand for food due to limited farming areas and a fast-growing global population [1,21]. Global food production must double by 2050 to meet the demands of an expanding population and changing dietary preferences [22]. This leads to the livestock industry (and meat production sector) playing a significant role as a source of environmental pollution [23], contributing to the increase in GHG emissions [24,25], and producing large amounts of biowaste (such as pig slurry), which requires proper management; otherwise, it will contribute to land and water degradation [26,27]. Specifically, pork, one of the most frequently consumed meats worldwide, presents several waste management problems that need to be considered, such as odour issues, GHG emissions, pathogen contamination, and soil degradation [21,28].

Although the current trend in market preferences is to reduce meat consumption, it still has considerable weight in terms of production, and it is estimated that global meat production will increase by 2030 [29]. One of the most relevant livestock sectors is the swine industry, with pig meat representing 34% of the total in 2021 [30]. In 2023, global pig meat production reached 123.1 million tonnes (Figure 1), which represents an increase of 0.7% from 2022 [31].

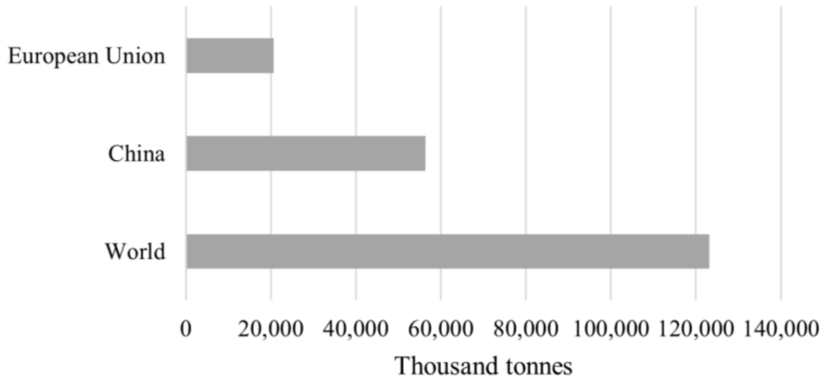

Figure 1. Pig meat production in 2023 [30,32].

The swine sector continues to be one of the most relevant livestock sectors, with the EU being the world's second-biggest producer of pork (Figure 1) and the biggest exporter of pork and pork products. In Portugal's particular case, the swine industry accounts for 10% of the total food industry and 50% of the total meat industry. Large amounts of manure, which requires proper management to prevent significant environmental problems, are generated during large-scale production of pig meat and livestock farming intensification [21].

1.2. EU Strategies for Livestock Management—What Has Been Done So Far and Next Goals

The demands of the global market, the effects of climate change on biodiversity, and the quality of the soil and water present challenges to the continuing growth in livestock production. To support farmers in addressing these issues and adapting to the shifting attitudes and expectations of the public, EU agriculture policy has undergone significant transformation in recent decades [22]. The EU presides over several sectors, among which are climate, energy, agriculture, research, and innovation.

As an example, the European Green Deal focuses on three fundamental objectives for clean energy transition that are expected to help reduce GHG emissions: (i) to guarantee a secure and affordable EU energy supply, (ii) to modernise the EU energy market, and (iii) to prioritise energy efficiency, primarily concerning renewable sources [5].

The Farm to Fork Strategy is at the heart of the European Green Deal for a fair, healthy, and environmentally friendly food system. However, the circular bio-based economy is still a mostly unexplored potential for farmers and their cooperatives. As stated in the Farm to Fork Strategy (2020), farmers should take advantage of opportunities to lower methane emissions from livestock by investing in anaerobic digesters to produce biogas from agricultural leftovers and waste, such as manure, and by developing the generation of renewable energy [33].

Another important political instrument from the EU is the revised Renewable Energy Directive EU/2023/2413, adopted in 2023, which sets Europe's new 2030 climate targets. Bearing in mind that the energy sector is responsible for more than 75% of the GHG emissions from the EU, it becomes important to increase the share of renewable energy across several sectors of the economy, raising the renewable energy target to a minimum of 42.5% and reducing the GHG emissions by at least 55% by 2030, and aiming to become a climate-neutral continent by 2050.

In addition, the European Commission has published the REPowerEU plan, which stands on three pillars: save energy, produce clean energy, and diversify the EU's energy supplies. The EU's prospects for achieving the proposed results are promising; the target level for 2020 was exceeded by 2%. Besides being a significant accomplishment, this is also an important milestone on the EU's path towards climate neutrality by 2050.

Portugal also overachieved its established target for renewable energy in 2020 and is committed to developing strategies for the energy transition. Portugal launched for public consultation (still needs approval to be implemented) a Biomethane Action Plan (BAP) on the horizon of 2024–2040, which represents a strategic vision for the production and application of biomethane, focusing on synergies between sectors. Among the several goals for BAP, there are a few that need to be highlighted, such as: (i) to prioritise the use of livestock effluent for biogas production; and (ii) to provide agro-industrial and agricultural companies with training and capacity building surrounding the proper operation of anaerobic digesters, including anaerobic co-digestion.

Although this is not yet a final implementation plan, it is undoubtedly a very important step towards AD promotion and implementation, livestock effluent valorisation (among other waste streams), circular bioeconomy, and energetic transition.

2. Main Concepts Used in This Review

For a better understanding of the concepts discussed throughout the article, some terms are defined in advance (Table 1), based on the Glossary of terms on livestock and manure management 2011 [34] to facilitate the reading of this review.

Table 1. Definition of concepts covered in the overview.

Concepts	Definition
Livestock	Refers to domesticated animals, kept for food, wool, skin, or fur production, or to be used in land farming, or for recreational purposes.
Housed livestock	Livestock that is housed inside during the year, either entirely or partially.
Manure	A general term for any organic substance that supplies nutrients to soil to replace organic fertilizers.
Livestock manure	Manure from housed livestock, typically depending on the kind of animal housing system, but usually containing a combination of faeces and urine with or without bedding material.
Manure management	Includes the collection, storage, transport, and land application of manures, possibly including treatment.
Slurry	Refers to the faeces and urine from housed livestock that are often combined with or without bedding material and wastewater during management to create liquid manure that has a dry matter content of between 1 and 10% w/w.
Pig/swine	Refers to a porcine animal that has been domesticated and raised for meat production.

3. Methodology

3.1. Anaerobic Digestion of Pig Slurry at Mesophilic Conditions

Pig slurry presents environmental issues, making it important to ensure its adequate management. AD can contribute to this challenge [1], being a promising bioengineering process that produces energy (biogas) and promotes the treatment of organic wastes, preventing them from being discarded [1,17]. It generates an organic-rich digestate with a potential agronomic value. Digestate valorisation is fundamental to a circular economy model, with the advantage of lower cost (compared to mineral fertilizers), and potential as one solution to future practice problems associated with the further treatment of digestates [35,36].

Before starting the literature review, some assumptions were settled to define the search, which focused on research articles on the AD of pig slurry/manure on pig farms published over the last 20 years (2004–2024) to describe the approach of the subject's development and methods.

The bibliographic databases used for this purpose were Science Direct, Web of Science, and Scopus. A group of keywords was determined and applied in different combinations, using different Boolean operators (AND/OR and their combinations) to form different search strings: "anaerobic digestion", "biogas", "pig slurry", "pig manure", "mesophilic", "farm", "pilot scale", "lab scale", "full scale". However, some results were unrelated to the focus of the study. As an example, articles that included terms such as "composting", "food waste", "batch", "dung", "lignocellulosic biomass", "municipal solid waste", "microalgae", "sewage sludge", "hydrothermal", and "two-stage" were excluded from the review.

The search conducted on Web of Science resulted in 3494 articles, which needed to be reduced. Web of Science offers a selection tool called "Highly Cited Papers"; yet even with this filter and excluding review articles, a significant number of articles remained, and the results obtained were still around 3000. To overcome this, the option to sort by relevance was selected. This option uses a ranking method that takes into account the number of times the search phrases are included in each record, sorts records in decreasing order, and then displays top-ranked records first on the list. Articles were sorted by "relevance" and the first 200 were analysed. The search in the Scopus database yielded more than 3000 articles; using the same approach, the Scopus results were sorted by relevance and the first 200 titles were analysed. Finally, the Science Direct search resulted in a total of 278 articles and, after excluding review articles, 115 remained to be analysed.

Thus, a total of 515 articles were retrieved for in-depth examination. The results with titles close to the topic of this review were chosen, the abstracts were reviewed to determine eligibility, and the results were then compared to the previous studies to filter out duplicates, reaching a total of 56 articles for deep analysis. Then a full reading was conducted, resulting in a total of 20 articles selected. Throughout all the routes previously described, 15 additional articles were considered using the snowballing method, where reference lists are consulted to identify new possible articles [37]. In the end, a total of 35 articles were included in the final review. The selection process is summed up in Figure 2.

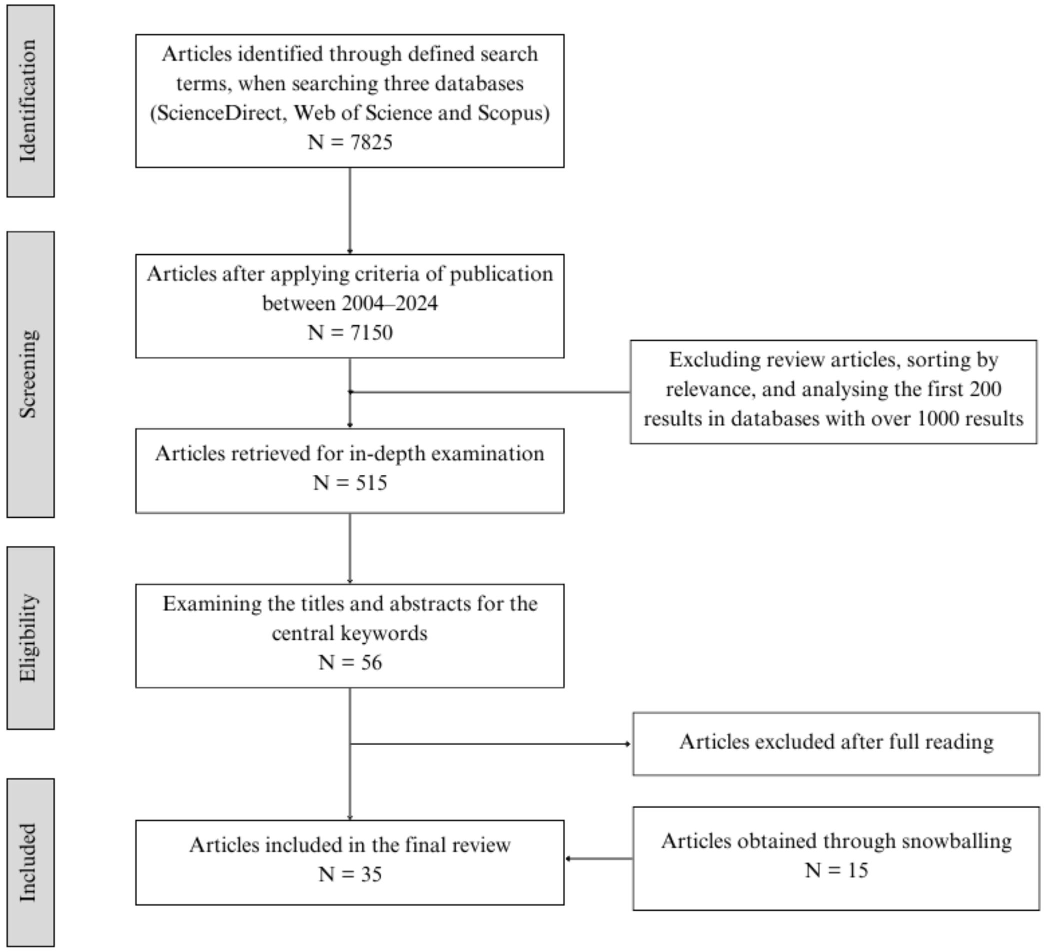

Figure 2. Flow chart of the article selection process for the present review.

3.2. The Role of Biochar Addition in Biogas and Digestate

As the research progressed, more studies began to appear on the importance of studying new strategies to improve the efficiency of the AD process, as well as to increase biogas production and improve the quality of the digestate for agronomic valorisation. Then, the focus of the search followed the valorisation of the digestate and the use of additives in AD to optimize the process, specifically the role of biochar in mesophilic anaerobic digestion of pig slurry and its effect on biogas and digestate. So, a simultaneous literature search was then performed focusing on these subjects to enrich the global overview. Following the same criteria used previously, a new group of keywords was selected: “biochar”, “anaerobic digestion”, “pig”, “slurry”, “manure”, “biogas”, and “digestate”, aiming to evaluate the role of biochar addition to the AD process for biogas production and digestate valorisation.

The searches conducted on Web of Science and Scopus resulted in more than 1000 articles, which were synthetised. In Web of Science database, the selection tool “Highly Cited Papers” was used, which reduced the results to 200 articles. On the other hand, the Scopus results were sorted by “relevance” and the first 200 titles were analysed. Science Direct produced 276 results, all of which were analysed. Also, seven articles were analysed using the snowballing method [37]. Results with appealing titles were chosen, the abstracts were reviewed to determine eligibility, and the results were then compared to the previous studies to filter out duplicates, reaching a total of 17 selected articles.

4. Pig Slurry, from Biowaste to Bioenergy: Searching for Management Solutions

The pursuit of economic circularity and the growing significance of industry synergy has led to the search for new strategies of rerouting pig slurry (PS) management on livestock farms. PS is decreasingly viewed as biowaste without value and has come to be considered a resource with the potential to recover nutrients which could provide agronomic valorisation, facilitating the efficient recycling of plant nutrients [38,39] and the production of bioenergy with little or no global warming potential, such as biogas/biomethane [39,40]. Furthermore, according to Awasthi et al. [2], manure should not be viewed as waste but as an essential resource that may be used to reduce GHG emissions by producing bioenergy. To that effect, the EC Regulation nbr. 1069/2009 refers to biogas production as a management example for manure [40]. Scarlat et al. [41] investigated the biogas potential of farm manure (cattle, pigs, sheep/goats, and poultry) for the whole of Europe and concluded that 942 million tonnes could be collected, giving an estimated theoretical biogas potential of 43 billion m^3 biogas. In 2016, an estimated 53.3 million tonnes of manure was used for biogas plants, producing around 4 TWh of dung-based power, of which about 16% was pig manure [42]. Castro and Silva et al. [24] report that in Brazil, appropriate manure management resulting from pork production through biogas technology covers the energy consumption of 5 million people.

Back in 2012, Molinuevo-Salces et al. [43] reported that the growing trend of intensive and concentrated farming activities in limited areas had led to an increased focus on pig slurry treatment in Europe. Mehta et al. [38] state that rerouting manure to AD facilities would offer a way to improve control and could redistribute nutrients more effectively from surplus to deficiency areas or farther afield. Furthermore, it would offer the chance to promote nutrient recovery and collection.

With the proper management strategies, the adverse effects caused by the volume of pig slurry generated in livestock farms would be considerably reduced, depleting odours and GHG emissions, increasing nutrient recycling and recovery, and boosting agro-energy transition. On the other hand, improper management can have negative effects on the environment, increasing the risk of air and water pollution as well as the potential for several pathogens to contaminate food crops [39].

In Portugal, PS from swine farms is the second most produced livestock effluent, representing 17% of the total livestock effluents [44]. In the scope of the National Renewable Energy Action Plan launched by the Directorate-General for Agriculture and Rural Development, livestock effluents are prioritised in terms of their destination: (1) agronomic valorisation; (2) organic valorisation in composting units; (3) organic and energy recovery in biogas units; (4) energy recovery in combustion or co-incineration units; (5) treatment in wastewater treatment plants; and finally, (6) landfill disposal after pressure sterilisation.

5. Anaerobic Digestion: Biogas and Digestate from Pig Slurry Management

AD is already an established, well-known, and trusted biotechnology. However, its potential is far from fully exploited. Although it is based on a complex and delicate microbial consortium [45], under appropriate operational conditions, it has demonstrated remarkable versatility and adaptability to various challenges that may arise in large-scale plants [46] and is an effective option of manure management [25,28]. PS is regarded as a great substrate for the AD process because of its high nutritional content and variety, which produces adequate bacterial growth, buffering capacity, and ability to prevent rapid pH fluctuations inside the biodigesters [47].

AD is a biotechnological process that works under anaerobic conditions and converts organic matter into biogas through several symbiotic interactions between microorganisms [17,45] also producing an effluent, named digestate, that has a potential agronomic value for use as an organic amendment [48], allowing the recovery of nutrients and assigning new economic values to AD biotechnology [2].

Biogas could play a major role in the reduction of GHG emissions if used to replace fossil fuels. In 2011, Kaparaju and Rintala [25] stated that at that time AD was the only available technological solution that could both produce positive energy balances and significantly reduce GHG emissions caused by manure management. In a study conducted by Ji et al. [49] where ten treatment technologies were compared for PS management, the biogas profitability of AD was notable. Methane and carbon dioxide make up the majority of biogas composition, but also other trace gases, like hydrogen sulphide, carbon monoxide, hydrogen, ammonia, oxygen, and water vapour, are present in biogas [17]. When biogas is upgraded, it produces biomethane, which can be injected into the natural gas network or used in the transport sector [27,50].

Many authors assume that the only main product of AD is biogas [51], and digestate is a by-product of the process. However, there is a need to shift the paradigm to consider digestate as a main product as well. There are already authors following this path. This explains the increase in studies on the improvement of the AD process by enhancing the digestate while bearing in mind nutrient recovery [1,36].

Digestate is one of the main products of the AD process, alongside biogas, but it is necessary to consider it in terms of its potential for other purposes, such as agronomic valorisation. As early as 1993, Flotats et al. [52] reported that the farm used as a case study in that work selected crops according to land application to optimise the available nutrients, while implementing a fertilisation plan based on regional soil and climate characteristics. Thirty years later, there is still a lively debate about the use of digestate for nutrient recovery and agronomic valorisation [28,35]. While the application of digestate is undoubtedly of interest as a more sustainable option for agronomic valorisation [35] and there are already studies proving the positive effects of its application on soil quality [7,39], it remains essential to research the best application strategy [23,36].

Bioavailable nutrients, particularly N, P, and K, are abundant in the digestate [1]. It is expected that compared to raw slurry, the digestate includes more accessible nitrogen (in the form of NH_4^+–N). Due to these qualities, the digestate can be used as a fertiliser in agriculture to improve crop productivity, soil fertility, and enhance nutrient recycling [1,48,53].

6. Practical Cases of AD Biogas Plants

Throughout the studied period for this review (2004–2024), it was possible to observe that the older research concentrated on comprehending the principles of the AD process [21,25,54], whereas more recent studies targeted increasing efficiency, looking for new methods to improve biogas production and/or its quality, including digestate valorisation [28,48,55]. Among the articles obtained, 14 were selected for a deep examination since they focused their research on practical case studies at small- and lab-scale [25,27,43,47,48,56] or farm- and full-scale [25,28,52,53,57–60] trials under mesophilic conditions, all between 2009 and 2022, with the majority of incidences (64% of the referred articles) between 2011 and 2018. The retrieved studies were mostly located in Europe (half of them), three in China, two in the United States of America, one in Brazil, and one in South Korea.

Pilot-scale studies are important since they can mimic the operational conditions of full-scale biogas plants and help overcome setbacks of implementation on a larger scale. Moreover, these studies often present interesting results that can be considered the "worst-case scenario", since there are pre-treatments only applied due to the constraints of the laboratory-scale digesters. However, laboratory-scale studies are also of great importance, since they enable quick and affordable access to the possibility of scaling up, and even test several different methods at the same time. Thus, lab-scale testing can be used to optimise the process and acquire designing data once an appropriate process configuration has been identified. This can reduce the requirement for more costly large-scale testing. Regarding this, it has become increasingly important to study manure treatment systems that can be easily implemented at full scale [28]. Ji et al. [49] concluded from the comparison of ten PS treatment technologies that AD is a good choice for large-scale farms, considering the environmental and economic benefits. Additionally, it is important to investigate the application of pre-treatments that can be applied to modify the substrates' physicochemical structures and improve their biodegradability, potentially enhancing the anaerobic process and improving biogas production [6,45,47].

From the studies presented in Table 2, most studies were conducted with HRTs above 20 days. Xu et al. [58] also studied an HRT of 40 days for manures from feeder-to-finisher in North Carolina in a 7600 m^3 digester, achieving 65% v/v of CH_4, which is aligned with the quality of biogas reported by other authors with lower HRTs [58–60]. However, that study [58] did not report values of biogas production, since its purpose was to assess the removal of efficiencies from a full-scale innovative swine waste-to-energy management system, studying a combined system that links AD with a microturbine for electricity generation and an aeration basin where intermittent ventilation occurs for nitrogen management purposes.

Six studies were conducted on reactors on small scales (with volumes lower than 10 L), with HRTs varying from 15 [27,60] to 30 days [25]. Curiously, the highest biogas productions (0.31 m^3 CH_4/kg VS) are presented by the highest HRT of 30 days [25] and the lowest by an HRT of 15 days (0.38–0.52 m^3 CH_4/kg VS) [27], with similar organic loading rates (2.0 kg VS/(m^3·d) and 1.5 kg VS/(m^3·d), respectively). Silva et al. [27] evaluated the impact of varying feeding regimes at an OLR of 1.5 g VS/($L_{reactor}$·d), achieving specific methane productions of 0.38 L CH_4/g VS for daily feeding and 0.52 L CH_4/g VS for intermittent starvation periods of two days. On the other hand, the value presented by Kaparaju and Rintala [25] refers to the mean CH_4 yields during a stable gas production period of 30 days, under an OLR of 2.0 kg VS/(m^3·d).

The percentage of CH_4 presented in the studies shown in Table 2 is in line with the average values reported by other studies (55–75% *v*/*v*)[26,46].

Data presented by Flotats et al. [52] is particularly interesting since it refers to a biogas plant in operation for a long time, more exactly, 20 years, treating an average of 3700 m^3/year of pig slurry. This biogas plant ended its operation due to changes in the farm's production goals and the type of livestock bred. While in operation, this plant provided an annual average of 45.9% of the total energy required to heat the houses on the swine farm, situated near the Pyrenees, in the northern region of Catalonia (Spain). Some of the factors that led to this success were that the plant: (a) was built at the same time as the rest of the farm, leading to lower investment costs and effective integration as part of the farm; (b) was simple by design; (c) ensured maintenance and supervision; and (d) had an integrated vision of the livestock farm and biogas plant, considering pig slurry manure as an energy source and nutrient resource.

Kaparaju and Rintala [25] studied the impact of AD on mitigating GHG emissions and concluded that GHG emissions reduction could be achieved by directly substituting fossil fuels (meaning that replacing fossil fuels with the biogas produced contributed almost 60% to the reduction of GHG emissions on pig farms) and indirectly by lowering the production and consumption of mineral N fertilisers. In that study, the authors showed that by using an energy balance, pig farms could reach self-sufficiency in terms of their energy needs and still sell around 80% of their produced heat and electricity.

Wang et al. [60] monitored a biogas plant for a year and the data collected allowed them to draw conclusions about the seasonality that a full-scale biogas plant would experience. In that work, a waste-to-energy system was proposed, where the waste progressed through the following route: solid manure was sent for composting to produce a fertiliser for agricultural use, while the "flushed slurry" obtained from washing the barn floors went to biogas production. The biogas produced was stored and then supplied to households, and the digestate produced was stored and then forwarded to agronomic applications. In the end, the authors concluded that even with a variety of seasonal climate conditions, mesophilic swine manure can be effectively used in waste-to-energy systems. Wang et al. [60] raised a crucial issue regarding large-scale biogas plants. With increased pork production and pig slurry, there is a need for adequate waste management and for resource recovery technologies to ensure the sustainable growth of the industry. To achieve this, renewable energy production through AD can be of great importance.

Another important consideration is the need for hierarchisation of pig slurry from the pigs' different stages of life according to the end-use for energy recovery. In Silva et al.'s work [27], a new strategy was presented based on the use of pig slurry from the fattening/finishing phase. This selection was made considering the higher organic content of this specific breeding stream, which was expected to optimise the potential of biogas production. Table 2 shows other studies that have been carried out with slurry from the fattening/finishing phase [25,57,58,60].

Over the years (Table 2), several studies have mentioned the need to valorise digestate, and some of them already present plans for agronomic valorisation, presenting waste-to-energy systems where nutrient recovery is also framed [52,53,57].

An overall conclusion after observing the studies about biogas plants is that there is a lack of policies protecting farmers and of subsidies to encourage infrastructure implementation and maintenance. Across all the listed works in Tables 2 and 3, some management factors stand out for the success of biogas plants: the importance of planning and monitoring and the need for policies and subsidies. The integration of these topics could shift the paradigm and contribute to increasing the attractiveness of AD technology.

Table 2. Selected studies on biogas plants: type and volume of reactors, operational conditions, and plant performance.

Origin and Location	Type of Reactor	Volume	HRT	OLR	CH_4% *v/v*	Biogas Production (In Some Cases Expressed as CH_4)	Reference
			Full-, farm-scale				
Swine farm, Spain	Concrete plug-flow digester (farm-scale, on-farm system)	144 m^3	n.d.	0.70–3.90 kg VS/(m^3·d)	n.d.	10.30–15.40 m^3 biogas/m^3 slurry or 124 m^3/d	[52]
Feeder-to-finish swine manure, North Carolina	Anaerobic digester with no further specification	7600 m^3	n.d.	n.d.	55–70	n.d.	[57]
Feeder-to-finish swine manure, North Carolina	Anaerobic digester with no further specification	7600 m^3	40 d	n.d.	65 ± 2	n.d.	[58]
Pig farm, Finland	Full-scale anaerobic digestion	65 m^3	30 d	2.00 kg VS/(m^3·d)	n.d.	32 m^3 CH_4/d	[25]
Farrow-to-wean piglet production, Brazil	CSTR	700 m^3	n.d.	1.69 ± 0.34 kg VS/(m^3·d)	n.d.	0.65 ± 0.23 Nm^3 biogas/($m^3_{reactor}$·d) 0.38 ± 0.14 Nm^3 biogas/kg VS	[28]
University Experimental Farm, Germany	Completely stirred anaerobic reactors	Total volume = 10 L Working volume = 8 L	25 d	2.30–4.30 kg ODM/(m^3·d)	65	0.70–0.94 L/($L_{reactor}$·d)	[59]
Pig farm, northwest China	Large-scale biogas plant, CSTR	Effective volume = 600 m^3	n.d.	n.d.	61	679 m^3/d	[53]
	Household biogas production	Total volume = 8 m^3	n.d.	n.d.	57	0.80 m^3/d	

Table 2. *Cont.*

Origin and Location	Type of Reactor	Volume	HRT	OLR	CH_4% *v*/*v*	Biogas Production (In Some Cases Expressed as CH_4)	Reference
Swine farm, China	Mesophilic up-flow solid reactors	Gestation, farrowing, piglet, nursery phases Total volume = 500 m^3 Working Volume = 400 m^3 Fattening phase Total volume = 700 m^3 Working Volume = 525 m^3	15–22 d	0.80–1.80 kg VS/(m^3·d)	63	0.27–0.43 Nm^3/kg VS 157–548 Nm^3/d 0.30–0.43 m^3 CH_4/kg VS	[60]
Small-, lab-scale							
Swine farm, South Korea	Semi-continuous anaerobic digestion in Schott Duran bottle	Total volume = 500 mL Working volume = 200 mL	20 d	4.71 g COD/(L.d)	n.d.	187 mL CH_4/g VS	[56]
Pig farm, Spain	CSTR	Total volume = 7 L Working volume = 5 L	15–25 d	0.63–0.41 g VS/(L.d)	69–49	201–90 mL CH_4/g VS	[43]
Pig farm, Finland	Semi-continuous CSTR	4 L	30 d	2.00 kg VS/(m^3·d)	n.d.	0.31 m^3 CH_4/kg VS	[25]
Local pig farm, Ireland	Pilot-scale anaerobic digester with no further specification	Total volume = 480 L Working volume = 360 L	30 d	0.87 kg VS/(m^3·d)	58	154 mL CH_4/g VS	[48]
Swine livestock facility, Portugal	CSTR	Total volume = 6.86 L Working volume = 4.8 L	23 d	0.56 ± 0.11 kg VS/(m^3·d)	57	86.90 ± 15.90 L/kg VS 0.07 ± 0.02 $m^3/m^3_{reactor}\cdot d$	[47]
Swine livestock facility, Portugal	CSTR	Working volume = 4.8 L	15 d	1.50 ± 0.06 g VS/(L·d)	73–75	0.38–0.52 L CH_4/g VS 3.50–4.70 L/d	[27]

n.d.: not defined, ODM: organic dry matter.

Table 3. Benefits and drawbacks of the different biogas plant scales.

Study	Benefits	Drawbacks	Ref.
	Full-, farm-scale		
Swine on-farm system, concrete plug-flow digester 144 m^3, Spain	Participation of farmers, concern for maintaining the farm's environmental integrity, and the idea that managing manure is an essential component of farming duties.	Odour control.	[52]
Pig farm, full-scale anaerobic digester 65 m^3, Finland	The pig farm can be self-sufficient or even sell excess heat and electricity to the grid or local community.	In addition to investment costs and energy potential, farm AD plant revenue is also influenced by energy markets, end-product sales, and the possible imposition of carbon taxes. CH_4 emissions on the farm would be void if the whole manure produced on the farm was collected and utilized for energy production.	[25]
Feeder-to-finish swine operation, anaerobic digester 7600 m^3, North Carolina	Innovative waste management with effective treatment of wastes while generating energy. Scalability, proving that it applies to various farm sizes and kinds.	The system requires careful monitoring and upkeep.	[57]
Feeder-to-finish swine manure, anaerobic digester 7600 m^3, North Carolina	The swine waste-to-energy system was effective all year round in managing nutrients, generating energy, and eliminating organic waste.	Need to pay attention to nitrogen management. The existence of a lagoon in the system to store liquid overflows can lead to ammonia emissions and local air pollution.	[58]
Local pig farm, pilot-scale anaerobic digester 360 L, Ireland	The pilot scale study showed better results than the trials carried out on a laboratory scale.	Presence of potential inhibitors in the AD process of PS mono-digestion.	[48]
Swine farm, mesophilic up-flow solid reactors 400 and 525 m^3, China	Despite varying seasonal climates, mesophilic swine biogas plants can be effective waste-to-energy systems in rural locations.	The need for proper waste management and resource recovery technologies. Also, need for incentives and encouragement from the government to implement biogas plants from a waste management perspective.	[60]

Table 3. *Cont.*

Study	Benefits	Drawbacks	Ref.
Pig farm, large-scale biogas plant CSTR 600 m^3, northwest China	Digestate valorisation as organic fertiliser in local villages. Sustainable environmental practices in the production of clean energy and the reduction of pollution emissions.	The potential for global warming and photochemical oxidation increased due to higher CO_2 emissions.	[53]
Pig farm, household biogas production 8 m^3, northwest China	Sustainable environmental practices in the production of clean energy and the reduction of pollution emissions.	Reduced efficiency in comparison to the large-scale biogas plant in terms of energy consumption and environmental effects. Higher potentials for acidification compared to large-scale biogas plants.	
Farrow-to-wean piglet production, CSRT 700 m^3, Brazil	Complete system on-farm technology. Energy and nutrient recovery.	Higher energy consumption in cold months.	[28]
	Small-, lab-scale		
Pig farm, CSTR 4 L, Finland	Allow the calculation of the amount of renewable energy in the form of electricity and heat to further extrapolate to a full-scale plant. Pig slurry has been shown to be a good substrate for methanogenesis.	According to the findings, the effects of AD technology and achievable CH_4 yields on transferring laboratory-scale findings to the farm scale can differ depending on the livestock farming methods used (due to variations in feed, waste management techniques, and/or seasonality).	[25]
Swine farm, Schott Duran bottle 200 mL, South Korea	Rich in trace elements.	A low C/N ratio could lead to ammonia inhibition.	[56]
Pig farm, CSTR 5 L, Spain	Results from this experiment allowed an estimation for a full-scale plant. High buffer capacity of pig slurry.	Low biodegradability and C/N ratio.	[43]
Farm, CSTR 8 L, Germany	This type of study is important to decide the suitable operational parameters to implement at medium and small-scale biogas plants.	The investment to install a combined heat and power plant in medium or small-scale biogas plants.	[59]
Swine livestock facility, CSTR, 4.8 L, Portugal	Easiness of implementing the studied pre-treatment at a full-scale plant.	Low C/N ratio.	[47]
Swine livestock facility, CSTR, 4.8 L, Portugal	Results demonstrated the process' adaptability and versatility. Changing feeding frequencies can increase bioenergy production's flexibility and provide farmers with greater autonomy in selecting the optimum course of action. The digestate met the legal need for agronomic valorisation.	Need to sieve the substrate to avoid clogging the reactor pipework of a laboratory unit.	[27]

However, besides the implementation of policies and subsidies, the net energy balance of each AD plant is the principal factor for successful development of AD technology. One of the most important metrics for evaluating the operational, financial, and environmental success of AD plants is the net energy balance. While a negative balance suggests inefficiencies that need to be evaluated to overcome the drawbacks, a positive balance guarantees that the plant will provide significant energy savings and environmental advantages. Simultaneously, strategies like the installation of policies and subsidies can be investigated and considered [61].

Concerning the biogas plant presented by Flotats et al. [52], the authors state that its success could be attributed to several factors: construction planning (the biogas plant was constructed simultaneously with the rest of the farm), which reduced investment costs; the maintenance and supervision tasks performed by local technicians; and the global integrated vision of swine manure as a resource for energy and nutrients to the farm.

In the work developed by Wang et al. [60], it is also discussed how crucial planning and monitoring are to the success of biogas plants. Additionally, it is mentioned that from the standpoint of waste management, the government must also provide incentives and support for the installation of biogas facilities.

A good example of financial incentives for renewable energy production is reported by Siegmeier, Blumenstein, and Möller [46]. In Germany, high feed-in prices for electricity generated from renewable biofuels were among the financial incentives offered by the Renewable Energy Sources Act (EEG). It is then up to individual farmers to decide whether to invest in AD technology. Over the years, EEG has been updated, and major amendments have been made. The latest amendment was in 2023, where renewable energies were reinforced as a central pillar of the energy transition [62].

7. New Directions for AD Improvement

There is a wide range of substrates that could be used for biogas production through the AD process, and a variety of pre-treatments can be considered to improve process efficiency. Among them are physical, chemical, thermal, biological, and/or combined methods [45,55].

Along with the study of new strategies to improve the efficiency of the AD process and increase biogas production, it has also become important to study ways of improving the quality of the digestate for further valorisation [36,63].

As stated before, the direction of research concerning the AD process has begun to change in recent years, mostly focusing on how to improve the process and how to valorise the main products, rather than on implementing it at full-scale, as seen in Table 2. It is at this point that studies about additives begin to emerge, investigating their role in the process and how AD technology could benefit from these additives.

Various additives are used to improve the AD process; some examples are shown in Table 4. These additives can promote an increase in microorganism activity and therefore enhance the efficiency of the AD process. Biochar is considered by some authors as one of the most popular additives to apply to AD [1,19]. It stands as a promising, sustainable, and cost-effective option with numerous advantages [51]. Carbon-based materials have drawn a lot of interest, owing to characteristics such as chemical stability, high electrical conductivity, and porous structure [4,17].

Although there were already a few studies about activated carbons in AD, Luo et al. [20] stated that studies of biochar application during AD remained uncommon until 2015. Effectively, biochar addition to AD has been increasingly studied, but there are still many gaps to fill.

Table 4. Additives used for enhancing the AD process.

Additives to the AD Process	References
Activated carbon	[20]
Metal ions	[9]
Metal oxides	[51]
Magnetite powder	[64]
Zeolites	[1]
Biochar	[1,19]

8. Biochar as an Additive to Enhance the Quality of AD Main Products

In the literature search, the earliest studies produced in both the Science Direct and Scopus databases related to this topic were from 2011 and 2012 respectively, which highlights the relative novelty of this topic. Analysis of the results from Science Direct shows there has been an increase in focus on the subject in recent years. Articles published between 2021 and 2023 account for 57% of the articles published in the last 13 years. This explains the fact that the articles selected fall within the 2015–2023 period. This review intends to address the lack of information concerning the combination of AD with biochar addition, using pig slurry as substrate, and its effect on biogas production and digestate properties to be applied as an organic fertilizer in agronomic valorisation. Furthermore, it intends to contribute to the limited information available on continuous operation systems, namely CSTR, of biogas production. Focusing on an upscaling perspective, some factors need to be taken into account, like cost of production and transportation. However, one possible route could be to use the non-marketable fractions of biochar (smaller fractions, which currently do not have a valorisation route), thus giving them value and increasing synergy between industries.

Biochar is a carbonaceous material, porous and biostable, with a high specific surface area and abundant surface functional groups, that can be produced from a wide range of biomaterials. Combining it with other factors (like heating rate, temperature during carbonisation or pyrolysis, inert gas used, retention time in the pyrolytic reactor, mixing rate during carbonisation or pyrolysis, among others) invariably influences its physical and chemical characteristics and performance [20,35], which in turn affects how each biochar behaves or responds to the final application. Due to the breakdown of lignocellulosic biomass and microstructural rearrangement, the high treatment temperature makes biochar more structurally complicated, producing more intricate fused ring organic carbon structures [51]. Pyrolysis (300–700 °C) and hydrothermal carbonization (180–300 °C) are two of the most widely used thermochemical techniques for producing biochar: pyrolysis occurs in an oxygen-free atmosphere and hydrothermal carbonization occurs in the presence of subcritical water. The two types of biochar have distinctly different physicochemical characteristics as a result of the various production procedures. For instance, hydrothermal carbonization, which uses pressurised water, encourages the demineralization of biomass ash composition, which results in a typically lower percentage of ash content. The performance of biochars as an additive to support the AD process will necessarily be impacted by these differences in production [65,66].

By using organic wastes (from a wide range of raw biomasses, including forest remains, wood processing by-products, agriculture by-products, agri-food biowastes, among many others) to produce biochar, carbonization and pyrolysis can be viewed as potent technologies for managing biowaste. This promotes economic circularity by turning biowastes into new products with new uses and reintroducing them to the market, while also reducing risks to the environment and human health [51]. Biochar began to be used as a soil amendment focused on carbon sequestration and as an alternative to activated carbon [20]. Later, the possibility of applying it for other purposes emerged [51]. Therefore, it is not surprising that the effect of biochar on the soil is more widely studied than its effect on the AD process. For example, it is known that the land application of biochar increases the carbon storage capacity of soils and improved soil properties while minimizing the adverse effects of heavy metals and may boost crop yield and growth performance by altering the chemical composition of the soil, which can increase microbial activity and make some mineral nutrients available [7,35,65]. There are also works reporting a reduction in nitrogen leaching after biochar application to soil [67].

Biochar addition to AD of PS is particularly interesting due to the high nitrogen content of PS and the capacity of biochar to adsorb ammonia, reducing its inhibitory effects during the AD process [4]. Biochar reduces the toxic effects of ammonia nitrogen by acting as a carrier to immobilize and enrich microorganisms and facilitate interspecies electron/hydrogen transfer between methanogens and other bacteria, and as an adsorbent to encourage the combination of oxygen-containing functional groups on the surface of biochar with NH_4^+. These two main mechanisms are how biochar reduced the inhibition of ammonia nitrogen [68].

8.1. The Role of Biochar in Biogas Production

In the AD process, biochar can play a key role as a support medium to increase microbial communities and promote bacteria growth and metabolic activity, acting as a multifunctional additive to enhance AD performance [65,68]. In addition to providing refuge for microbial adhesion and enrichment, the micropores and organic functional groups formed on the surface of the biochar may serve as active sites for the adsorption of ammonium and other contaminants [69]. Among the many benefits that the addition of biochar can offer to AD, the ones that stand out the most are the facilitation of Direct Interspecies Electron Transfer (DIET) that it is enabled by the electrochemical properties of biochar, avoiding inhibitory conditions, reducing GHG emissions, improving the buffering capacity of the process (by stabilizing the pH), and reducing the ammonia inhibitory effect over the anaerobic bacteria [4,19,65]. Overall, an improvement in AD performance when biochar is added is reported (Table 5), supported by an increase in methane yield, a decrease in volatile fatty acid accumulation, and a decrease in the lag phase [35,65,70].

Table 5. Case studies of biochar addition to AD trials of PS.

Biochar Origin	Experiment Setup	Aim of the Study	Highlights of the Study	Ref.
Pyrolysis of agricultural residues at 500 °C	4 reactors with working volumes of 3 L: 2 control trials and 2 with the addition of 150 g biochar; T: 38 °C.	The effect of adding biochar to mesophilic CSTR reactors for the anaerobic digestion of swine manure at various OLR.	The generation of biogas and methane was increased by the addition of biochar under similar operating circumstances. As OLR rose, biochar's impact diminished. Higher VS removal rates in the reactors with biochar.	[65]

Table 5. *Cont.*

Biochar Origin	Experiment Setup	Aim of the Study	Highlights of the Study	Ref.
Hydrolysisdehydrated pig manure at 235 °C	AD experiments in CSTR with a working volume of 1.6 L; T: 35 °C; Biochar addition at a concentration of 4 g/L.	Knowing the development and mechanism of ARGs in AD of PS and sewage sludge affected by total solids and biochar	At both the start-up and all OLR feeding stages, the biochar trials' methane content and production rate were significantly higher than those of the control trials. Biochar addition to AD showed little influence on TAN and SCOD	[69]
Pyrolysis of rice husks at 300 °C	AD batch experiments using serum bottles with 500 mL working volume; T: 37 °C; Biochar addition at ratios of 0%, 5%, 10%, 15%, and 20% (on TS basis of PS).	The effects of biochar on the AD performance of PS and DIET reactions, the response of antibiotic resistance genes (ARGs) to varying doses of biochar, and the potential mechanisms of biochar enhancement	Methane yield may be increased and lag phase time during AD of PS could be decreased with an appropriate dosage of 5–10% biochar (depending on TS). AD process may be negatively impacted by an excessive amount of biochar. The addition of biochar to AD may limit the spread of ARGs.	[70]
Biochar purchased in Desheng Activated Carbon Factory of Liyang, China	AD experiments with working volumes of 10 and 12 L; T: 25 ± 1 °C. Biochar addition at ratios of 0%, 3%, 5%, and 7% to the PS (based on the dry weight).	To assess the impact of various biochar ratios on the generation of biogas during the AD process and the potential hazards of heavy metals in the digestate.	Biochar trials had higher methane yields and methane content. The various proportions of biochar did not significantly differ from one another. The studied heavy metals' ecological risk was marginally elevated by the AD process. Nevertheless, all digestates were still categorized as having a moderate risk.	[71]
Pyrolysis of cedarwood sawdust at 500 °C	Anaerobic batch experiment (working volume of 90 mL); T: 35 ± 1 °C; 1.35 g biochar added to each bottle.	The effects of adding biochar to swine manure at different levels of ammonia stress on AD. Additionally, digestate was screened to assess the viability of acclimated microorganisms to maintain methanogenesis.	The addition of biochar had a significant impact on methane production rate acceleration and lag time shortening when compared to the control conditions, particularly when ammonia stress was severe. The biochar groups exhibited elevated metabolic activity and greater microbial biomass, which resulted in a favourable reaction to ammonia stress conditions.	[4]

ARGs: Antibiotics resistance genes; TAN: total ammoniacal nitrogen; SCOD: soluble chemical oxygen demand.

A general conclusion from several authors focuses on the fact that the problems associated with biochar addition to AD systems are often linked to the dosage used (addition ratio, substrate:biochar), the materials used for biochar production, and/or the conditions of the production. However, most of these studies are conducted in batch or CSTRs trials with low working volumes (Table 5). The present work identified a lack of studies considering biochar addition to pig slurry AD trials. So, it is necessary to further study the role of biochar addition on semi-continuous AD processes in CSTR and with different substrates and operational conditions to fill the existent gap [65,68].

8.2. The Role of Biochar in Agronomic Valorisation

Additionally, when biochar is added to the AD process, there are other factors to consider, including biogas yield. Biochar can also play an important role in digestate properties for further agronomic valorisation [7,36]. Particularly, biochar's ability to interact with organic and inorganic compounds through the functional groups on its surface enhances the digestate quality after AD [65,72]. Numerous processes, including adsorption, electrostatic contact, ion exchange, and precipitation, contribute to this. The bioavailability of the nutrients in the biochar-digestate matrix for crop development and nutrient uptake may be impacted by such dynamics [72,73]. Additionally, it could improve the soil's nutritional balance by stopping nutrients from percolating through the soil into streams and waterways, which would boost plant productivity, change microbial habitats, and have an effect on the bacterial communities' activity and composition in the soil [73,74]. Biochar addition is expected to help the immobilization/entrapment of the organic and inorganic contaminants. Because of its absorption capabilities, biochar's application to soil has also been shown to shield plants from hazardous organic compounds, reduce nitrous oxide (N_2O) and methane emissions from soil, as well as adsorb NH_4^+-N through chemisorption and physical adsorption [74]. According to Pastorelli et al. [74], applying biochar to soil may affect the activity of the methanotrophic microbial community by acting as a substrate for microbial growth, affecting nutrient availability, and fostering microbial metabolism. All things considered, applying biochar to AD and digestate management has several hygienic advantages, such as decreased pathogens, the adsorption of toxic materials, odour control, and enhanced digestate stability, in addition to the enhancement of electron transfer between microbial species involved in AD.

According to Luo et al. [20], soil can be directly treated with the digestate from the fermentation process where biochar is added to enhance its qualities without endangering the environment.

Greenberg et al. [23] state that it may be more advantageous to combine biochar with digestate to act as an organic fertilizer compared to biochar alone, reporting that biochar by itself is insufficient in providing nutrients. According to that study, one way to boost the organic matter linked to aggregates and minerals in a reasonably short amount of time is to coapply biochar with organic fertilisers, like digestate.

Elbashier et al. [73] obtained similar outcomes, showing that the combination of digestate and biochar increased plant growth, soil nutrient availability, water use efficiency, and physiological parameters, making it a very effective fertilization approach when compared to mineral fertilizer. The combination of digestate and biochar was also found to boost the rate of photosynthesis. This could be because biochar helps to improve the net photosynthetic rate by lowering soil respiration, soluble salt concentration, and CO_2 emissions [73].

Cardelli et al. [7] tested the use of biochar and digestate from biogas production to increase soil biological activity. The authors concluded that the digestate application to soil resulted in an improvement in the soil's chemical and biological characteristics. The co-application of digestate and biochar mixed led to a lower CO_2 production when compared to digestate application, reduced the soluble organic compounds, limited the amount and activity of microorganisms, and enriched the C-sink of the soil.

However, there is a lack of information regarding the enrichment of digestate with biochar for agronomic valorisation, especially, if one focuses on digestate from the AD of PS. Theoretically, applying biochar and digestate together will raise the amount of soil organic carbon in more physically stable fractions because of the co-metabolite present and the formation of organic coverings [36]. Further research is needed since contradictory reports can be found in the literature. For example, Cardelli et al. [7] showed that adding biochar to digestate led to a decrease in enzyme activity and limited the growth of microorganism activity; Biederman et al. [75] refer to no changes in the plant community size, suggesting limited decomposition of the biochar material and no increase in soil nutrient availability with the addition of biochar. However, once more, it is critical to remember that the physical characteristics of both the recipient soils and the biochar determine how well the biochar interacts with the environment [63].

Overall, the addition of biochar to the AD process needs further research to improve methane production, stabilise microbial communities, reduce inhibitors such as ammonia and VFAs, and simultaneously improve digestate quality for agricultural use. This not only reflects an improvement in the AD process but also contributes to a circular economy and closes the nutrient loop in agriculture.

9. Conclusions

An overview and summary of the most recent developments in anaerobic digestion (AD) of pig slurry are included in this article, along with an update on ongoing research to promote sustainable development and help the EU reach its GHG reduction targets using AD. The ongoing efforts of the last 20 years aim to address technical and economic challenges and highlight the need for innovative solutions for pig slurry management. The focus is on the optimisation of biogas production, giving prominence to digestate valorisation due to its added agronomic value.

The future of the AD of pig slurry (PS) will probably concentrate on cutting-edge technologies including the incorporation of additives, such as biochar to improve process efficiency and environmental sustainability.

Although the studies on biochar addition to AD are increasing, there is a knowledge gap regarding (1) the effect of biochar addition to semi-continuous AD of PS, (2) the agronomic value of the resulting digestate from AD with biochar, (3) the agronomic value of digestate from AD with PS with biochar addition after the AD process. Nevertheless, more studies are needed to investigate the effect of biochar in biogas production to be able to attest to its viability for upscaling.

Along with the importance of planning and monitoring, it is also critical to develop new opportunities for farmers to create collaborations between agro-industrial sectors, and incentives that promote the installation and maintenance of infrastructure. Combining these topics could change the paradigm and increase the appeal of AD technology.

Author Contributions: Conceptualization, I.S., N.L., H.R. and E.D.; methodology, I.S.; validation, I.S., N.L., H.R. and E.D.; investigation, I.S., N.L., H.R. and E.D.; resources, I.S., N.L., H.R. and E.D.; data curation, I.S., N.L., H.R. and E.D.; writing—original draft preparation, I.S.; writing—review and editing, N.L., H.R. and E.D.; visualization, I.S.; supervision, N.L., H.R. and E.D. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Fundação para a Ciência e a Tecnologia (FCT) through the strategic project UID/04129/2020 (LEAF) and a PhD grant to the first author (doi: https://doi.org/10.54499/2023.03381.BD). H. Ribeiro and E. Duarte acknowledge the support by national funds through FCT—Fundação para a Ciência e Tecnologia, I.P., under the projects UIDB/04129/2020 of LEAF-Linking Landscape, Environment, Agriculture and Food, Research Unit (doi: https://doi.org/10.54499/UIDB/04129/2020) and LA/P/0092/2020 of Associate Laboratory TERRA (doi: https://

doi.org/10.54499/LA/P/0092/2020). N. Lapa acknowledges the support from FCT—Fundação para a Ciência e a Tecnologia by national funds under the projects LA/P/0008/2020 (doi: https://doi.org/10.54499/LA/P/0008/2020) UIDP/50006/2020 (doi: https://doi.org/10.54499/UIDP/50006/2020) and UIDB/50006/2020 (doi: https://doi.org/10.54499/UIDB/50006/2020).

Data Availability Statement: Data sharing is not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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