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Perspective

An Overview of the Technological Evolution of Organic Waste Management over the Last Decade

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Abstract: Organic waste treatment, including its many strategies and objectives, is one of the most rapidly changing sectors of environmental technology. It is closely related to sustainability and other critical issues, such as global warming. The first years of this century were the time of a transition from traditional technologies for the "disposal of" waste, such as incineration (with poor energy recovery) or landfill (more or less controlled), to biotechnologies that are more profitable, such as composting and anaerobic digestion. However, recent developments are focused on advanced technologies in the framework of a circular bioeconomy, maximizing the production of biomaterials and renewable energy using raw organic waste or digested materials. This perspective paper delves into the second transition in the field of technologies for treating and valorizing organic waste, highlighting emerging technologies such as anaerobic digestion enhanced with nanomaterials or biochar to substitute fossil natural gas, solid-state fermentation to obtain bioproducts that have a "chemical twin" with a high environmental impact, and pyrolysis as a predominant thermal treatment due to the production of biochar, probably the most promising biomaterial in today's research. All these technologies exploit the potential of organic waste for bioenergy production and material utilization, in line with circular principles.

Keywords: anaerobic digestion; biochar; bioeconomy; composting; pyrolysis; solid-state fermentation; sustainability

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1. Introduction

Today, the world is facing severe environmental problems that urge consistent and science-based solutions with minimal or, preferably, positive environmental impacts. The framework of these changes is related to the concept of a circular economy and, more specifically, a circular bioeconomy. As precisely defined by Venugopal [1], a circular bioeconomy refers to "an economic system that combines the principles of circular economy and bioeconomy. It focuses on maximizing the value of biomaterial resources for as long as possible and minimizing waste generation. This approach utilizes renewable biological resources to produce food, materials, and energy, while also emphasizing investment in human, social, natural, and physical capital. In a circular bioeconomy, the utilization of biomass plays a significant role in continuous production and contributes to the overall improvement of the economy".

Circular bioeconomy paradigms are well aligned with the sustainable development goals (SDGs) promoted by the United Nations since their publication in 2015 [2]. Specifically, some closely related critical aspects between SDGs and a circular bioeconomy include sustainable agriculture (SDG2), sustainable management of water and its sanitation (SDG6), renewable energy (SDG7), sustainable industrialization (SDG9), smart cities (SDG11), sustainable production and consumption (SDG12), climate change (SDG13), and the conservation of soil and terrestrial ecosystems (SDG15).

In this global context, it is evident that the waste management sector can significantly contribute to achieving these goals, as it plays an important role in some of the above-mentioned SDGs. This sector becomes particularly relevant when waste management, especially for organic waste, is approached from a circular bioeconomy perspective. By utilizing organic waste as raw material or as a source of renewable energy, this sector not only reduces the dependency on finite resources but also fosters resource efficiency, enables nutrient recovery, minimizes environmental impact, and supports the development of sustainable bio-based industries. In doing so, it helps us transition away from linear, non-sustainable models (Figure 1).

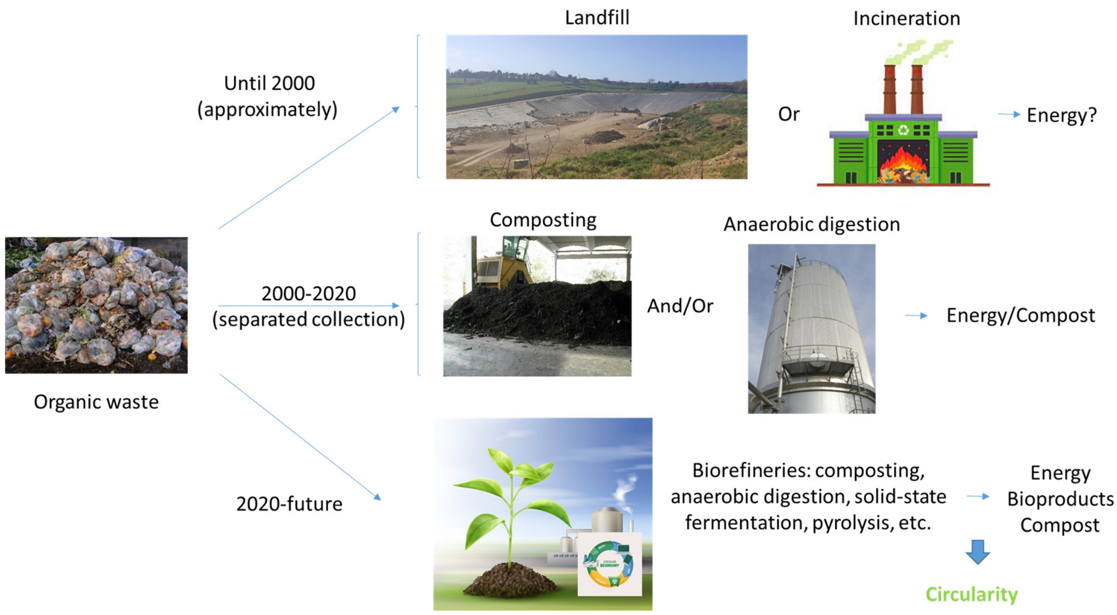


Figure 1. The transition of waste management in recent decades.

Although the waste management sector includes a wide range of potential approaches involving different feedstock, technologies, products, and environmental impacts [3–5], it is the opinion of the authors of this perspective paper that three specific areas have gained significant interest in waste management research, even though their level of implementation remains at pilot scale:

(1) Anaerobic digestion (AD) has received increased attention because of our complex global geopolitical situation, which has exponentially increased the use of additives to improve the performance of the process in terms of biomethane yield and production. Nanomaterials, in their different forms, and biochar are the most studied cases [6,7].

(2) The growing need for nature-based, biodegradable, and non-impacting biomaterials to substitute their chemically synthetized twins has promoted the use of solid-state fermentation (SSF) far beyond its biological definition as the biological solid-state aerobic transformation of organic biodegradable waste into bioproducts that permits the substitution of raw sources of materials and energy [8]. In this general view, it is important to keep in mind that SSF has its roots in another biotechnology, composting, which is also becoming popular again because of the increasing need for environmentally friendly organic biofertilizers [9].

(3) Thermal treatment technologies are also receiving growing attention. In previous decades, they were practically restricted to incineration on a commercial scale, which

has now been demoted in favor of other technologies. This is the particular case of pyrolysis, which is energy-neutral and produces biochar, which is gaining a predominant role in a wide number of applications [10] (The European Biochar Industry Consortium, 2024): fertilization, water and wastewater treatment, waste treatment, heterogeneous catalysis, and construction materials, among others.

Despite advancements in organic waste management, there remain several challenges that limit the large-scale implementation of circular bioeconomy strategies. Key gaps include the limited integration of emerging technologies into existing waste management infrastructures, the need for more scalable waste valorization processes, and economic or regulatory barriers that hinder the commercialization of bioproducts. Addressing these challenges is crucial for ensuring that innovative solutions move beyond the pilot scale.

Considering this context and these trends, the aim of this perspective paper is to provide readers with a comprehensive overview of this second transition in the organic waste management sector. Specifically, this transition is driven by AD (with biomethane as a substitute of fossil natural gas), SSF (to obtain an increasing catalog of bioproducts), and pyrolysis (for biochar production, with an endless list of applications), as well as the large number of interactions that can be found among these technologies [11].

2. Organic Waste as a Source of Bioproducts and Bioenergy

Organic waste is a broad term encompassing a wide variety of waste materials derived from both municipal and industrial sources. Municipal organic waste includes food waste generated by households, restaurants, and other food services, as well as green waste such as yard trimmings from parks and gardens [12]. This waste is known as the organic fraction of municipal solid waste (OFMSW) and can come from either source-separated collection systems or from the mechanical separation of mixed collection systems at treatment facilities, often resulting in lower-quality organic fractions [13]. Additionally, municipal sources of organic waste include sewage sludge and digestate (solid fraction) generated at wastewater treatment plants and urban waste management facilities based on AD. On the other hand, organic waste from industrial origins is generated mainly in the agricultural and food processing sectors. It includes crop residues, pruning waste, processing by-products, or inedible fractions. Other industries, such as textile industry, specifically those processes based on natural fibers, e.g., cotton or wool, also contribute to organic waste streams [14]. Regardless of origin, organic waste materials share the common characteristic of being biodegradable, to a greater or lesser extent. As such, they represent a valuable resource for bioprocessing to produce bioproducts and bioenergy, in line with circular bioeconomy principles.

However, the management of organic wastes is complex due to their variability. Furthermore, the inherent heterogeneity in their composition, variable generation rates, seasonality, and content of improper materials all contribute to the challenges of managing organic waste effectively [13]. As a result, waste management processes must be tailored to the specific characteristics of each waste stream, considering its origin, collection methods, and composition. An average characterization of the four main organic waste streams is presented in Table 1, and differences among them can be observed. For instance, OFMSW is richer in fats and proteins than digestate, which, on the contrary, is richer in more recalcitrant matter such as lignin. Similarly, agricultural and wood wastes also exhibit a higher content of lignin and, therefore, are more resistant to biodegradation, often requiring pretreatment steps [15]. For these materials, fungi-based processes represent a promising alternative due to their extensive repertoire of intracellular and extracellular enzymes and their ability to grow on solid substrates [16].

Table 1. Characterization of different organic waste streams.

Parameter	OFMSW	Solid Digestate	Agricultural Waste	Wood Waste
Humidity (%)	72.8 ± 7.6	71.3 ± 4.5 [a]	-	-
TS (%)	27.2 ± 7.6	28.7 ± 4.5 [a]	-	-
VS (% TS)	84.6 ± 9.9	87.4 ± 4.9 [a]	74.7 ± 1.2 [c]	79.8 ± 3.6 [c]
KN (g/kg)	7.9 ± 5.4	6.4 ± 1.4 [a]	-	-
TP (g/kg)	1.7 ± 2.5	2.5 ± 2.1 [a]	-	-
C (% TS)	46.6 ± 4.4	34.9 ± 8.6 [b]	37.1 ± 1.2 [c]	41.9 ± 2.3 [c]
H (% TS)	6.6 ± 0.6	5.0 ± 1.8 [b]	4.5 ± 0.2 [c]	4.9 ± 0.4 [c]
N (% TS)	2.9 ± 0.6	3.3 ± 2.0 [b]	0.7 ± 0.2 [c]	0.4 ± 0.1 [c]
S (% TS)	0.3 ± 0.2	0.9 ± 1.3 [b]	0.1 ± 0.0 [c]	0.1 ± 0.0 [c]
Fats (%VS)	17.5 ± 6.6	3.8 ± 2.2 [a]	-	-
Protein (%VS)	17.7 ± 5.5	11.9 ± 3.0 [a]	-	-
Raw fiber (%VS)	29.2 ± 15.0	30.4 ± 5.9 [a]	-	-
Lignin (%VS)	9.7 ± 5.3	24.1 ± 4.2 [a]	17.6 ± 5.2 [d]	22.3 ± 7.6 [d]
Carbohydrates (%VS)	55.5 ± 10.1	57.7 ± 7.9 [a]	64.8 ± 7.9 [d]	71.5 ± 8.5 [d]
Data range	43 samples from 22 countries	20 AD processes with different substrates	8 different types of crops	8 different types of wood
References	[12]	[a] [17]; [b] [15]	[c] [18]; [d] [19]	

TS, total solids; VS, volatile solids; KN, Kjeldahl nitrogen; TP, total phosphorous; dw, dry weight. The letter correspond to the references where values were obtained.

3. Towards a Second Transition in Organic Waste Management: Technologies, Bioproducts, and Renewable Energy

The richness and diversity within organic waste streams (Table 1) has led to the development of more advanced and substrate-specific technologies, other than composting and AD, such as pyrolysis for biochar production and SSF for the generation of high-value bioproducts. A qualitative comparison analysis is presented in Table 2. In terms of energy balance, both AD and pyrolysis yield positive results; however, it has been highlighted that the high water content of organic waste requires high energy expenditure for drying in pyrolysis [20]. From an economic perspective, SSF opens the door for obtaining higher-value bioproducts [21], and pyrolysis produces a wide range of products that have further applications [22], although they are also associated with higher costs. All technologies offer environmental benefits compared to landfill or incineration. In this section, these technologies and their potential integration (Figure 2) are evaluated in depth.

Table 2. Qualitative comparison of technologies for organic waste valorization.

Parameter	Composting	Anaerobic Digestion	Pyrolysis	Solid-State Fermentation (SSF)
Energy balance	− − −	+ + +	+	− −
Cost	+	+ +	+ + +	+ +
Revenue	−/+	+	+ +	+ + +
Scalability (TRL)	9	9	9	5–7
Environmental impact	+ +	+ + +	+	+ + +
Carbon sequestration	+	/	+ + +	/

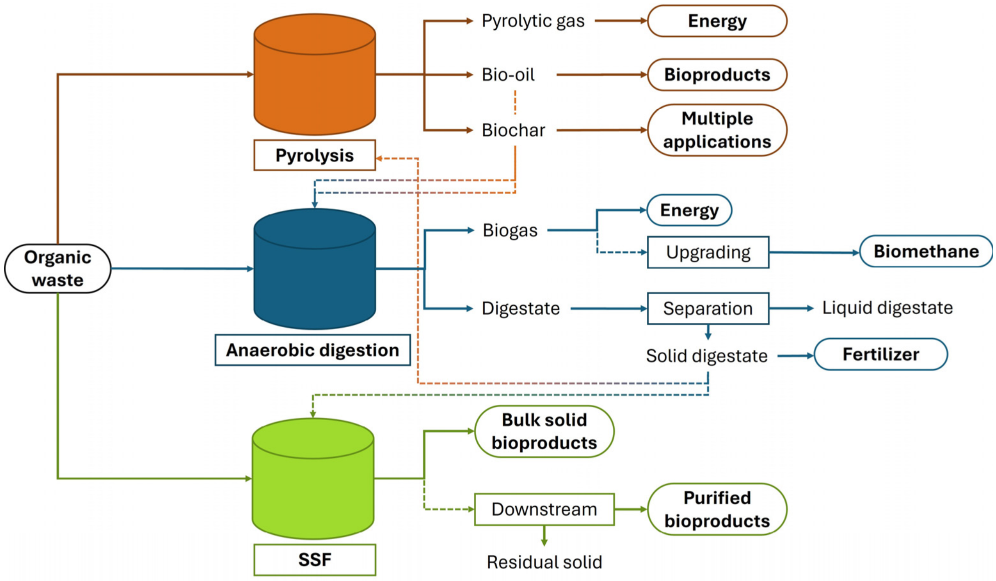


Figure 2. Process diagrams for each technology and their interactions (dotted lines).

3.1. The Rise of Anaerobic Digestion

3.1.1. Biogas and Biomethane

AD is a well-known process through which a complex bacterial consortium breaks down organic matter of different typologies in the absence of oxygen. This organic matter presents a medium-to-high level of biodegradability [23]. To prevent the presence of oxygen, anaerobic digestion takes place in sealed bioreactors, where these complex microbial communities digest the waste and produce the resultant biogas and digestate (the solid and liquid material end-products of the AD process), which are the main products discharged from the digester. Although AD is well implemented in some parts of the world and is a consolidated biotechnology for treating excess sludge produced in wastewater treatment plants [24], its current prominence has transcended this secondary role to become the first option when dealing with biodegradable organic waste. This is a consequence of the extensive search for renewable energy sources that, at the same time, must be locally available [25], which in turn will reduce the importance of energy accessibility in a complex geopolitical situation. AD combines all these advantages, which explains the proliferation of plants (already built or in the design stage) in several parts of the world, especially in Europe and China [26,27].

Regarding the products of AD, research tends to consider biogas a clean renewable energy source and highlights its numerous advantages as such [28]. While this is true, an increased use of AD inherently implies an increase in the generation of the other main product of AD, digestate, which needs a renewed perspective in terms of being a profitable material for a large number of applications, as discussed further in this perspective paper. Coming back to biogas, it is also evident that a transition regarding its use is occurring right now. Thus, the beginning of AD's implementation in waste or wastewater treatment plants some decades ago was associated with the use of cogeneration units, which, after purification and hydrogen sulfide removal, burn biogas to simultaneously produce heat in the form of water vapor and electricity. The destination of these two forms of energy could be the treatment plant itself or its use to meet external demands [29].

However, today's use of biogas is taking a step forward. In an increasing number of AD plants producing large amounts of biogas, it is cleaned, but also upgraded, removing or transforming the considerable percentage of carbon dioxide that it contains. Although several physicochemical technologies are available for biogas upgrading, the use of membranes is probably the most popular in full-scale facilities [30]. Among biotechnology approaches, the role of biomethanation is emerging. Biomethanation is based on the biological process of methanogenesis, carried out by hydrogenotrophic methanogens, by which carbon dioxide is transformed into methane with hydrogen [31]. This process is gaining relevance, but its full-scale implementation will depend on the availability and cost of "green" hydrogen. Anyway, the objective in this case is the substitution of fossil natural gas by compressing and injecting this methane-enriched biogas into the existing natural gas grids [32].

In conclusion, it is evident that all these recent advances have caused AD to be listed prominently as a renewable energy source, which is starting to change the origin and typology of organic waste from raw waste to its corresponding digested version.

3.1.2. Advanced Additives: Nanomaterials and Biochar

Alongside the ex situ upgrading of biogas, there are plenty of studies in the scientific literature related to the emerging trend of searching for approaches that partially upgrade biogas with high methane content and increase biogas-specific production per mass of organic matter. This is the case with some additives, such as nanomaterials and, more recently, biochar. Although this strategy is not capable of achieving carbon dioxide-free biomethane, there is no need for external hydrogen, which makes this approach economically attractive [6].

Regarding nanomaterials, although a large number of metallic elements, oxides, and even carbon nanostructures [33] have been found to affect the production of biogas, it is important to highlight that iron nanoparticles, in several oxidation states, are the most promising materials [34]. The reasons for this fact are clear: on the one hand, they are economically feasible and can be obtained from iron scraps; on the other hand, iron is a non-toxic element which is not inhibitory for the AD process and which, furthermore, permits the safe use of digestate. Since the discovery of the positive effect of magnetite nanoparticles on AD in terms of biogas production in 2014, many studies have been published, although few of them were conducted in a continuous or semi-continuous mode of operation [34], which is important for evaluating the long-term stability of the nanoparticles and their impact on the process. The use of nanoparticles in AD has shown improvements in environmental impact analysis, as the increase in biogas production is associated with a lower consumption of fossil fuels [35]. However, the fate of these nanomaterials once they are incorporated into the digestate remains an unanswered research question, especially if the digestate is used as a fertilizer or for other agricultural applications, because it could lead to the unintended spread of nanomaterials in soil ecosystems [6]. Therefore, further studies on the persistence and long-term effects of nanomaterials in agricultural systems are needed to assess their impact on ecosystems. Additionally, the cost–benefit ratio of using nanomaterials in AD should be carefully assessed to ensure that the technological benefits outweigh the economic costs. It is evident that the use of nanoparticles needs a rigorous sustainability assessment, in economic but also environmental terms, before considering its implementation at full scale.

A different and even more recent approach is the use of biochar to enhance anaerobic digestion. In this case, this strategy should be considered differently when compared to that of using nanomaterials. Biochar is obtained from the pyrolysis of organic waste, especially that with high lignocellulosic content [36]. Moreover, biochar is being used in a wide number of environmental applications [37], but also as a substitute for other non-renewable materials [10], with a clear increasing interest. In the field of anaerobic digestion, the effects of biochar on the process have recently been reviewed by several authors [38,39]. Although the role of biochar will be discussed later in this paper, it is important to highlight the lack of continuous full-scale studies. Nevertheless, existing research shows highly promising results, with significant increases in biogas production and in situ methane enrichment observed in a semi-continuous study at 1000 L [40], a continuous study at 16 L [41], and batch lab-scale experiments [42].

3.1.3. Digestate: Problem or Opportunity?

Although at a different pace than that of biogas, the rise of AD has caused the appearance of innovative sustainable alternatives for digestate management, beyond its classical use as an organic biofertilizer, which continues to be its main destination [43]. Among all the alternatives proposed for digestate, some of them can be considered quite consolidated, while some others look very attractive in sustainability terms but are still at a low technology readiness level.

The consolidated strategies include very different approaches, from biological treatments, such as composting, to thermochemical treatments. The composting of digestate is well known and results in a sanitized product that is free of odors and retains a high level of digestate nutrients, if properly managed [44]. A variation of composting, biodrying, has the same principles, but in this case, the objective is to have a refuse-derived fuel after the biological process [45].

In relation to emerging digestate treatments, several technologies with very different objectives can be observed in the recent literature. Table 3 compiles some of them.

Table 3. Emerging applications of digestate.

Technology	Objective	Challenges	References
Cultivation of insects	Protein production	Scale-up and economic analysis Some pilot plants are in operation	[46]
Vermicomposting	Vermicompost as high-quality fertilizer	Sensibility of earthworms to inhibitory substances and waste self-heating	[47]
Mushroom cultivation	Mushroom production	Highly controlled process: moisture, temperature, and absence of light	[48]
Fungal (submerged) fermentation	Biofuel (biodiesel or bioethanol) production	Liquid medium, not natural for fungi Pretreatment of digestate Sterile conditions	[49,50]
Microalgal cultivation	Production of high-value biomass	High cost Scale-up is surface-intensive Sensitive to contamination or environmental variations	[51]
SSF	A wide variety of bioproducts: biostimulants, biopesticides, etc.	Scale-up Purification and downstream	[52,53]
Pyrolysis	Production of biochar	High moisture content reduces the efficiency of the process	[22]
Pelletizing	Biofuel production	Limited experience Loss of nutrients	[54]

It is worthwhile to mention that Table 3 points out the differences in the technology readiness level of the strategies presented. In general, SSF has great potential as a source of bioproducts in the framework of a circular bioeconomy [8], and it will be discussed in detail in the following subsection.

3.2. The Emerging Role of Solid-State Fermentation

3.2.1. SSF Unlocks the Potential of Organic Solid Waste, Including Digestate

SSF is a biotechnological process characterized by the growth of microorganisms in a solid matrix under aerobic conditions without the addition of free water. In SSF, the solid substrate serves as both a nutrient source and a physical support for microbial development. The main reason for the growing research interest in SSF in the last decade is that it enables the direct utilization of solid organic waste as a substrate with minimal or no pretreatment, thereby reducing processing costs and energy requirements [8]. SSF has historically been considered a low-tech process and has been implemented widely in the traditional fermented foods industry [21]. The rise of technological advances in and research on SSF has mainly occurred in the context of its application in the enzyme industry [55]. When using organic solid municipal wastes, it has been described as an evolution of composting [11], and as such, it presents both advantages and challenges: it allows for cost-effective, decentralized production with minimal infrastructure, making it accessible and adaptable to various applications, yet this same simplicity can limit scalability, process control, and industrial adoption in highly standardized and automated settings [55]. For example, the sterilization or the loading of solid substrates into large-scale bioreactors is more challenging than for liquid substrates, which are pumpable [55]. However, converting solid waste into liquid effluents involves the use of energy-intensive or water-consuming pretreatments. Enzymatic hydrolysis is a commonly adopted biological alternative, though it still results in a solid residue containing the unhydrolyzed fraction [56].

In this sense, the potential of SSF does not lie in substituting more established and automatized technologies but rather in its integration into existing waste management and biorefinery systems. For instance, SSF can be applied to the solid fraction of different organic wastes after enzymatic hydrolysis, where soluble sugars have already been extracted for biofuel or biochemical production [13]. Alternatively, SSF can be applied before enzymatic hydrolysis or AD processes to enrich organic waste with enzymes produced in situ and improve the conversion efficiency of the subsequent step [57,58]. The bioproducts that can be obtained from SSF processes are endless. Among them, enzymes have been the most studied, primarily due to their high commercial value, which promotes the search for alternative enzymes sources [56]. Other valuable bioproducts that have been produced via SSF are biosurfactants, biopesticides, antioxidants, or pigments [21]. These products provide sustainable alternatives to conventional chemical products in various industries, from agriculture to food and cosmetics. The implementation of SSF in a biorefinery context would enable the valorization of solid-waste effluents into higher-value products, providing alternative sources of revenue, and, equally importantly, would contribute to achieving a real zero-waste strategy, because its residual product, if any, is easily compostable.

Additionally, as introduced in the previous section, SSF presents an innovative alternative for processing digestate, the residual byproduct of AD. Given the increasing regulatory restrictions on digestate application in soils, SSF offers a sustainable pathway for valorizing this material beyond its fertilizing properties [52]. Although few studies have explored the use of digestate as a SSF substrate, recent research is investigating its potential with different microbial strains. For instance, an SSF process using *Bacillus thuringiensis*, the workhorse of biopesticide producers, has been scaled up to 290 L, achieving a 2.4-fold increase in production in terms of microbial spores. The resulting material exhibited low phytotoxicity and high stabilization, highlighting its potential for agricultural applications [59]. The cultivation of microorganisms from a different kingdom, fungi, has also been demonstrated. Different *Trichoderma* species were successfully grown on digestate mixed with agro-food waste at a laboratory scale [60]. Digestate presents certain characteristics that initially might appear unfavorable for SSF processes, such as a strong endogenous microbial community, a low content on easily biodegradable matter and higher levels of recalcitrant compounds, such as lignin (Table 1), or a high pH and alkalinity. However, the previous examples demonstrate that the search for robust microbial strains with specific advantages, or the use of co-substrates containing more accessible sugars, can help mitigate these challenges.

Despite its benefits, it should not be forgotten that SSF presents technical challenges, primarily due to the heterogeneity inherent in the use of the solid substrates [55], which have yet to be overcome. Unlike with liquid substrates, where a homogeneous mixture can be achieved and maintained relatively easily, SSF systems inherently lack uniform mixing, leading to poor mass transfer and the formation of gradients in nutrient availability, moisture content, and temperature [21]. These features can result in non-uniform production, localized substrate depletion, or difficulties in process modeling and control. However, the potential benefits of SSF's implementation justify further research and technological development to optimize its scalability and efficiency.

3.2.2. Solid Fermentation for Solid Applications

Using organic waste as a substrate in fermentation processes is a strategy aimed at reducing production costs by avoiding the cost of raw materials [18], but this approach is not coherent with downstream processes that are too complex or require high levels of purity, unless the final product justifies the effort. Therefore, it is essential to reconsider the final use of the bioproducts generated via SSF and explore alternatives that allow for their application in solid form. Certainly, this is not a universal approach, but in some situations, the direct use of the entire solid matrix without extensive purification steps to isolate specific molecules can be an interesting alternative. For example, in the production of mixed enzymes for bulk applications such as AD [58], enzymatic hydrolysis of other organic wastes [61] or enzyme-mediated bioremediation processes [62] could be employed.

In other cases, the choice between the downstream processing or direct application of SSF-derived product will be crucial in determining the overall feasibility of the process. For instance, digestate might be unsuitable for pharmaceutical or food applications due to current regulatory restrictions and safety concerns; thus, its potential in soil-related applications is a more promising alternative. SSF products derived from digestate could be applied as enriched soil amendments [59], benefiting agricultural practices. Recent research has explored the use of SSF products derived from green waste as soil amendments with biostimulant properties, demonstrating positive results in lettuce cultivation [63]. Additionally, SSF can provide novel solutions for other soil-related applications, such as biopesticides. The ability of SSF to support the growth of microorganisms with insecticidal properties, such as *Beauveria bassiana* [64] or *Bacillus thuringiensis* [59], indicates that SSF-derived solid products could contribute to the pest control market. More research on this topic is needed to optimize product formulations, assess product stability, and determine appropriate storage conditions.

Overall, the decision to implement downstream processing will be case-specific, depending on the initial substrate and the intended application of the final product. More refined applications will require additional purification steps, but as discussed, this is not the only viable approach for SSF products. In many cases, particularly those related to agriculture and environmental applications, the direct use of the fermented solid matrix can be an effective and sustainable alternative.

3.3. Pyrolysis as Predominant Thermal Treatment for Biochar Production

3.3.1. Pyrolysis as a Source of Biochar

Thermal pretreatments have traditionally been used in waste management. The first strategy implemented was the incineration of mixed municipal solid waste (MSW), with the recovery of energy and the disposal of ashes in sanitary landfills. Although this technology is still widely used in many countries [65,66], other thermal treatments that have objectives beyond energy production are gaining a predominant role nowadays [67]. This is the case of pyrolysis, whose recent relevance is mainly attributed to its ability to produce biochar. In fact, other thermal treatments such as gasification or hydrothermal carbonization can also produce biochar, although their use is quite limited [68].

During organic waste or biomass pyrolysis, three main products are obtained: a solid (biochar), a liquid (bio-oil), and a gas (pyrolytic gas/syngas). The pyrolysis process is energy-neutral, since the temperature required for the thermal decomposition of biomass is achieved by the heat generated from the combustion of a part of this biomass. Moreover, many factors have an influence on the pyrolysis process (feedstock characteristics, pressure and process temperature, among others) and can change the ratio and properties of the three products obtained [69].

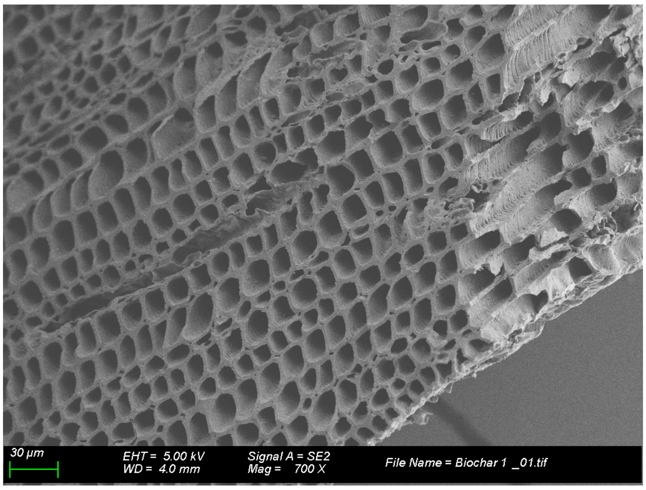
From an environmental perspective, pyrolysis and biochar have another important benefit: the biomass used as feedstock results in a material that is much more difficult to decompose, either by biological or physicochemical processes. Thus, the atmospheric carbon dioxide that has been consumed by biomass for its growth is immobilized, and this implies a positive carbon balance. In fact, biochar is considered a versatile and scalable product with the potential to contribute to generating carbon credits, in agreement with sustainable development goals [70], and its critical function as a negative-emission technology at a regional level has been pointed out recently [71].

3.3.2. Understanding Biochar

According to the International Biochar Initiative [72], biochar is "the solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment". In practice, biochar is a carbon-rich material similar to coal but generated from different types of biomass through a pyrolysis process, as explained before. Due to this, it represents a sustainable alternative to activated carbon and its multiple applications, since it shares many of its characteristics, but comes from a renewable source. Figure 3 shows some pictures of biochar (a macroscopic view and under electronic microscopy).

(**a**)

Figure 3. *Cont.*



(**b**)

Figure 3. Images of biochar from forestry biomass: (**a**) macroscopic view; (**b**) under electronic microscopy.

Figure 3 is interesting since it shows the reason why biochar has gained exponential attention in several fields, especially in environmental technologies. Thus, when biochar is observed at high resolution (Figure 3b), a complex structure is revealed, with a high degree of porosity. This particular structure results in a large specific surface area, reaching hundreds of square meters per gram, a highly relevant characteristic of the material that can be modulated according to the conditions of the pyrolysis process [73]. In fact, this parameter means that biochar has multiple applications in fields such as water treatment, the cleaning of polluted gases, and, recently, the treatment of organic waste [74]. On top of its high surface area and porous structure, the abundance of functional groups present in biochar allows for the adsorption and retention of contaminants such as heavy metals or organic compounds [7]. Its stability and ability to bind pollutants have placed it in the spotlight as a material for environmental remediation.

3.3.3. The Potential Role of Biochar in Modern Waste Management

Anaerobic Digestion

As explained in Section 3.1.2, the main role of biochar in anaerobic digestion is the increase in biomethane production, both in terms of biogas production and in terms of biogas methane content. In addition to this, two emerging research fields within the framework of anaerobic digestion where biochar is gaining attention are biogas upgrading and improved fertilizer properties using digestate. In the first case, biochar has a higher carbon dioxide adsorption capacity than activated carbon, and it can also remove up to 78% of hydrogen sulfide, a typical contaminant found in biogas [39]. This is mainly due to its large porosity and surface area and the presence of basic and hydrophobic functional groups [75,76]. In addition, its high electron exchange capacity favors the bioconversion of carbon dioxide into methane and promotes the release of basic cations that help solubilize carbon dioxide into carbonate/bicarbonate [77]. In the case of the use of digestate as organic fertilizer, biochar is able to retain many compounds (organic molecules, phosphate, ammonium, nitrate, nitrite, metals, carbon dioxide, etc.), which favors the use of nutrients by plants and avoids the leaching of heavy metals [75]. It also improves the water retention capacity of the soil [78]. Finally, it is important to emphasize that a clear advantage of biochar compared to other adsorbents is that it does not require regeneration, since it can be directly applied to soil for nutrient retention [78].

Composting

In general, the presence of biochar has important benefits in the composting of organic waste, both in the performance of the process [79] and in compost quality [74]. In particular, biochar has been demonstrated to be a powerful additive that minimizes the gaseous emissions from the composting of a wide range of different organic waste. These emissions include GHGs (greenhouse gases, methane and nitrous oxide, specifically), ammonia, volatile organic compounds (VOCs), and unpleasant odors. As this topic is highly relevant, it is important to note that the absence of studies at full scale makes these results quite preliminary, with an evident need for validation. Particularly, this is the case of ammonia, the main polluting/odorous gas emitted from composting, whose emission also results in a decrease in the fertilization properties of compost. Thus, it has been observed that biochar reduces ammonia emissions [80], although the opposite phenomenon has also been reported [81]. This is supported by other research that describes that the main factor controlling ammonia emissions in composting is temperature [82], which is clearly related to the composting scale [83].

In the case of other gases, the patterns and mechanisms of emissions reduction seem clearer. Thus, regarding GHGs, the reduction in methane emissions can reach 80% and it is associated with better aeration due to an increase in porosity and, therefore, a reduction in anaerobic zones [84]. In the case of nitrous oxide, the reduction in emissions has been reported to reach values up to 38% and has been associated with a decrease in the presence of denitrifying microbial populations that generate this gas [84]. In the case of VOCs, the situation is very complex, given the high number of VOC families emitted from composting [85], although some preliminary experiments have also observed a positive effect of biochar in reducing these emissions, which result from a simple deodorization process [86].

4. General Perspective

The integration of circular economy principles into production systems and society as a whole has driven significant innovation in waste management over the last decade due to the paradigm shift from viewing waste as a burden to recognizing it as a valuable resource. In the present perspective article, novel and innovative technologies have been discussed. One well-established strategy is anaerobic digestion, which has already demonstrated scalability and market viability, as evidenced by the rapid expansion of the production of biogas and, consequently, digestate in many regions of the world. Two additional emerging strategies, with lower technology readiness levels, characterized by their versatility and flexibility in terms of substrate utilization are solid-state fermentation and end-use applications of biochar. This adaptability is key in the potential integration of these technologies into a holistic waste management system to increase sustainability, resource efficiency, and a more resilient bioeconomy. To fully leverage the potential of these technologies, policy support and targeted incentives that encourage investment will be crucial.

Furthermore, the role of digital technologies, including artificial intelligence (AI) and the Internet of Things (IoT), should be considered. Research on the topic is increasing [87], particularly on optimizing waste management logistics [88] and improving waste characterization [89], but also on the optimization and control of complex technological conversion processes [29]. The integration of these digital solutions could improve waste management systems.

Looking ahead, further research is needed to refine these technologies, improve their economic feasibility, and develop integrated models that maximize synergies between different waste valorization strategies.

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References

1. Venugopal, V. Green Processing of Seafood Waste Biomass towards Blue Economy. *Curr. Res. Environ. Sustain.* **2022**, *4*, 100164. [CrossRef]
2. Sustainable Development. THE 17 GOALS. Available online: https://sdgs.un.org/goals (accessed on 20 October 2024).
3. Stephen, J.L.; Periyasamy, B. Innovative Developments in Biofuels Production from Organic Waste Materials: A Review. *Fuel* **2018**, *214*, 623–633. [CrossRef]
4. Alibardi, L.; Astrup, T.F.; Asunis, F.; Clarke, W.P.; De Gioannis, G.; Dessì, P.; Lens, P.N.L.; Lavagnolo, M.C.; Lombardi, L.; Muntoni, A.; et al. Organic Waste Biorefineries: Looking towards Implementation. *Waste Manag.* **2020**, *114*, 274–286. [CrossRef]
5. Tian, H.; Li, J.; Yan, M.; Tong, Y.W.; Wang, C.H.; Wang, X. Organic Waste to Biohydrogen: A Critical Review from Technological Development and Environmental Impact Analysis Perspective. *Appl. Energy* **2019**, *256*, 113961. [CrossRef]
6. Barrena, R.; Moral-Vico, J.; Font, X.; Sánchez, A. Enhancement of Anaerobic Digestion with Nanomaterials: A Mini Review. *Energies* **2022**, *15*, 5087. [CrossRef]
7. Manga, M.; Aragón-Briceño, C.; Boutikos, P.; Semiyaga, S.; Olabinjo, O.; Muoghalu, C.C. Biochar and Its Potential Application for the Improvement of the Anaerobic Digestion Process: A Critical Review. *Energies* **2023**, *16*, 4051. [CrossRef]
8. Sánchez, A. A Perspective of Solid-State Fermentation as Emergent Technology for Organic Waste Management in the Framework of Circular Bioeconomy. *ACS Sustain. Resour. Manag.* **2024**, *1*, 1630–1638. [CrossRef]
9. US Composting Council. Benefits of Compost. Available online: https://www.compostingcouncil.org/page/CompostBenefits (accessed on 20 October 2024).
10. The European Biochar Industry Consortium. Beyond Carbon Sequestration: The Wide-Ranging Applications of Biochar. Available online: https://www.biochar-industry.com/2023/2023-biochar-use-cases/ (accessed on 20 October 2024).
11. Artola, A.; Font, X.; Moral-Vico, J.; Sánchez, A. The Role of Solid-State Fermentation to Transform Existing Waste Treatment Plants Based on Composting and Anaerobic Digestion into Modern Organic Waste-Based Biorefineries, in the Framework of Circular Bioeconomy. *Front. Chem. Eng.* **2024**, *6*, 1463785. [CrossRef]
12. Campuzano, R.; González-Martínez, S. Characteristics of the Organic Fraction of Municipal Solid Waste and Methane Production: A Review. *Waste Manag.* **2016**, *54*, 3–12. [CrossRef]
13. Molina-Peñate, E.; Artola, A.; Sánchez, A. Organic Municipal Waste as Feedstock for Biorefineries: Bioconversion Technologies Integration and Challenges. *Rev. Environ. Sci. Bio/Technol.* **2022**, *21*, 247–267. [CrossRef]
14. Wojnowska-Baryła, I.; Bernat, K.; Zaborowska, M. Strategies of Recovery and Organic Recycling Used in Textile Waste Management. *Int. J. Environ. Res. Public Heath* **2022**, *19*, 5859. [CrossRef]
15. Klüpfel, C.; Yuan, B.; Biller, P.; Herklotz, B. Hydrothermal Liquefaction as a Treatment Technology for Anaerobic Digestate: A Review. *Renew. Sustain. Energy Rev.* **2025**, *210*, 115156. [CrossRef]
16. Losantos, D.; Sarra, M.; Caminal, G. OPFR Removal by White Rot Fungi: Screening of Removers and Approach to the Removal Mechanism. *Front. Fungal Biol.* **2024**, *5*, 1387541. [CrossRef]
17. Romio, C.; Ward, A.J.; Møller, H.B. Characterization and Valorization of Biogas Digestate and Derived Organic Fertilizer Products from Separation Processes. *Front. Sustain. Food Syst.* **2024**, *8*, 1415508. [CrossRef]
18. Khasraw, D.; Martin, C.; Herbert, J.; Li, Z. A Comprehensive Literature Review of Biomass Characterisation and Application for Iron and Steelmaking Processes. *Fuel* **2024**, *368*, 131459. [CrossRef]
19. Cho, E.J.; Trinh, L.T.P.; Song, Y.; Lee, Y.G.; Bae, H.J. Bioconversion of Biomass Waste into High Value Chemicals. *Bioresour. Technol.* **2020**, *298*, 122386. [CrossRef]
20. Li, H.; Feng, K. Life Cycle Assessment of the Environmental Impacts and Energy Efficiency of an Integration of Sludge Anaerobic Digestion and Pyrolysis. *J. Clean. Prod.* **2018**, *195*, 476–485. [CrossRef]
21. Oiza, N.; Moral-Vico, J.; Sánchez, A.; Oviedo, E.R.; Gea, T. Solid-State Fermentation from Organic Wastes: A New Generation of Bioproducts. *Processes* **2022**, *10*, 2675. [CrossRef]
22. Liu, J.; Huang, S.; Chen, K.; Wang, T.; Mei, M.; Li, J. Preparation of Biochar from Food Waste Digestate: Pyrolysis Behavior and Product Properties. *Bioresour. Technol.* **2020**, *302*, 122841. [CrossRef]

23. US EPA. How Does Anaerobic Digestion Work? Available online: https://www.epa.gov/agstar/how-does-anaerobic-digestion-work (accessed on 3 November 2024).
24. Subbarao, P.M.V.; D' Silva, T.C.; Adlak, K.; Kumar, S.; Chandra, R.; Vijay, V.K. Anaerobic Digestion as a Sustainable Technology for Efficiently Utilizing Biomass in the Context of Carbon Neutrality and Circular Economy. *Environ. Res.* **2023**, *234*, 116286. [CrossRef]
25. Zhang, H.; Liu, G.; Xue, L.; Zuo, J.; Chen, T.; Vuppaladadiyam, A.; Duan, H. Anaerobic Digestion Based Waste-to-Energy Technologies Can Halve the Climate Impact of China's Fast-Growing Food Waste by 2040. *J. Clean. Prod.* **2020**, *277*, 123490. [CrossRef]
26. Gadirli, G.; Pilarska, A.A.; Dach, J.; Pilarski, K.; Kolasa-Więcek, A.; Borowiak, K. Fundamentals, Operation and Global Prospects for the Development of Biogas Plants—A Review. *Energies* **2024**, *17*, 568. [CrossRef]
27. Ciuła, J.; Generowicz, A.; Gronba-Chyła, A.; Wiewiórska, I.; Kwaśnicki, P.; Cygnar, M. Analysis of the Efficiency of Landfill Gas Treatment for Power Generation in a Cogeneration System in Terms of the European Green Deal. *Sustainability* **2024**, *16*, 1479. [CrossRef]
28. Finecomess, S.A.; Gebresenbet, G. Future Green Energy: A Global Analysis. *Energies* **2024**, *17*, 3039. [CrossRef]
29. Gaska, K.; Generowicz, A.; Gronba-Chyła, A.; Ciuła, J.; Wiewiórska, I.; Kwaśnicki, P.; Mala, M.; Chyła, K. Artificial Intelligence Methods for Analysis and Optimization of CHP Cogeneration Units Based on Landfill Biogas as a Progress in Improving Energy Efficiency and Limiting Climate Change. *Energies* **2023**, *16*, 5732. [CrossRef]
30. Gkotsis, P.; Kougias, P.; Mitrakas, M.; Zouboulis, A. Biogas Upgrading Technologies—Recent Advances in Membrane-Based Processes. *Int. J. Hydrogen Energy* **2023**, *48*, 3965–3993. [CrossRef]
31. Angelidaki, I.; Karakashev, D.; Batstone, D.J.; Plugge, C.M.; Stams, A.J.M. Biomethanation and Its Potential. *Methods Enzymol.* **2011**, *494*, 327–351. [CrossRef]
32. Cavana, M.; Leone, P. Biogas Blending into the Gas Grid of a Small Municipality for the Decarbonization of the Heating Sector. *Biomass Bioenergy* **2019**, *127*, 105295. [CrossRef]
33. Ziganshina, E.E.; Bulynina, S.S.; Ziganshin, A.M. Anaerobic Digestion of Chicken Manure Assisted by Carbon Nanotubes: Promotion of Volatile Fatty Acids Consumption and Methane Production. *Fermentation* **2022**, *8*, 641. [CrossRef]
34. Casals, E.; Barrena, R.; Gonzalez, E.; Font, X.; Sánchez, A.; Puntes, V. Historical Perspective of the Addition of Magnetic Nanoparticles into Anaerobic Digesters (2014–2021). *Front. Chem. Eng.* **2021**, *3*, 745610. [CrossRef]
35. Hijazi, O.; Abdelsalam, E.; Samer, M.; Attia, Y.A.; Amer, B.M.A.; Amer, M.A.; Badr, M.; Bernhardt, H. Life Cycle Assessment of the Use of Nanomaterials in Biogas Production from Anaerobic Digestion of Manure. *Renew. Energy* **2020**, *148*, 417–424. [CrossRef]
36. Kan, T.; Strezov, V.; Evans, T.J. Lignocellulosic Biomass Pyrolysis: A Review of Product Properties and Effects of Pyrolysis Parameters. *Renew. Sustain. Energy Rev.* **2016**, *57*, 1126–1140. [CrossRef]
37. Prochnow, F.D.; Cavali, M.; Dresch, A.P.; Belli, I.M.; Libardi, N.; de Castilhos, A.B. Biochar: From Laboratory to Industry Scale—An Overview of Scientific and Industrial Advances, Opportunities in the Brazilian Context, and Contributions to Sustainable Development. *Processes* **2024**, *12*, 1006. [CrossRef]
38. Parra-Orobio, B.A.; Soto-Paz, J.; Oviedo-Ocaña, E.R.; Vali, S.A.; Sánchez, A. Advances, Trends and Challenges in the Use of Biochar as an Improvement Strategy in the Anaerobic Digestion of Organic Waste: A Systematic Analysis. *Bioengineered* **2023**, *14*, 2252191. [CrossRef]
39. Zhao, W.; Yang, H.; He, S.; Zhao, Q.; Wei, L. A Review of Biochar in Anaerobic Digestion to Improve Biogas Production: Performances, Mechanisms and Economic Assessments. *Bioresour. Technol.* **2021**, *341*, 125797. [CrossRef]
40. Zhang, L.; Lim, E.Y.; Loh, K.C.; Ok, Y.S.; Lee, J.T.E.; Shen, Y.; Wang, C.H.; Dai, Y.; Tong, Y.W. Biochar Enhanced Thermophilic Anaerobic Digestion of Food Waste: Focusing on Biochar Particle Size, Microbial Community Analysis and Pilot-Scale Application. *Energy Convers. Manag.* **2020**, *209*, 112654. [CrossRef]
41. Shen, R.; Yao, Z.; Yu, J.; Luo, J.; Zhao, L. Enhanced Performance and Microbial Communities of Anaerobic Digestion with Biochar in Pilot-Scale Continuous Stirred-Tank Reactors: Effects of Substrate Concentration and Hydraulic Retention Time. *Sustain. Energy Fuels* **2022**, *6*, 5324–5336. [CrossRef]
42. García-Prats, M.; González, D.; Sánchez, A. Characterization of Biochars of Different Origin and Application to the Anaerobic Digestion of Source-Selected Organic Fraction of Municipal Solid Waste under Batch Conditions and at Different Dosages. *Front. Chem. Eng.* **2024**, *6*, 1384495. [CrossRef]
43. Doyeni, M.O.; Stulpinaite, U.; Baksinskaite, A.; Suproniene, S.; Tilvikiene, V. The Effectiveness of Digestate Use for Fertilization in an Agricultural Cropping System. *Plants* **2021**, *10*, 1734. [CrossRef]
44. Czekała, W.; Nowak, M.; Piechota, G. Sustainable Management and Recycling of Anaerobic Digestate Solid Fraction by Composting: A Review. *Bioresour. Technol.* **2023**, *375*, 128813. [CrossRef]
45. Guerra-Gorostegi, N.; González, D.; Puyuelo, B.; Ovejero, J.; Colón, J.; Gabriel, D.; Sánchez, A.; Ponsá, S. Biomass Fuel Production from Cellulosic Sludge through Biodrying: Aeration Strategies, Quality of End-Products, Gaseous Emissions and Techno-Economic Assessment. *Waste Manag.* **2021**, *126*, 487–496. [CrossRef]

46. Fu, S.F.; Wang, D.H.; Xie, Z.; Zou, H.; Zheng, Y. Producing Insect Protein from Food Waste Digestate via Black Soldier Fly Larvae Cultivation: A Promising Choice for Digestate Disposal. *Sci. Total Environ.* **2022**, *830*, 154654. [CrossRef]
47. Cucina, M.; Castro, L.; Font-Pomarol, J.; Escalante, H.; Muñoz-Muñoz, A.; Ferrer, I.; Garfí, M. Vermifiltration as a Green Solution to Promote Digestate Reuse in Agriculture in Small-Scale Farms. *J. Environ. Manag.* **2024**, *368*, 122164. [CrossRef]
48. Fornito, S.; Puliga, F.; Leonardi, P.; Di Foggia, M.; Zambonelli, A.; Francioso, O. Degradative Ability of Mushrooms Cultivated on Corn Silage Digestate. *Molecules* **2020**, *25*, 3020. [CrossRef] [PubMed]
49. Zhong, Y.; Ruan, Z.; Zhong, Y.; Archer, S.; Liu, Y.; Liao, W. A Self-Sustaining Advanced Lignocellulosic Biofuel Production by Integration of Anaerobic Digestion and Aerobic Fungal Fermentation. *Bioresour. Technol.* **2015**, *179*, 173–179. [CrossRef] [PubMed]
50. Monlau, F.; Sambusiti, C.; Ficara, E.; Aboulkas, A.; Barakat, A.; Carrère, H. New Opportunities for Agricultural Digestate Valorization: Current Situation and Perspectives. *Energy Environ. Sci.* **2015**, *8*, 2600–2621. [CrossRef]
51. Xia, A.; Murphy, J.D. Microalgal Cultivation in Treating Liquid Digestate from Biogas Systems. *Trends Biotechnol.* **2016**, *34*, 264–275. [CrossRef]
52. Rodríguez, P.; Cerda, A.; Font, X.; Sánchez, A.; Artola, A. Valorisation of Biowaste Digestate through Solid State Fermentation to Produce Biopesticides from *Bacillus thuringiensis*. *Waste Manag.* **2019**, *93*, 63–71. [CrossRef]
53. Molina-Peñate, E.; del Carmen Vargas-García, M.; Artola, A.; Sánchez, A. Filling in the Gaps in Biowaste Biorefineries: The Use of the Solid Residue after Enzymatic Hydrolysis for the Production of Biopesticides through Solid-State Fermentation. *Waste Manag.* **2023**, *161*, 92–103. [CrossRef]
54. Czekała, W. Solid Fraction of Digestate from Biogas Plant as a Material for Pellets Production. *Energies* **2021**, *14*, 5034. [CrossRef]
55. Hölker, U.; Lenz, J. Solid-State Fermentation—Are There Any Biotechnological Advantages? *Curr. Opin. Microbiol.* **2005**, *8*, 301–306. [CrossRef]
56. Escamilla-Alvarado, C.; Pérez-Pimienta, J.A.; Ponce-Noyola, T.; Poggi-Varaldo, H.M. An Overview of the Enzyme Potential in Bioenergy-Producing Biorefineries. *J. Chem. Technol. Biotechnol.* **2017**, *92*, 906–924. [CrossRef]
57. Chablé-Villacis, R.; Olguin-Maciel, E.; Toledano-Thompson, T.; Alzate-Gaviria, L.; Ruiz, H.A.; Tapia-Tussell, R. Enzymatic Hydrolysis Assisted with Ligninocellulolytic Enzymes from *Trametes hirsuta* Produced by Pineapple Leaf Waste Bioconversion in Solid-State Fermentation. *Biomass Convers. Biorefinery* **2023**, *13*, 9095–9106. [CrossRef]
58. Zou, L.; Qi, Z.; Cheng, H.; Yu, B.; Li, Y.Y.; Liu, J. Advanced Anaerobic Digestion of Household Food Waste Pretreated by in Situ-Produced Mixed Enzymes via Solid-State Fermentation: Feasibility and Application Perspectives. *Environ. Res.* **2024**, *252*, 119137. [CrossRef] [PubMed]
59. Mejias, L.; Ruiz, D.; Molina-Peñate, E.; Barrena, R.; Gea, T. *Bacillus thuringiensis* Derived Biopesticides from Biowaste Digestate at 290-L Demonstration Scale through Solid-State Fermentation. *Environ. Technol. Innov.* **2025**, *37*, 103974. [CrossRef]
60. Alias, C.; Bulgari, D.; Gobbi, E. It Works! Organic-Waste-Assisted *Trichoderma* spp. Solid-State Fermentation on Agricultural Digestate. *Microorganisms* **2022**, *10*, 164. [CrossRef] [PubMed]
61. Knesebeck, M.; Schäfer, D.; Schmitz, K.; Rüllke, M.; Benz, J.P.; Weuster-Botz, D. Enzymatic One-Pot Hydrolysis of Extracted Sugar Beet Press Pulp after Solid-State Fermentation with an Engineered *Aspergillus niger* Strain. *Fermentation* **2023**, *9*, 582. [CrossRef]
62. de Moura Dickel, J.D.; Carvalho, J.K.; Silveira, M.A.D.; Menegotto dos Santos, P.; Rodrigues, M.L.F.; Fagundes-Klen, M.R.; Rosa, C.A.; Johann, S.; Buzanello, C.V.; da Silva de Lucca, R.A.; et al. *Aspergillus sclerotiorum* Lipolytic Activity and Its Application in Bioremediation of High-Fat Dairy Wastewater Environments. *Environ. Sci. Pollut. Res.* **2023**, *30*, 35517–35527. [CrossRef]
63. Solano Porras, R.C.; Ghoreishi, G.; Sánchez, A.; Barrena, R.; Font, X.; Ballardo, C.; Artola, A. Solid-State Fermentation of Green Waste for the Production of Biostimulants to Enhance Lettuce (*Lactuca sativa* L.) Cultivation under Water Stress: Closing the Organic Waste Cycle. *Chemosphere* **2025**, *370*, 143919. [CrossRef]
64. Sala, A.; Artola, A.; Barrena, R.; Sánchez, A. Harnessing Packed-Bed Bioreactors' Potential in Solid-State Fermentation: The Case of *Beauveria bassiana* Conidia Production. *Fermentation* **2024**, *10*, 481. [CrossRef]
65. Yu, S.; Dong, H. Uncover Cost-Benefit Disparity of Municipal Solid Waste Incineration in Chinese Provinces. *Sustainability* **2020**, *12*, 697. [CrossRef]
66. AlMokmesh, S.F.; AlKhulaifi, K.A.; AlMutairi, A.S.; Al-Ajmi, A.S. Incineration Innovation: A Path to Efficient and Sustainable Municipal Solid Waste Management in Kuwait. *Processes* **2024**, *12*, 1873. [CrossRef]
67. Prajapati, P.; Varjani, S.; Singhania, R.R.; Patel, A.K.; Awasthi, M.K.; Sindhu, R.; Zhang, Z.; Binod, P.; Awasthi, S.K.; Chaturvedi, P. Critical Review on Technological Advancements for Effective Waste Management of Municipal Solid Waste—Updates and Way Forward. *Environ. Technol. Innov.* **2021**, *23*, 101749. [CrossRef]
68. Pecchi, M.; Baratieri, M. Coupling Anaerobic Digestion with Gasification, Pyrolysis or Hydrothermal Carbonization: A Review. *Renew. Sustain. Energy Rev.* **2019**, *105*, 462–475. [CrossRef]
69. Altıkat, A.; Alma, M.H.; Altıkat, A.; Bilgili, M.E.; Altıkat, S. A Comprehensive Study of Biochar Yield and Quality Concerning Pyrolysis Conditions: A Multifaceted Approach. *Sustainability* **2024**, *16*, 937. [CrossRef]
70. Salma, A.; Fryda, L.; Djelal, H. Biochar: A Key Player in Carbon Credits and Climate Mitigation. *Resources* **2024**, *13*, 31. [CrossRef]

71. Deng, X.; Teng, F.; Chen, M.; Du, Z.; Wang, B.; Li, R.; Wang, P. Exploring Negative Emission Potential of Biochar to Achieve Carbon Neutrality Goal in China. *Nat. Commun.* **2024**, *15*, 1085. [CrossRef] [PubMed]
72. International Biochar Initiative (IBI). Why Biochar. Available online: https://biochar-international.org/why-biochar/ (accessed on 20 October 2024).
73. Elnour, A.Y.; Alghyamah, A.A.; Shaikh, H.M.; Poulose, A.M.; Al-Zahrani, S.M.; Anis, A.; Al-Wabel, M.I. Effect of Pyrolysis Temperature on Biochar Microstructural Evolution, Physicochemical Characteristics, and Its Influence on Biochar/Polypropylene Composites. *Appl. Sci.* **2019**, *9*, 1149. [CrossRef]
74. García-Prats, M.; Olivera-Begué, E.; González, D.; Sánchez, A. Biochar: An Emerging Material for the Improvement of Biological Treatment of Organic Waste. *Waste Manag. Bull.* **2024**, *2*, 120–126. [CrossRef]
75. Chiappero, M.; Norouzi, O.; Hu, M.; Demichelis, F.; Berruti, F.; Di Maria, F.; Mašek, O.; Fiore, S. Review of Biochar Role as Additive in Anaerobic Digestion Processes. *Renew. Sustain. Energy Rev.* **2020**, *131*, 110037. [CrossRef]
76. Nie, W.; He, S.; Lin, Y.; Cheng, J.J.; Yang, C. Functional Biochar in Enhanced Anaerobic Digestion: Synthesis, Performances, and Mechanisms. *Sci. Total Environ.* **2024**, *906*, 167681. [CrossRef] [PubMed]
77. Kumar, M.; Dutta, S.; You, S.; Luo, G.; Zhang, S.; Show, P.L.; Sawarkar, A.D.; Singh, L.; Tsang, D.C.W. A Critical Review on Biochar for Enhancing Biogas Production from Anaerobic Digestion of Food Waste and Sludge. *J. Clean. Prod.* **2021**, *305*, 127143. [CrossRef]
78. Masebinu, S.O.; Akinlabi, E.T.; Muzenda, E.; Aboyade, A.O. A Review of Biochar Properties and Their Roles in Mitigating Challenges with Anaerobic Digestion. *Renew. Sustain. Energy Rev.* **2019**, *103*, 291–307. [CrossRef]
79. Wang, Y.; Akdeniz, N. Mathematical Modeling of Biochar's Role in Elevating Co-Composted Poultry Carcass Temperatures. *Waste Manag.* **2024**, *173*, 40–50. [CrossRef]
80. Firmino, M.V.; Trémier, A. Investigation of Biochar Ratio, Pyrolysis Temperature and Digestate Type Impact Over Nitrogen Losses Along Digestate Composting. *Waste Biomass Valori.* **2024**, *15*, 4807–4821. [CrossRef]
81. Hestrin, R.; Enders, A.; Lehmann, J. Ammonia Volatilization from Composting with Oxidized Biochar. *J. Environ. Qual.* **2020**, *49*, 1690–1702. [CrossRef]
82. Pagans, E.; Barrena, R.; Font, X.; Sánchez, A. Ammonia Emissions from the Composting of Different Organic Wastes. Dependency on Process Temperature. *Chemosphere* **2006**, *62*, 1534–1542. [CrossRef]
83. Barrena, R.; Canovas, C.; Sánchez, A. Prediction of Temperature and Thermal Inertia Effect in the Maturation Stage and Stockpiling of a Large Composting Mass. *Waste Manag.* **2006**, *26*, 953–959. [CrossRef]
84. Nguyen, M.K.; Lin, C.; Hoang, H.G.; Sanderson, P.; Dang, B.T.; Bui, X.T.; Nguyen, N.S.H.; Vo, D.V.N.; Tran, H.T. Evaluate the Role of Biochar during the Organic Waste Composting Process: A Critical Review. *Chemosphere* **2022**, *299*, 134488. [CrossRef]
85. González, D.; Colón, J.; Sánchez, A.; Gabriel, D. A Systematic Study on the VOCs Characterization and Odour Emissions in a Full-Scale Sewage Sludge Composting Plant. *J. Hazar. Mat.* **2019**, *373*, 733–740. [CrossRef]
86. Sánchez-Monedero, M.A.; Sánchez-García, M.; Alburquerque, J.A.; Cayuela, M.L. Biochar Reduces Volatile Organic Compounds Generated during Chicken Manure Composting. *Bioresour. Technol.* **2019**, *288*, 121584. [CrossRef]
87. Abdallah, M.; Abu Talib, M.; Feroz, S.; Nasir, Q.; Abdalla, H.; Mahfood, B. Artificial Intelligence Applications in Solid Waste Management: A Systematic Research Review. *Waste Manag.* **2020**, *109*, 231–246. [CrossRef] [PubMed]
88. Olawade, D.B.; Fapohunda, O.; Wada, O.Z.; Usman, S.O.; Ige, A.O.; Ajisafe, O.; Oladapo, B.I. Smart Waste Management: A Paradigm Shift Enabled by Artificial Intelligence. *Waste Manag. Bull.* **2024**, *2*, 244–263. [CrossRef]
89. Pinhal Luqueci Thomaz, I.; Fernando Mahler, C.; Pereira Calôba, L. Artificial Intelligence (AI) Applied to Waste Management: A Contingency Measure to Fill out the Lack of Information Resulting from Restrictions on Field Sampling. *Waste Manag. Bull.* **2023**, *1*, 11–17. [CrossRef]