applied sciences

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Review

Digestate Quality Originating from Kitchen Waste

Joanna Mioduska *, **Aleksandra Grabowiec** and **Jan Hupka**

Department of Process Engineering and Chemical Technology, Faculty of Chemistry,
Gdansk University of Technology, Narutowicza 11/12, 80–233 Gdansk, Poland;
aleksandra.grabowiec@pg.edu.pl (A.G.); jan.hupka@pg.edu.pl (J.H.)
* Correspondence: joanna.mioduska@pg.edu.pl

Abstract: This paper examines the influence of biomass directed to anaerobic digestion on the quality of digestate, specifically focusing on the presence of undesirable substances, such as plastics, including biodegradable ones. It analyses the susceptibility of selected bioplastics to degradation and addresses the problem of reliable identification of microplastics in both feedstock—directed to anaerobic digestion—and produced digestate. The review indicates the advantages of using kitchen waste as a feedstock for anaerobic digestion. The constant availability of kitchen waste as a raw material, its homogeneous composition, and the fact that it is not subjected to seasonal fluctuations, facilitates its management in the anaerobic digestion process. However, to ensure the desired quality of a digestate, it is important to carry the selective collection of waste at the source. The review refers to the issues of quality, materials, and regulations, and it may be useful for readers entering the subject of a material loop, as well as those already involved in the subject, including local government units. Anaerobic digestion of kitchen waste is an important part of a renewable economy, providing year-round constantly available substrate for energy production that is not seasonally dependent.

Keywords: anaerobic digestion; digestate; feedstock; kitchen waste; product function category; component material category; microplastics; circular economy

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Citation: Mioduska, J.; Grabowiec, A.; Hupka, J. Digestate Quality Originating from Kitchen Waste. *Appl. Sci.* **2023**, *13*, 10353. https://doi.org/10.3390/app131810353

Academic Editor: Ramaraj Boopathy

Received: 28 July 2023
Revised: 8 September 2023
Accepted: 14 September 2023
Published: 15 September 2023

1. Introduction

Digestate is a stabilised residue and by-product from the methane fermentation process—i.e., the process of microbiological decomposition of organic waste, which is one of the methods of neutralising biowaste in anaerobic conditions with simultaneous production of biogas. Biogas plants process food waste from the agricultural industry or organic fraction of municipal solid waste (OFMSW), preferably selectively collected kitchen waste.

The OFMSW is a heterogeneous mixture of an organic fraction contained in biowaste that includes food waste and kitchen waste, as well as brushes, leaves, grass, and other season-dependent yard waste [1]. It is derived from municipal waste and is most often selected at the source. In turn, kitchen waste is generally defined as leftovers from kitchen activities, such as peels, rinds, and other scraps from food processing produced in households. The morphology of kitchen waste is more homogeneous and less seasonal than OFMSW, making it a suitable substrate for anaerobic digestion [2], with high certainty that there will be no shortage of feedstock.

After the anaerobic digestion (AD) process, the nutrients present in the reactor feedstock are converted into more easily assimilable forms for plants [3]. The resulting digestate is, therefore, a material rich in organic matter, as well as mineral compounds, including so-called 'primary macronutrients': nitrogen, phosphorus, and potassium, and 'secondary macronutrients': calcium, magnesium, sodium, and sulphur [4]. A valued raw material for agriculture is created as a by-product [5], which after further processing can be used for nutrient enrichment and as a soil texture improver or fertiliser.

According to the currently promoted European Union (EU) policy, organic fertilisers, which include digestate, have the potential to initiate changes in the modern agricultural and farming sector, as they are a good and sustainable alternative to traditional mineral fertilisers. Fertilisers from digestate provide nutrients to plants or fungi. Their application is also in line with the assumptions of the circular economy since digestate may enrich the soil on which new food products will grow. These will eventually end up as substrates for anaerobic digestion, and hence nutrients will be allowed to be recycled and the loop will be closed.

Digestate usage provides both economic and environmental added value. The treatment of selectively collected organic fractions in the anaerobic digestion process reduces the amount going to landfill. This is relevant concerning current EU objectives, which state that by the year 2023, only 10% of all municipal waste produced can be disposed of in landfills (EC, 1999), 65% of MSW must be recycled, and biowaste will have to be collected separately [6]. Additionally, the EU Fertiliser Product Regulation, which entered into force in 2022, creates conditions conducive to the use of digestate [4].

The management of digestate is important not only in the environmental dimension but also from the economic and social point of view. The recently observed economic slowdown, as well as the increase in gas prices, which translated into an increase in fertiliser prices, and their limited or even suspended production, which temporarily took place in 2022, further support the need for the widespread use of digestate as an alternative source of fertiliser.

It is estimated that over 500 kg [7] of municipal waste per person is produced annually in the EU, of which approximately 34% is the so-called biowaste, including waste from gardens and parks, as well as kitchen waste from individuals, but also from offices, restaurants, wholesales, canteens, and retail premises [8]. In the European Union area, up to 60% of the overall municipal biowaste is comprised of food waste from households, general kitchen waste, and that from the retail sector [9]. In 2020, the European Union inhabitants produced on average up to 70 kg of food waste in their households [10].

The requirements for EU countries to limit waste landfilling and the ways of managing bio-waste and related by-products, such as digestate, will be discussed increasingly more often. The attention will concern both the implementation of the circular economy assumptions, as well as ensuring the security of food production by becoming independent from external suppliers of fertilisers for the agricultural sector and individual recipients. The use of digestate in agriculture is also an advantage that comes from limiting the use of phosphate rock, which has been classified by the European Commission as a critical raw material [11].

The amounts of kitchen waste will remain at a high level, and it is a good time for further development of waste-to-energy processes, particularly biowaste-to-energy, considering the safe and reasonable management of the by-products, i.e., digestate from selected municipal kitchen waste.

2. The Quality of Digestate

The quality of feedstock determines the quality of a digestate. It should be properly collected and sorted to ensure a safe and usable composition. Studies confirm that the quality and safety of digestate are closely related to the quality of the material directed to the methane fermentation process, which determines the applicability and profitability of digestate [12–15].

It is advantageous when the digestate comes from biogas plants that operate based on material from the agri-food industry, to which the feedstock is supplied by specific companies, in the form of, e.g., residues from filtration and extraction processes, such as whey or fruit pulp. The feedstock from such plants is most often better than non-homogeneous feed from selected municipal waste because it is known, repeatable, and free of undesirable contaminants. Thus, the biogas plant can achieve higher and predicted efficiency of methane production, and the waste itself in the form of digestate will more reliably meet the standards and legal requirements in terms of safety of further use. The downside limiting the use of raw materials from the agri-food industry, especially in the case of fruit and vegetables, is their seasonality. In turn, the selectively collected at-source kitchen waste is not subjected to seasonal fluctuations and also has a homogeneous composition. Those properties make feedstock pretreatment not a critical issue, and kitchen waste is an attractive feedstock for large and regional biogas plants.

Undesirable substances negatively affecting quality should be considered both in terms of presence in the process input and unwanted residue in the post-fermentation mass. They might reduce the efficiency of the methane fermentation process and biogas production, or not react and end up in the post-fermentation material, limiting the possibility of digestate further use as a valuable material in fertilisation or making it unsuitable for further use at all. On the one hand, these will be substances that are toxic to microorganisms involved in the AD process, e.g., antibiotics or other toxins, and on the other, substances that pose a threat if further used in the environment, i.e., pathogens, heavy metals, plastics, and other foreign solids such as metals or glass particles [16–18].

In the case of delivering food waste to a biogas plant, an effective automated depackaging system is needed in order to ensure that pieces from packaging will not contaminate feedstock. In the case of kitchen waste, the situation is simpler, because the waste collected from households most often is contained in one package. In addition, depending on the regulations that are in force in each country or region, waste can be collected into paper bags or so-called crafted bags instead of traditional plastic ones. Crafted bags are gaining in popularity, especially in regions where it is estimated that kitchen waste will end up in industrial composting plants. Examples are Mater-Bi® (Novamont S.p.A., Novara, Italy) or Ecopond® (Kingfa Sci. and Tech. Co., Ltd., Guangdong, China) bioplastic materials, which according to the information on the packaging are 'commercially compostable'.

Generally, it could be assumed that the digestate from the anaerobic digestion process, in which an organic fraction selected from municipal waste is used as a reactor feedstock, will require additional processing to meet the quality requirements for further use in agriculture. The main limitation may be the presence of undesirable substances and those whose fate in the process is not fully investigated. In this regard, one of the solutions is to study how to increase and control the degradation efficiency of biodegradable plastics. A team from the University of California, Berkeley, and Lawrence Berkeley National Laboratory is working on a solution to prevent the forming of microplastics from biodegradable plastics by adding small amounts of appropriate enzymes and components to polylactic acid and polycaprolactone [19,20]. This makes the materials compact, less susceptible to fragmentation, and easier to identify and remove. The addition of single enzymes causes degradation to occur at the ends of molecular chains, thus cutting off each link in the chain and preventing the formation of microplastics. At the same time, the goal of easy degradation under an elevated temperature or by water immersion conditions is achieved. Therefore, there is a chance that if we manage to increase the scale of these types of experiments, the safety of using digestate will increase, thus more easily meeting agricultural and legal requirements.

3. Conventional and Biodegradable Plastics

The main contaminants entering the AD process along with kitchen waste are plastics, mainly coming from food packaging, which often ends up in the waste stream through negligence, or plastic bags in which waste is most often collected. It is assumed that plastics account for up to 1.5% of food waste in Italy [21]. Also, the results of the morphology studies of food waste delivered to treatment plants in Poland confirm the presence of plastics in the selectively collected fractions of biowaste [22,23]. Therefore, if the untreated biowaste stream is directed to a biogas plant, it is very likely that a digestate produced as a by-product will contain plastics that were not decomposed in the anaerobic digestion process. Other sources of plastic in kitchen waste, which do not necessarily result from carelessness or poor segregation, are stickers on uneaten products, e.g., with a bar code or information about the country of origin, as well as popular tea bags. Both sources consist of small waste, which often ends up in a biowaste stream because of the belief of many people that this is where they should end up. In this regard, an expected change would be the introduction of tea packaging and stickers on food products that degrade through composting and/or AD to eliminate this source of plastic as a contaminant in the kitchen waste stream. In addition, measurable effects could be achieved by an educational campaign on proper waste segregation.

An even greater threat is identified as the presence of plastic wastes smaller than 5 mm, called microplastics, in the environment. Microplastics are problematic because, due to their small size, they are difficult to separate from the rest of the post-fermentation material, as well as from the material entering the reaction chamber in the biogas plant. An additional difficulty is the still missing or expensive methods of identifying microplastics and the lack of appropriate devices to remove this type of contamination, especially in the case of particles below 2 mm. The presence of microplastics in the waste stream directed to the biogas plant results from, among others, the operations to which it is subjected, including those related to tearing the bags containing the waste and shredding the feedstock. It is also considered that microplastic particles can be present within food itself [24]. In addition, there are more warnings about the possibility of further decomposition of microplastics to nano size (nanoplastics), which is supposed to be accumulated in plants through the root system [25]. Therefore, digestate management, having regard to the above, should be well defined in process design to ensure the safety of its use.

Degradation of plastics requires not only the right time but also proper conditions such as pH, temperature, sunlight, and type of environment (water, air, soil). It is known that conditions favourable to degradation will not always occur in the environment where plastic, including biodegradable ones, ends up [26]. In such a situation, it will not easily and completely decompose, but rather it will disintegrate into smaller fragments, known as microplastics.

Another group considered as undesirable in the stream of kitchen waste are bioplastics. According to data presented in a study by the Hochschule Hannover University of Applied Sciences and Arts, the share of biodegradable polymers is increasing in the market; however, by 2025, non-biodegradable bio-based polymers will still constitute around 37% out of 2.91 Mt bioplastics global production capacities [27]. The popularity and production of bioplastics are growing year by year. The problem comes to their handling and is related to the lack of appropriate information indicating which waste stream they should end up in, including biodegradable materials that are used as food packaging. Often, intuition suggests that they should be treated as kitchen waste or plastic, while due to the limitations of the processing capacity of recycling plants, they constitute expensive residual waste, which will probably eventually be incinerated.

The forecasts indicate that not only biodegradable bioplastics will be present in the OFMSW and kitchen streams in the future, but also non-biodegradable bioplastics. Visual distinguishing between these two types of bioplastics is generally impossible, and therefore the knowledge about their fate in the environment and consequently, the chosen method of proceeding and management, i.e., through anaerobic digestion (AD) and composting, is becoming a major issue.

The challenge related to ensuring the quality of the feedstock directed to the AD process is both the identification and assessment of the impact of the presence of biodegradable plastic materials in kitchen waste on their fate in the process and further on the consequences of their presence in the digestate. Most commonly, biodegradable plastics are designed to break down under industrial aerobic conditions. Due to their appearance, they often end up in the stream of traditional plastic waste, or due to the description informing about their susceptibility to decomposition, they are thrown into biowaste. Currently, there are no uniform guidelines in the EU regarding the correct handling of this type of waste.

In addition, as in the case of the traditional source of microplastics in nature, there are increasingly more articles informing about the emerging microplastics originating from bioplastics. In particular, scientists warn about the low degradation rate of biodegradable plastics and the possibility of creating microplastics also from biodegradable plastics, which can therefore pose an equally great threat to the environment [28–32]. Cut fragments of plastics are formed, being not necessarily easy to decompose and moreover difficult to identify and further remove. Such a material should degrade directly without fragmenting. The assumption of introducing biodegradable plastics to the market was their simple decomposition into carbon dioxide and valuable biomass [33], but research shows that this is not always the case, since exact conditions and time are needed for each compound to degrade [34,35].

In this regard, attention should be paid to the need for a reliable assessment of the usefulness of biodegradable plastics in the food packaging industry, which may further affect the composition of kitchen waste. On the one hand, paying attention to the quality of the material and, on the other, to the method of appropriate management—aerobic or anaerobic—should be specified by the manufacturer placing the material on the market.

4. Susceptibility of Selected Bioplastics to Degradation

It is generally believed that the intention of introducing bioplastics to the market was their susceptibility to relatively rapid decomposition, while in the case of bioplastics, it is a major simplification of their definition, as it does not apply to all materials referred to by this name. Bioplastics are often mistakenly treated as biodegradable, but it should be emphasised that this is not the rule and there are both biodegradable and non-biodegradable bioplastics [36]. The prefix bio- means that instead of fossil fuels, renewable sources, mainly plants, were used to produce the polymer.

Figure 1 shows the types of plastics with the source of origin and susceptibility to degradation.

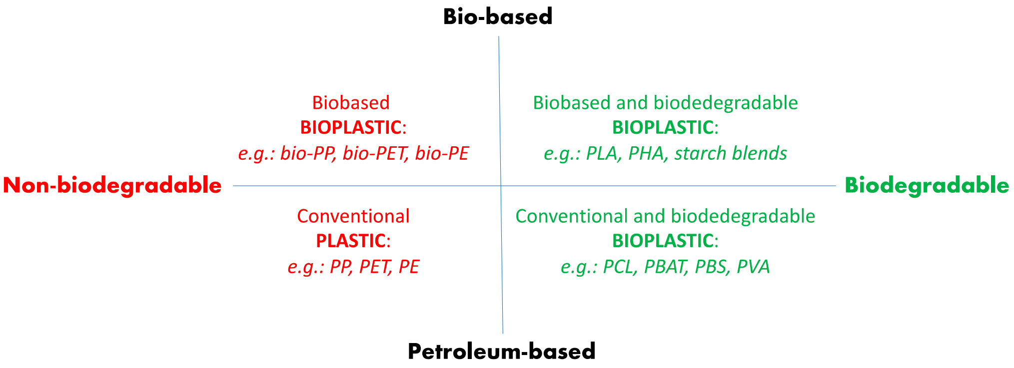

Figure 1. Types of plastics concerning the source of origin and susceptibility to degradation. Green highlights represent biodegradable plastics, while red highlights indicate non-biodegradable ones [37].

Plastic is considered biodegradable if it is mineralised in the environment by naturally occurring microorganisms such as bacteria, fungi, yeast, or algae. The biodegradation process undergoes three stages: biodeterioration—involving physical and chemical actions leading to physical degradation, biofragmentation—with the appearance of oligomers more easily degraded by enzymes, and final microbial assimilation followed by mineralisation—where formed monomers are assimilated by microorganisms with simultaneous production of metabolites: CO_2, CH_4, and H_2O [26,38].

The most popular synthetic biodegradable plastic on the market is currently polylactide (PLA), which, among others, has been approved for contact with food [39], and it is widely used in 3D printers [40,41]. PLA and other, biodegradable plastics, including biocomposites, often contain additives that may change the properties of the plastic and change its susceptibility to degradation [26,42,43].

The form in which a given plastic occurs is also of importance when assessing the susceptibility to biodegradation. Shopping bags are made of much thinner materials than, for example, a food tray, cup, or straw. It can be expected that products made of thicker materials will take longer to completely degrade, and if placed in unfavourable conditions, may become similar pollution as traditional plastic.

In the AD process, the fate of bioplastics, including biodegradable ones, requires further elucidation research. An increasing number of studies indicate the persistence of this type of material to decompose in anaerobic conditions (Table 1).

Table 1. Susceptibility of selected biodegradable materials to anaerobic degradation.

No	Type of Material/ Environment	Observation	Ref.
1	Polylactic acid—(PLA) / Water solutions with adjusted pH (NaOH, HCl)	Influence of PLA pre-treatment on biogas yield and solid reduction. Alkaline treatment enhanced PLA solubilisation, up to 97–99% weight loss after a 15-day incubation period. Untreated PLA revealed only 54% weight loss.	[44]
2	Starch-based shopping bags (SBSB) and polylactic acid (PLA) tableware / Pilot-scale dry mesophilic anaerobic digestion (35 days), composting (58 °C, 90 days)	Degradation rate after: - anaerobic digestion: SBSB at around 30%, PLA at around 4%, - composting: SBSB at around 48%, PLA at around 15%. Predicted complete degradation: SBSB—1.6 years, PLA—7.2 years.	[45]
3	PBAT/PLA bags / Mesophilic and thermophilic AD, 44 days	Mesophilic AD: - no visible change or damage of plastic films. Thermophilic AD: - physical disintegration was observed.	[46]
4	PLA bio-based foil / Mesophilic AD (37 °C, 1 year), OxiTop system	- Water diffusing into the structure was observed. - Minor structural changes and pores observed under 1000-fold microscope magnification.	[47]

The scientific reports collected in Table 1 confirm the presence of plastics in biowaste after anaerobic reduction processes. The experiments present low susceptibility of biodegradable plastics to degradation under anaerobic conditions. Simultaneously, there are also single studies in which bioplastic residues after anaerobic digestion, in the case of transferring them to the soil, revealed a positive effect on inhibiting the activity of pathogenic bacteria [48]. In this respect, it is rational to continue the study of the fate of individual bioplastics and be attentive to their handling, so as not to make them as persistent waste as their conventional originals.

Table 2 contains examples determining the susceptibility of selected bioplastics to degradation under aerobic conditions.

Bioplastics considered biodegradable need adequate time for complete degradation, which is not always possible, especially in industrial conditions. The definition of biodegradability itself does not indicate a time frame. Moreover, new scientific results suggest microplastics from biodegradable plastics can be created at a faster rate than would be the case with conventional oil-based plastics [53–55], which confirms the need for a thorough examination of bioplastics' fate in the environment. In the case of bioplastics not regarded as biodegradable, their properties and performance will be similar to their conventional alternatives [56]. Concerning the above, it seems that a safe solution in the case of collecting kitchen waste intended for anaerobic digestion, not composting, is to use bags from conventional plastics, which will not uncontrollably degrade into microplastics before the waste is removed from them.

Table 2. Susceptibility of selected biodegradable materials to aerobic degradation.

No	Type of Material/ Environment	Observation	Ref.
1	Plastic mulch / Compost and agricultural soils at warm and cool climate	18-week experiments in compost gave surface area reduction between 85 and 99%. 36-month experiments in soil gave surface reduction results that ranged varying on area and climate type, between 26 and 83%. Faster degradation was observed in compost, while it was concluded that mulch fragments in soil may not degrade for many years.	[49]
2	PLA based green biocomposite: - neat PLA (NPLA) - PLA/cellulose nanocrystal (CNC) - PLA/gum arabic - PLA/chitosan / Food waste compost–thermophilic conditions without external inoculum	Biodegradation tests were carried out per ASTM D5338–15 standard, concerning the amount of CO_2 produced. The experiments revealed around 90% degradation within 37 days. 110 days exposure resulted in the following degradation trend: PLA/chitosan (around 95%) > NPLA (around 90%) > PLA/CNC (around 82%) > PLA/gum arabic (around 71%).	[50]
3	Plastic films: PBAT- polybutylene co-adipate co-terephthalate / PLA/PHA–polylactic acid/poly-hydroxy−alkanoate / Material placed in a mesh-bag and buried in the compost	18-week composting resulted in 99% macroscopic degradation of PLA/PHA and 97% of PBAT. Simultaneously, the release of micro- and nanoparticles from biodegradable films was observed.	[51]
4	PCL—polycaprolactone, PHB—polyhydroxybutyrate (PHB), PLA, PBS—poly(1,4 butylene) succinate / Soil and compost, up to 21 months, varying temperatures, additionally soil with uncontrolled—environmental conditions	The temperature was recognised as a major factor influencing degradation rate and efficiency. Higher temperature contributed to greater weight loss. In compost: PCL: 100% degradation was observed within 91 days, at 50 °C. PLA: 275 days were needed for 100% degradation at 50 °C. At lower temperatures, no material weight loss was observed. PHB: similar degradation trend was observed at varying temperatures. ≈275 days resulted in degradation of around 96% at 50 °C, around 80% at 37 °C, and around 60% at 25 °C. PBS: ≈275 days resulted in degradation of around 60% at 50 °C, and at lower temperatures no higher than 10%. In soil: PCL: regardless of the temperature (25–37 °C), more than 50% weight loss was observed after around 275 days of the experiment. PLA: did not degrade in soil. PHB: after around 275 days, 30% weight loss was observed at 25 °C, and more than 60% at 37 °C. PBS: negligible weight loss was observed at 25 °C, and less than 50% at 37 °C.	[52]

Another example of proceeding in the case of low susceptibility of biodegradable bioplastics to AD is the digestate treatment through aerobic stabilisation—composting. The selected data collected in Table 2 confirm the greater susceptibility of biodegradable plastics to aerobic degradation, but also in this case the process has to be carefully planned, as not all bioplastics which are biodegradable are compostable.

5. The Challenge of Microplastics' Determination

The problem of biodegradable waste management is largely due to the lack of regulations and guidelines related to their sorting. Thus, quality control of the bioreactor feedstock becomes more demanding, and the process itself becomes less controllable. Not all sorting technologies incorporate tools for identifying biodegradable plastics, nor for detecting the presence of microplastics, especially if smaller than 2 mm, resulting in the presence of microplastics after the mechanical biological treatment process, in compost or digestate [12,57–59]. One of the reasons for this situation is certainly the costs, and the other is technical difficulties regarding the applicable method of identifying bioplastics, particularly in real time.

There are four major means of identifying microplastics below 2 mm: microscopic, spectroscopic, thermoanalytical, chemical methods, or a combination thereof. These methods have high efficiency in detecting microplastics. FTIR spectroscopy reaches detection limits of down to 20 μm, while Raman microspectroscopy can identify particles down to 1 μm in size [57,60]. Pyrolysis GC-MS allows the plastic types of particles > 100 μm to be identified [61], from complex matrices and mixtures [62], while the ATR-FTIR was proven to be efficient for the identification of larger particles (>500 μm) [63,64]. To analyse smaller particles, ATR-FTIR coupled with a microscope (μ-ATR-FTIR) is recommended [65].

The methods used to identify microplastics are effective, but costly, especially regarding process scale-up. In addition, the identification of microplastics is used more often to assess microplastic release from fabrics [66] to identify the presence in water samples [67], beach sand [68], marine bottom sediments [69], or aquatic organisms [70], so in relatively clean matrices. In turn, the identification of microplastics in waste management processes is not a common practice, especially as a continuous operation. In the case of an increase in the share of bioplastics in biowaste, the challenge will be to improve the methods of cleaning the feedstock from plastic impurities. It is necessary to consider either efficient identification and further separation or conscious leaving of selected compostable materials susceptible to AD decomposition in a specific plant and process. Studies show that various biodegradable materials, e.g., polylactic acid (PLA) and poly-hydroxy−alkanoate (PHA), have different degradation times and methane-generating potential [21,71]; therefore, the decision to leave these compounds in the feedstock should depend on individually selected bioreactor operating conditions and eventual type of pre-treatment used.

On the other hand, a complex matrix of a digestate, and the uncertainty regarding the amount of microplastics, should be considered before either digestate is rejected or not from agriculture applications. The reliability of analytical methods in the case of complex matrices is lower, and therefore the decision on the quality requires more care, whether it refers to the input or output materials.

6. Quality Concerns—Regulations

In the stream of kitchen waste, we can expect the presence of biodegradable materials used as food packaging, including those in which ready-made food is portioned or nets in which we place products when shopping. This type of packaging very often intuitively goes to the OFMSW as waste. In the EU, you can find bags with a special 'commercially compostable' mark, which are made of 'biodegradable material designed to contain organic waste'.

Organic recycling of packaging and packaging materials allows for both aerobic composting and anaerobic bio-gasification conditions in municipal or industrial installations for biological waste treatment. This is the result of the implementation of the EN 13432:2000 standard, which, by the Decision of the European Commission 2001/524/EC, has been recognised as harmonised with Directive 94/62/EC. For example, for products to be labelled as 'commercially compostable', they must pass the appropriate certification system following the standard. Products of aerobic and anaerobic organic recycling contain valuable nutrients, so per the principle of sustainable development, they should be managed in the best possible way in the environment. One possibility is to use them as soil improvers and fertilisers. However, for this to happen, they must undergo several refining processes and tests that will ensure their safe use.

In 2019, the European Commission published Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products, amending Regulations (EC) No. 1069/2009 and (EC) No. 1107/2009 and repealing Regulation (EC) No. 2003/2003. Consequently, the Fertilising Product Regulations (EU) 2019/1009 came into force on 16 July 2022. Regulation 2019/1009 sets out the provisions that should be met by fertilising products made available on the EU market and indicates the categories of component materials that may form fertilising products. The regulation established the rules for placing on the market organic and mineral fertilisers and agents supporting the cultivation of plants, liming agents, soil improvers, substrates for cultivation, and biostimulants. Some of the substrates for fertilisers introduced in the regulation are categories: CMC3—compost, and CMC5—digestate other than fresh crop digestate.

According to the provisions of Regulation 2019/1009, the presence of physical impurities in the form of plastics larger than 2 mm is allowed. However, the aim is to systematically reduce the permissible limits, set at 2.5 g/kg of dry matter by 2029. Thus, it is possible for the ingredients used in fertiliser products to contain, among others, polymers and certain by-products previously not allowed under Directive 2008/98/EC. Additionally, following the regulation in force, it has become possible to use post-fermentation products that come from biowaste from the selective collection at the source. In mid-2029, again an assessment of the defined limits will be carried out to set new ones based on the progress achieved in the efficiency of the separate collection of organic waste.

In addition, Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018, amending Directive 2008/98/EC on waste, introduced a provision favourable to the Member States, allowing from the beginning of 2027 to count municipal biowaste as recycled waste if they have been separately collected or separated at source and then subjected to aerobic or anaerobic treatment.

In 2019 Amendment to Annex V to EU REACH Regulation (EC) No. 1906/2006 (EU REACH Regulation) was introduced, according to which not only compost and biogas but also digestate are materials exempted from the obligation to register by Article 2(7)(b) of that regulation. It translated into shorter procedures and lower costs related to the use of digestate.

On 23 June 2021, additional Commission Delegated Regulation (EU) 2021/1768 [72] entered into force, adapting to Regulation (EU) 2019/1009 of the European Parliament and the Council, to technical progress, amending Annexes I, II, III, and IV to the regulation of the European Parliament and of the Council (EU) 2019/1009.

In turn, on 5 May 2022, the Commission Delegated Regulation (EU) 2022/1519 was published, amending Regulation (EU) 2019/1009 of the European Parliament and of the Council regarding the requirements applicable to EU fertilising products and further processing of the digestate. The document refers to the need to define the rules for further processing of the post-fermentation product, e.g., the separation of digestate into a solid and liquid fraction. It was noted that Regulation (EU) 2019/1009 should enable producers to further process the fermentation product or its fractions with methods that effectively close the loop of valuable components and nutrients.

Fertilising Product Regulations (FPR) (EU) 2019/1009, among others, define the requirements of CE-marked fertilising products available on the EU market. Compost and digestate as components of fertiliser products may also be present on national markets according to separate regulations that apply in each area, since FPR does not replace national legislation. However, compliance with local marketing regulations does not allow for affixing the CE marking. Member States may have similar but different national rules for fertilising products, and hence its producer's choice to sell the fertiliser as 'EC fertiliser' or 'domestic fertiliser'.

It is worth emphasising that currently there is no regulation imposing an obligation to assess the plastic content in digestate from kitchen waste. In the UK, the related PAS110 regulation has been introduced to certify digestate, covering the identification of physical contaminants such as plastics. However, despite the regulation being in force, there are no corresponding guidelines regarding methods for analysing physical contaminants [73]. Several peer-reviewed scientific papers on plastic content in digestate from biowaste, including kitchen waste, present a wide range of results, varying from 70 to more than 7000 plastic particles per kilogram [12,74–76]. Additionally, some results are presented as a percentage of dry mass per sample [77,77], thus limiting the possibility of unit conversion and comparisons when the size of an impurity is unknown. The lack of standardisation and uniform methods for determining the presence of plastics in digestate from kitchen waste or biowaste poses difficulties in establishing officially applicable safe limits [78]. In this regard, it is likely that in the upcoming years, concerns about the assessment of the risk of plastic debris in digestate from kitchen waste will rise.

7. Digestate as Component Material Category

The European Waste Catalogue (EWC) provides common terminology for generated waste type. In the case of wastes that come from anaerobic treatment processes, three following types can be distinguished [79]:

- 19 06 05 is a liquor from the anaerobic treatment of animal and vegetable waste;
- 19 06 04 is a digestate from the anaerobic treatment of municipal waste;
- 19 06 06 is a digestate from anaerobic treatment of animal and vegetable waste.

The above wastes are considered to be non-hazardous. They can be ceased as waste and become a component material category, such as CMC 5. Further, CMC 5 can make up a product function category (PFC) and gain application in agriculture as

- PFC1—fertiliser: organic, organo-mineral, or inorganic and either solid or liquid;
- PFC3—soil improver: organic or inorganic;
- PFC4—growing medium;
- PFC7—fertilising product blend.

Before being placed on the market, PFCs must be properly tested in terms of quality (minimum content of nutrients and carbon) and safety (heavy metals, pathogens, contaminants, stability) and receive an EU declaration of conformity. Tests are carried out in units with the appropriate authorisation, so-called conformity assessment bodies, which the European Commission assigned as a notified body and provided with an individual identification number for carrying out the conformity assessment of EU fertilising products under Regulation (EU) 2019/1009. Such bodies can evaluate various product types within certain modules, and in the case of CMC 5, mandatory is module D1, for any EU fertilising product, ensuring the compliance of the EU fertilising products with the Fertilising Products Regulation (EU/2019/1009). Module D1 refers to the quality assurance of the production process. The manufacturer is obliged, among others, to prepare technical documentation, which, in addition to a general description of the product and the declared fertilising function, contains a detailed description of the production process, with detailed operations, their location, and the results of testing of input and output material. In turn, the notified body evaluates the quality system introduced by the fertiliser manufacturer as well as its compliance with the requirements and law, and then conducts an audit. Additionally, under the guidelines contained in EC Regulation 2019/1009, each product function category must meet the relevant standards and must not exceed the designated limit values for contaminants, which are presented in the example of selected PFCs in Table 3 [4].

Table 3. Limit values of elements in selected PFCs.

No.	Element	PFC1—Organic	PFC3—Organic	PFC4
		(mg/Dry Matter)		
1	cadmium	1.5	2	1.5
2	hexavalent chromium	2	2	2
3	mercury	1	1	1
4	nickel	50	50	50
5	lead	120	120	120
6	arsenic	40	40	40
7	copper	<300	<300	<300
8	zinc	<800	<800	<800

Following the guidelines of the regulation, pathogens in PFC must not exceed the following limits:

- for five tested samples, *Salmonella* spp. absence in 25 g or 25 mL;
- for five tested samples, *Escherichia coli* or *Enterococcaceae* limit 1000 in 1 g or 1 mL.

Additionally, the PFC guidelines for both liquid and solid states refer to the minimum content of micronutrients (% by mass) as well as minimum levels of nitrogen, phosphorus pentoxide, potassium oxide, and organic carbon.

The European Commission has also requested the European Committee for Standardisation (CEN) to develop applicable standards of EU conformity referring to:

- sampling and sample preparation;
- test methods for the determination of elements (heavy metals and others);
- test methods for the detection of microorganisms.

Consequently, the first technical specifications (TS) appeared in April 2022, and the first harmonised standards are expected to be published in 2024 and 2025.

It is worth pointing out that EU fertilising products may contain digestate that does not meet the national end-of-waste criteria, but it is enough if they comply with the requirements of the CMCs to be placed on the market in any EU country.

EU fertilising products must be safe for humans, animals, plants, and the environment; hence, the aim of the requirements set out in the regulations is to ensure they present no risk. Fertilising products certified with a CE mark will guarantee that they

- meet the requirements for a PFC;
- meet the requirements for a CMC;
- are labelled according to the requirements in FPR;
- pass the Conformity Assessment Procedure.

The Fertilising Product Regulation legalises the further use of digestate in agriculture and sets rules for its quality, including the presence of selected bacteria or upper limit values for elements. However, it does not regulate microplastics' eventual, unintentional presence in PFCs. Instead of being an unofficial consent for microplastic presence in PFCs, this approach may result from doubts while assessing the quality of complex matrices.

Digestate originating from kitchen waste and other municipal organic fractions has two unquestionable benefits. As a product function category, it meets the circular economy expectations and enables for closing the loop of valuable nutrients for the environment.

8. Conclusions

As a main product of the anaerobic digestion process, the use of digestate results from both economic and environmental considerations, especially if it is produced close to the location of future use. Considering sustainable development, the use of digestate is an example of environmental and economic motivation. It is in line with the assumptions that waste should be treated as raw materials that are not wasted but given further utilitarian properties.

The composition of digestate depends on the substrates constituting the input to the biogas plant, therefore following the principle of green chemistry—requiring authorisation of its content—to prevent at the source rather than to deal with the negative effects at further stages of processing. The digestate quality depends on the biomass used as a feedstock. The presence of contaminants such as antibiotics, heavy metals, and other chemicals may be toxic to useful bacteria involved in AD and cause disturbances in the process. Undesired substances in a feedstock may also contribute to limiting the application properties of the digestate. The organic fraction that serves as a substrate for AD can be also contaminated with ubiquitous and emerging concern microplastics and micro-bioplastics.

Organic fertilisers from biowaste fermentation and/or composting may be a neglected source of microplastics in the environment. To secure the appropriate quality input for the AD process, it is certainly necessary to carry out selective collection of biowaste at the source, preferably kitchen waste. In the case of kitchen waste, feed preparation is not a critical issue regarding securing the quality of digestate.

The examination of factors contributing to the effective management of biowaste streams suggests that the success of transforming kitchen waste into energy and valuable products depends on the discipline and involvement of residents into the municipal waste collecting system. Their attitude to a recycling programme will directly affect the quality of the stream from which the digestate used in agriculture will be produced.

Author Contributions: Conceptualisation, J.M.; Writing—Original Draft Preparation, J.M.; Writing—Review and Editing, J.M. and J.H.; Funding Acquisition, J.M., A.G. and J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research leading to these results has received funding from the Norway Grants 2014–2021 via the National Centre for Research and Development.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Paritosh, K.; Yadav, M.; Mathur, S.; Balan, V.; Liao, W.; Pareek, N.; Vivekanand, V. Organic Fraction of Municipal Solid Waste: Overview of Treatment Methodologies to Enhance Anaerobic Biodegradability. *Front. Energy Res.* **2018**, *6*, 75. [CrossRef]
2. Yan, Y.-J.; Li, X.; Lu, C.-S.; Kobayashi, T.; Zhen, G.-Y.; Hu, Y. A Review on Start-Up Phase Optimization of Kitchen Waste Anaerobic Digestion. *Fermentation* **2023**, *9*, 603. [CrossRef]
3. Tambone, F.; Scaglia, B.; D'Imporzano, G.; Schievano, A.; Orzi, V.; Salati, S.; Adani, F. Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost. *Chemosphere* **2010**, *81*, 577–583. [CrossRef] [PubMed]
4. European Parliament, Council of the European Union. Official Journal of the European Union. 2019. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019. Available online: https://eur-lex.europa.eu/eli/reg/2019/1009/oj (accessed on 26 June 2023).
5. Logan, M.; Visvanathan, C. Management strategies for anaerobic digestate of organic fraction of municipal solid waste: Current status and future prospects. *Waste Manag. Res.* **2019**, *37* (Suppl. S1), 27–39. [CrossRef]
6. López-Gómez, J.P.; Latorre-Sánchez, M.; Unger, P.; Schneider, R.; Lozano, C.C.; Venus, J. Assessing the organic fraction of municipal solid wastes for the production of lactic acid. *Biochem. Eng. J.* **2019**, *150*, 107251. [CrossRef]
7. Eurostat. Municipal Waste Statistics, 2021. Municipal Waste Generated 2006–2021. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Municipal_waste_statistics (accessed on 26 June 2023).
8. European Parliament, Council of the European Union. Official Journal of the European Union. 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098&qid=1694764606184 (accessed on 26 June 2023).
9. Publications Office of the European Union. European Environmental Agency, Report No 4/2020. Bio-Waste in Europe—Turning Challenges into Opportunities. 2020. Available online: https://www.eea.europa.eu/publications/bio-waste-in-europe (accessed on 26 June 2023).

10. Eurostat. Food Waste: 127 kg per Inhabitant in the EU in 2020. Available online: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220925-2 (accessed on 29 August 2023).
11. European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs; Blengini, G.; El Latunussa, C.; Eynard, U.; Torres De Matos, C.; Wittmer, D.; Georgitzikis, K.; Pavel, C.; Carrara, S.; Mancini, L.; et al. Study on the EU's List of Critical Raw Materials—Final Report, Publications Office. 2020. Available online: https://data.europa.eu/doi/10.2873/11619 (accessed on 26 June 2023).
12. Weithmann, N.; Möller, J.N.; Löder, M.G.J.; Piehl, S.; Laforsch, C.; Freitag, R. Organic fertilizer as a vehicle for the entry of microplastic into the environment. *Sci. Adv.* **2018**, *4*, eaap8060. [CrossRef]
13. Malhotra, M.; Aboudi, K.; Pisharody, L.; Singh, A.; Banu, J.R.; Bhatia, S.K.; Varjani, S.; Kumar, S.; González-Fernández, C.; Kumar, S.; et al. Biorefinery of anaerobic digestate in a circular bioeconomy: Opportunities, challenges and perspectives. *Renew. Sustain. Energy Rev.* **2022**, *166*, 112642. [CrossRef]
14. Beggio, G.; Schievano, A.; Bonato, T.; Hennebert, P.; Pivato, A. Statistical analysis for the quality assessment of digestates from separately collected organic fraction of municipal solid waste (OFMSW) and agro-industrial feedstock. Should input feedstock to anaerobic digestion determine the legal status of digestate? *Waste Manag.* **2019**, *87*, 546–558. [CrossRef]
15. Knoop, C.; Tietze, M.; Dornack, C.; Raab, T. Fate of nutrients and heavy metals during two-stage digestion and aerobic post-treatment of municipal organic waste. *Bioresour. Technol.* **2018**, *251*, 238–248. [CrossRef]
16. Kupper, T.; Bürge, D.; Bachmann, H.J.; Güsewell, S.; Mayer, J. Heavy metals in source-separated compost and digestates. *Waste Manag.* **2014**, *34*, 867–874. [CrossRef]
17. Lehmann, L.; Bloem, E. Antibiotic residues in substrates and output materials from biogas plants—Implications for agriculture. *Chemosphere* **2021**, *278*, 130425. [CrossRef] [PubMed]
18. Carraturo, F.; Panico, A.; Giordano, A.; Libralato, G.; Aliberti, F.; Galdiero, E.; Guida, M. Hygienic assessment of digestate from a high solids anaerobic co-digestion of sewage sludge with biowaste by testing Salmonella Typhimurium, Escherichia coli and SARS-CoV-2. *Environ. Res.* **2022**, *206*, 112586. [CrossRef] [PubMed]
19. DelRe, C.; Jiang, Y.; Kang, P.; Kwon, J.; Hall, A.; Jayapurna, I.; Ruan, Z.; Ma, L.; Zolkin, K.; Li, T.; et al. Near-complete depolymerization of polyesters with nano-dispersed enzymes. *Nature* **2021**, *592*, 558–563. [CrossRef] [PubMed]
20. Xu, T.; Delre, C.; Kwon, J. Bioactive Plastics with Programmable Degradation and Microplastic Elimination. Global Patent Index EP 4084830 A4, 28 June 2023.
21. U.S. Environmental Protection Agency Office of Research and Development. *Emerging Issues in Food Waste management, Plastic Contamination*; 2019. Available online: https://www.epa.gov/system/files/documents/2021-08/emerging-issues-in-food-waste-management-plastic-contamination.pdf (accessed on 26 June 2023).
22. Śniadecka, N. Investigation on Utilization of Organic Fraction of Municipal Solid Waste. Ph.D. Thesis, Gdansk University of Technology, Gdańsk, Poland, 2017. Available online: https://mostwiedzy.pl/pl/publication/download/1/badania-nad-zagospodarowaniem-organicznej-frakcji-odpadow-komunalnych_17700.pdf (accessed on 26 June 2023).
23. Jędrczak, A. Properties of the Organic Fraction Directed to Biostabilization in Mbt Installations during the Heating Season. *Civ. Environ. Eng. Rep.* **2018**, *28*, 65–78. [CrossRef]
24. Sewwandi, M.; Wijesekara, H.; Rajapaksha, A.U.; Soysa, S.; Vithanage, M. Microplastics and plastics-associated contaminants in food and beverages; Global trends, concentrations, and human exposure. *Environ. Pollut.* **2023**, *317*, 120747. [CrossRef]
25. Yin, L.; Wen, X.; Huang, D.; Du, C.; Deng, R.; Zhou, Z.; Tao, J.; Li, R.; Zhou, W.; Wang, Z.; et al. Interactions between microplastics/nanoplastics and vascular plants. *Environ. Pollut.* **2021**, *290*, 117999. [CrossRef]
26. Industrial Biotechnology Innovation Centre. A Review of Standards for Biodegradable Plastics. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/817684/review-standards-for-biodegradable-plastics-IBioIC.pdf (accessed on 26 June 2023).
27. Hannover, H.; University of Applied Sciences and Arts, Institute for Bioplastics and Biocomposites. Biopolymers Facts and Statistics. 2021. Available online: https://www.ifbb-hannover.de/files/IfBB/downloads/faltblaetter_broschueren/f+s/Biopolymers-Facts-Statistics-einseitig-2021.pdf (accessed on 26 June 2023).
28. Wei, X.-F.; Bohlén, M.; Lindblad, C.; Hedenqvist, M.; Hakonen, A. Microplastics generated from a biodegradable plastic in freshwater and seawater. *Water Res.* **2021**, *198*, 117123. [CrossRef]
29. Su, Y.; Cheng, Z.; Hou, Y.; Lin, S.; Gao, L.; Wang, Z.; Bao, R.; Peng, L. Biodegradable and conventional microplastics posed similar toxicity to marine algae Chlorella vulgaris. *Aquat. Toxicol.* **2022**, *244*, 106097. [CrossRef]
30. Weinstein, J.E.; Dekle, J.L.; Leads, R.R.; Hunter, R.A. Degradation of bio-based and biodegradable plastics in a salt marsh habitat: Another potential source of microplastics in coastal waters. *Mar. Pollut. Bull.* **2020**, *160*, 111518. [CrossRef]
31. Qin, M.; Chen, C.; Song, B.; Shen, M.; Cao, W.; Yang, H.; Zeng, G.; Gong, J. A review of biodegradable plastics to biodegradable microplastics: Another ecological threat to soil environments? *J. Clean. Prod.* **2021**, *312*, 127816. [CrossRef]
32. Wei, X.-F.; Capezza, A.J.; Cui, Y.; Li, L.; Hakonen, A.; Liu, B.; Hedenqvist, M.S. Millions of microplastics released from a biodegradable polymer during biodegradation/enzymatic hydrolysis. *Water Res.* **2022**, *211*, 118068. [CrossRef] [PubMed]
33. Cucina, M.; Nisi, P.; Tambone, F.; Adani, F. The role of waste management in reducing bioplastics' leakage into the environment: A review. *Bioresour. Technol.* **2021**, *337*, 125459. [CrossRef] [PubMed]
34. Fojt, J.; David, J.; Přikryl, R.; Řezáčová, V.; Kučerík, J. A critical review of the overlooked challenge of determining micro-bioplastics in soil. *Sci. Total Environ.* **2020**, *745*, 140975. [CrossRef] [PubMed]

35. Liao, J.; Chen, Q. Biodegradable plastics in the air and soil environment: Low degradation rate and high microplastics formation, *J. Hazard. Mater.* **2021**, *418*, 126329. [CrossRef] [PubMed]
36. Vasmara, C.; Marchetti, R. Biogas production from biodegradable bioplastics. *Environ. Eng. Manag. J.* **2016**, *15*, 2041–2048. [CrossRef]
37. Ali, S.S.; Elsamahy, T.; Abdelkarim, E.A.; Al-Tohamy, R.; Kornaros, M.; Ruiz, H.A.; Zhao, T.; Li, F.; Sun, J. Biowastes for biodegradable bioplastics production and end-of-life scenarios in circular bioeconomy and biorefinery concept. *Bioresour. Technol.* **2022**, *363*, 127869. [CrossRef]
38. Harrison, J.P.; Boardman, C.; O'Callaghan, K.; Delort, A.-M.; Song, J. Biodegradability standards for carrier bags and plastic films in aquatic environments: A critical review. *R. Soc. Open Sci.* **2018**, *5*, 171792. [CrossRef]
39. Conn, R.E.; Kolstad, J.J.; Borzelleca, J.F.; Dixler, D.S.; Filer, L.J.; Ladu, B.N.; Pariza, M.W. Safety assessment of polylactide (PLA) for use as a food-contact polymer. *Food Chem. Toxicol.* **1995**, *33*, 273–283. [CrossRef]
40. Tümer, E.H.; Erbil, H.Y. Extrusion-Based 3D Printing Applications of PLA Composites: A Review. *Coatings* **2021**, *11*, 390. [CrossRef]
41. Fontana, L.; Minetola, P.; Iuliano, L.; Rifuggiato, S.; Khandpur, M.S.; Stiuso, V. An investigation of the influence of 3d printing parameters on the tensile strength of PLA material. *Mater. Today Proc.* **2022**, *57*, 657–663. [CrossRef]
42. Oksiuta, Z.; Jalbrzykowski, M.; Mystkowska, J.; Romanczuk, E.; Osiecki, T. Mechanical and Thermal Properties of Polylactide (PLA) Composites Modified with Mg, Fe, and Polyethylene (PE) Additives. *Polymers* **2020**, *12*, 2939. [CrossRef]
43. Sharma, S.; Majumdar, A.; Butola, B.S. Tailoring the biodegradability of polylactic acid (PLA) based films and ramie- PLA green composites by using selective additives. *Int. J. Biol. Macromol.* **2021**, *181*, 1092–1103. [CrossRef] [PubMed]
44. Hobbs, S.R.; Parameswaran, P.; Astmann, B.; Devkota, J.P.; Landis, A.E. Anaerobic Codigestion of Food Waste and Polylactic Acid: Effect of Pretreatment on Methane Yield and Solid Reduction. *Adv. Mater. Sci. Eng.* **2019**, *2019*, 4715904. [CrossRef]
45. Cucina, M.; Nisi, P.; Trombino, L.; Tambone, F.; Adani, F. Degradation of bioplastics in organic waste by mesophilic anaerobic digestion, composting and soil incubation. *Waste Manag.* **2021**, *134*, 67–77. [CrossRef] [PubMed]
46. Peng, W.; Wang, Z.; Shu, Y.; Lü, F.; Zhang, H.; Shao, L.; He, P. Fate of a biobased polymer via high-solid anaerobic co-digestion with food waste and following aerobic treatment: Insights on changes of polymer physicochemical properties and the role of microbial and fungal communities. *Bioresour. Technol.* **2022**, *343*, 126079. [CrossRef] [PubMed]
47. Zaborowska, M.; Bernat, K.; Pszczółkowski, B.; Wojnowska-Baryła, I.; Kulikowska, D. Anaerobic Degradability of Commercially Available Bio-Based and Oxo-Degradable Packaging Materials in the Context of their End of Life in the Waste Management Strategy. *Sustainability* **2021**, *13*, 6818. [CrossRef]
48. Pilarska, A.A.; Marzec-Grządziel, A.; Paluch, E.; Pilarski, K.; Wolna-Maruwka, A.; Kubiak, A.; Kałuża, T.; Kulupa, T. Biofilm Formation and Genetic Diversity of Microbial Communities in Anaerobic Batch Reactor with Polylactide (PLA) Addition. *Int. J. Mol. Sci.* **2023**, *24*, 10042. [CrossRef]
49. Sintim, H.Y.; Bary, A.I.; Hayes, D.G.; Wadsworth, L.C.; Anunciado, M.B.; English, M.E.; Bandopadhyay, S.; Schaeffer, S.M.; DeBruyn, J.M.; Miles, C.A.; et al. In situ degradation of biodegradable plastic mulch films in compost and agricultural soils. *Sci. Total Environ.* **2020**, *727*, 138668. [CrossRef]
50. Kalita, N.K.; Sarmah, A.; Bhasney, S.M.; Kalamdhad, A.; Katiyar, V. Demonstrating an ideal compostable plastic using biodegradability kinetics of poly(lactic acid) (PLA) based green biocomposite films under aerobic composting conditions. *Environ. Chall.* **2021**, *3*, 100030. [CrossRef]
51. Sintim, H.Y.; Bary, A.I.; Hayes, D.G.; English, M.E.; Schaeffer, S.M.; Miles, C.A.; Zelenyuk, A.; Suski, K.; Flury, M. Release of micro- and nanoparticles from biodegradable plastic during in situ composting. *Sci. Total Environ.* **2019**, *675*, 686–693. [CrossRef]
52. Al Hosni, A.S.; Pittman, J.K.; Robson, G.D. Microbial degradation of four biodegradable polymers in soil and compost demonstrating polycaprolactone as an ideal compostable plastic. *Waste Manag.* **2019**, *97*, 105–114. [CrossRef] [PubMed]
53. Fan, P.; Yu, H.; Xi, B.; Tan, W. A review on the occurrence and influence of biodegradable microplastics in soil ecosystems: Are biodegradable plastics substitute or threat? *Environ. Int.* **2022**, *163*, 107244. [CrossRef] [PubMed]
54. Emadian, S.M.; Onay, T.T.; Demirel, B. Biodegradation of bioplastics in natural environments. *Waste Manag.* **2017**, *59*, 526–536. [CrossRef]
55. Yu, Y.; Griffin-LaHue, D.E.; Miles, C.A.; Hayes, D.G.; Flury, M. Are micro- and nanoplastics from soil-biodegradable plastic mulches an environmental concern? *J. Hazard. Mater. Adv.* **2021**, *4*, 100024. [CrossRef]
56. Siracusa, V.; Blanco, I. Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly(ethylene terephthalate) (Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications. *Polymers* **2020**, *12*, 1641. [CrossRef]
57. Sholokhova, A.; Denafas, G.; Mykhaylenko, V. The organic output from mechanical–biological treatment plants as a source of microplastics: Mini-review on current knowledge, research methodology and future study perspectives. *Waste Manag. Res.* **2021**, *39*, 652–663. [CrossRef]
58. Steiner, T.; Möller, J.N.; Löder, M.G.J.; Hilbrig, F.; Laforsch, C.; Freitag, R. Microplastic Contamination of Composts and Liquid Fertilizers from Municipal Biowaste Treatment Plants: Effects of the Operating Conditions. *Waste Biomass Valor* **2022**, *14*, 873–887. [CrossRef]
59. Edo, C.; Fernández-Piñas, F.; Rosal, R. Microplastics identification and quantification in the composted Organic Fraction of Municipal Solid Waste. *Sci. Total Environ.* **2022**, *813*, 151902. [CrossRef]

60. Agilent Application Note Environment. Analysis of Microplastics Using FTIR Imaging, Identyfing and Quantifying Microplastics in Wastewater, Sediment and Fauna. 2017. Available online: https://www.agilent.com/cs/library/applications/5991-8271EN_microplastics_ftir_application.pdf (accessed on 26 June 2023).
61. Dekiff, J.H.; Remy, D.; Klasmeier, J.; Fries, E. Occurrence and spatial distribution of microplastics in sediments from Norderney. *Environ. Pollut.* **2014**, *186*, 248–256. [CrossRef]
62. Huertas de la Torre, S.H. Pyrolysis-GC/MS, A Powerful Analytical Tool for Additives and Polymers Characterization. In *Recent Perspectives in Pyrolysis Research*; Bartoli, M., Giorcelli, M., Eds.; IntechOpen: London, UK, 2022. [CrossRef]
63. Käppler, A.; Fischer, M.; Scholz-Böttcher, B.M.; Oberbeckmann, S.; Labrenz, M.; Fischer, D.; Eichhorn, K.-J.; Voit, B. Comparison of µ-ATR-FTIR spectroscopy and py-GCMS as identification tools for microplastic particles and fibers isolated from river sediments. *Anal. Bioanal. Chem.* **2018**, *410*, 5313–5327. [CrossRef]
64. Thermoscientific White Paper WP53077. Guide to the Identification of Microplastics by FTIR and Raman Spectroscopy. 2018. Available online: https://assets.thermofisher.com/TFS-Assets/MSD/Application-Notes/WP53077-microplastics-identification-ftir-raman-guide.pdf (accessed on 26 June 2023).
65. Mariano, S.; Tacconi, S.; Fidaleo, M.; Rossi, M.; Dini, L. Micro and Nanoplastics Identification: Classic Methods and Innovative Detection Techniques. *Front. Toxicol.* **2021**, *3*, 636640. [CrossRef] [PubMed]
66. Fontana, G.D.; Mossotti, R.; Montarsolo, A. Assessment of microplastics release from polyester fabrics: The impact of different washing conditions. *Environ. Pollut.* **2020**, *264*, 113960. [CrossRef] [PubMed]
67. Barrows, A.P.W.; Christiansen, K.S.; Bode, E.T.; Hoellein, T.J. A watershed-scale, citizen science approach to quantifying microplastic concentration in a mixed land-use river. *Water Res.* **2018**, *147*, 382–392. [CrossRef] [PubMed]
68. Biver, T.; Bianchi, S.; Carosi, M.R.; Ceccarini, A.; Corti, A.; Manco, E.; Castelvetro, V. Selective determination of poly(styrene) and polyolefin microplastics in sandy beach sediments by gel permeation chromatography coupled with fluorescence detection. *Mar. Pollut. Bull.* **2018**, *136*, 269–275. [CrossRef]
69. Graca, B.; Szewc, K.; Zakrzewska, D.; Dołęga, A.; Szczerbowska-Boruchowska, M. Sources and fate of microplastics in marine and beach sediments of the Southern Baltic Sea—A preliminary study. *Environ. Sci. Pollut. Res.* **2017**, *24*, 7650–7661. [CrossRef] [PubMed]
70. Naidoo, T.; Sershen; Thompson, R.C.; Rajkaran, A. Quantification and characterisation of microplastics ingested by selected juvenile fish species associated with mangroves in KwaZulu-Natal, South Africa. *Environ. Pollut.* **2020**, *257*, 113635. [CrossRef]
71. Battista, F.; Frison, N.; Bolzonella, D. Can bioplastics be treated in conventional anaerobic digesters for food waste treatment? Environ. *Technol. Innov.* **2021**, *22*, 101393. [CrossRef]
72. European Commission. Official Journal of the European Union. 2021. Commission Delegated Regulation (EU) 2021/1768 of 23 June 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32021R1768 (accessed on 26 June 2023).
73. Scottish Environment Protection Agency; Aspray, T.J.; Dimambro, M.E.; Steiner, H.J. Investigation into Plastic in Food Waste Derived Digestate and Soil. 2017. Available online: https://www.sepa.org.uk/media/327640/investigation-into-plastic-in-food-waste-derived-digestate-and-soil.pdf (accessed on 6 September 2023).
74. Yang, Z.; Lü, F.; Hu, T.; Xu, X.; Zhang, H.; Shao, L.; Ye, J.; He, P. Occurrence of macroplastics and microplastics in biogenic waste digestate: Effects of depackaging at source and dewatering process. *Waste Manag.* **2022**, *154*, 252–259. [CrossRef] [PubMed]
75. Öling-Wärnå, V.; Åkerback, N.; Engblom, S. Digestate from Biowaste and Sewage Sludge as Carriers of Microplastic into the Environment: Case Study of a Thermophilic Biogas Plant in Ostrobothnia, Finland. *Water Air Soil. Pollut.* **2023**, *234*, 432. [CrossRef]
76. Porterfield, K.K.; Hobson, S.A.; Neher, D.A.; Niles, M.T.; Roy, E.D. Microplastics in composts, digestates, and food wastes: A review. *J. Environ. Qual.* **2023**, *52*, 225–240. [CrossRef]
77. Kawecki, D.; Goldberg, L.; Nowack, B. Material flow analysis of plastic in organic waste in Switzerland. *Soil. Use Manag.* **2021**, *37*, 277–288. [CrossRef]
78. WRAP; Aponte, L.F.; Kabir, M.; Tompkins, D. Plastics in Composts and Digestates. Final report. 2022. Available online: https://wrap.org.uk/sites/default/files/2023-07/WRAP-Plastics-in-Composts-Digestates-final-report.pdf (accessed on 6 September 2023).
79. Commission of the European Communities, Eurostat. Guidance on Classification of Waste According to EWC-Stat Categories, Supplement to the Manual for the Implementation of the Regulation (EC) No 2150/2002 on Waste Statistics. 2010. Available online: https://ec.europa.eu/eurostat/documents/342366/351806/Guidance-on-EWCStat-categories-2010.pdf/0e7cd3fc-c05c-47a7-818f-1c2421e55604 (accessed on 26 June 2023).