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Perspective

Two Birds with One Stone: Bioplastics and Food Waste Anaerobic Co-Digestion

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Abstract: Following the BBC's Blue Planet II nature documentary series on marine ecosystems, plastic packaging has come under public fire, with consumers demanding greener alternatives. The biodegradable properties of some bioplastics have offered a potential solution to the global challenge of plastic pollution, while enabling the capture of food waste through anaerobic digestion as a circular and energy-positive waste treatment strategy. However, despite their increasing popularity, currently bioplastics are being tested in environments that do not reflect real-life waste management scenarios. Bioplastics find their most useful, meaningful and environmentally-sound application in food packaging—why is there so little interest in addressing their anaerobic co-digestion with food waste? Here, we provide a set of recommendations to ensure future studies on bioplastic end-of-life are fit for purpose. This perspective makes the link between the environmental sustainability of bioplastics and the role of food waste anaerobic digestion as we move towards an integrated food–energy–water–waste nexus. It shines light on a novel outlook in the field of bioplastic waste management while uncovering the complexity of a successful path forward. Ultimately, this research strives to ensure that the promotion of bioplastics within a circular economy framework is supported across waste collection and treatment stages.

Keywords: bioplastics; food waste; anaerobic digestion; biodegradation; waste management; circular economy; bioeconomy; industrial ecology

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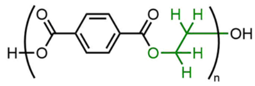
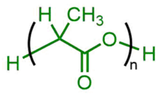
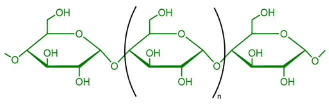
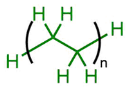
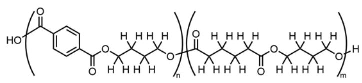
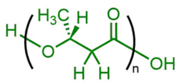
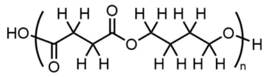
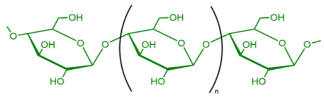
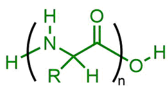
1. Introduction

Despite an ambitious early promise of solving the plastics crisis, at a global scale, plastic recycling as an end-of-life option is still lagging [1]. Food and drink packaging account for the largest share of the plastic market [2] and sales of packaged produce and food deliveries have skyrocketed during the COVID-19 pandemic [3]. Since mechanical recycling of plastic packaging remains highly challenging for multi-layered and food-contaminated plastics [4], designing materials that are compatible with food waste (FW) processing strategies is an attractive option in building a circular society. When derived from renewable resources and processed alongside organic fractions of municipal and commercial solid waste [5], bioplastics have been identified as a promising solution to plastic pollution while ensuring hygiene standards across the food supply chain [6].

Bioplastics are not all made from one single material; just as conventional plastics, they comprise a whole family of materials with differing feedstocks, properties and applications [7] (Table 1). A plastic material can be defined as a 'bioplastic' if it is either bio-based, biodegradable, or both [2,7]. Here, we focus on biodegradable bioplastics (BBPs), unless stated otherwise. The market share of bioplastics is expected to grow by 20% by 2024, reaching 2.87 million tonnes (Mt), of which 1.8 Mt is BBPs [8]. The steady growth of these bio-products drives the need to define end-of-life alternatives [9].

A range of methodologies have been developed to monitor the rate and extent of biodegradation of BBPs in various environments [10]. Although the scientific literature has primarily focused on aerobic conditions, such as industrial composting [11], composting alone as a disposal method for food and food packaging waste is currently limited. Under the Animal By-Products Regulation (2009/1069/EC), most composting facilities in the European Union (EU) are currently unsuitable for the treatment of FW [12], because open windrow composting cannot be used to process certain types of organic waste, including catering and animal wastes. Anaerobic digestion (AD), on the other hand, may represent a more suitable and valuable end-of-life option than composting [13,14], offering an energy-producing waste management strategy within the food–water–energy nexus.

Table 1. Most common industrially produced bioplastics.

Polymer	Monomer/Subunit	Common Feedstocks	Biodegradable	Chemical Structure	Bioplastic Market Share	Ref.
bio-PET	Ethanol (EtOH) and terephthalic acid (TPA)	Corn, sugar beet, sugarcane, wheat (EtOH) and fossil-based (TPA)	N		19.0%	[8,15,16]
PLA	Lactic acid	Corn, sugarcane	Y †		16.2%	[8,15,16]
Starch-based polymer	Starch (α-linked D-glucose)	Corn, potato, wheat, cassava, sugarcane	Y		15.8%	[8,15,16]
bio-PE	EtOH	Corn, sugar beet, sugar cane, wheat	N		9.1%	[8,15,16]
PBAT	Adipic acid, 1,4-butanediol (BD) and dimethyl-terephthalate	Fossil based #	Y		7.7%	[8,16,17]
PH3B (PHA) §	Hydroxy-alkanoate	Corn, vegetable oils, food waste, wastewater (through microbial fermentation)	Y		4.5%	[8,18]
PBS	Succinic acid and BD	Fossil based #	Y		3.8%	[8,16,17]
Cellulose-based polymer	Cellulose (ß-linked D-glucose)	Wood pulp	Y		<1%	[8,15]
Protein-based polymer	Amino acid	Wheat gluten, soy protein, milk casein	Y		<1%	[8,15]

PET: polyethylene terephthalate; PLA: polylactic acid; PE: polyethylene; PBAT: polybutylene adipate terephthalate; PBS: polybutylene succinate; PH3B: poly-3-hydroxybutyrate; PHA: polyhydroxyalkanoate. Atoms from biological sources are displayed in green, while black atoms reflect a fossil origin. † The biodegradability of PLA as a polymer is still contested. It requires an initial 'activation' temperature above 60 °C to trigger degradation, due to its comparatively high glass transition temperature (T_g) [17]. # PBAT and PBS are bioplastics in class transition, since partially bio-based versions of these compounds are currently being developed. Therefore, in the near future, PBAT and PBS are expected to be both bio-based and biodegradable [19]. § PH3B is the simplest and most commonly occurring form of PHA, which consists of a large class of polyesters prevalent in nature and synthesised by a range of microorganisms [18].

More recently, the degradation of BBPs under anaerobic conditions has been the subject of dedicated reviews [11,14,20]. However, these reviews focused on the process of biodegradation itself, rather than considering bioplastics within the existing organic waste management infrastructure. Moreover, biodegradation assays of BBPs have traditionally been performed either alone or in co-digestion with sewage sludge, while the suitability of BBPs in FW AD remains largely unexplored [20,21], with only a limited number of studies addressing FW and BBP co-digestion (see Table S1 for an overview of these studies). Here, we start by assessing the treatment of organic waste in the bioeconomy, followed by a critical discussion of current studies on BBPs and FW anaerobic co-digestion. While we touch upon technical aspects of anaerobic co-digestion, it is not the ambition of this perspective to provide a comprehensive review of the underlying biochemical details. Instead, it aims to frame the technical challenges faced by BBP and FW co-digestion within the wider sustainability context, which is often missing when taking a siloed approach. We discuss the complexity of a successful path forward and the need for coordinated action between all actors of the system. Though the focus is on a European context, the implications and recommendations we provide are relevant to wider circular economy and bioeconomy frameworks.

2. Status Quo: Organic Waste Management in the Bioeconomy

Now more than ever, water, food and energy constitute three of the major resource issues worldwide. Aiming to address them, the organic fraction of municipal solid waste (OFMSW), which includes food and garden (green) waste from households and household-like sources (e.g., institutional canteens, food markets, and retail businesses), is increasingly recognised as a resource rather than as waste, with the potential to move from linear to circular and energy-positive waste management strategies.

Across the EU, between 118 and 138 Mt of biowaste is generated annually [22], 100 Mt of which is OFMSW [23]. Currently, only up to 25% of this biowaste is captured and recycled into compost and digestate through separate organic waste collections [24]. The majority still ends up in residual waste, which is either landfilled or incinerated [24], both streams effectively acting as carbon and nutrient lock-in, effectively keeping them flowing back to the soil as bio-available components. The Landfill Directive (1999/31/EC) addressed this partly, obliging Member States to reduce the amount of biodegradable municipal waste that they landfill to 35% of 1995 levels by 2016. In 2018, the EU published its Circular Economy Package, new legislation that strengthens the waste hierarchy by restricting the amount of municipal waste sent to landfill, introducing new recycling targets and source-separate FW collections from households and businesses [25] (Table 2).

Table 2. Targets and timelines under the EU's Circular Economy Package [25].

Material Targeted	By 2023	By 2025	By 2030	By 2035
Plastic packaging recycled	-	50%	55%	-
Municipal waste recycled	-	55%	60%	65%
Municipal waste landfilled	-	-	-	$\leq$10%
Household food waste	Separate collection and landfill ban	-	-	-

Separately collected food waste will have to be either recycled or prepared for re-use. Numbers are in percentage (%) of total waste generated per category.

At a global scale, major cities across the world have also introduced separate FW collections, including Milan, Copenhagen, Paris, New York, San Francisco, Auckland, Cajicá and Seoul [26]. Though these decisions have taken place at a city level, they are often enabled by a supportive national legislative framework [26]. Remarkably, following a ban on direct landfilling of FW in 2005, FW recycling rates in South Korea rose from a mere 2% to over 90% within 20 years [27]. A number of countries have since then introduced policies aimed at the separation and treatment of FW, including Japan, Malaysia, Thailand and China [28]. In light of legislation targeting the capture and recovery of FW, AD provides a unique opportunity to move from a simple waste management strategy to a more holistic, energy-producing system.

2.1. Anaerobic Digestion for Food Waste Recycling

As natural systems around the globe are on the brink of collapse [29] and as topsoil loss from agricultural land threatens food production [30], ensuring a separate organics recycling stream is no longer an option: it is a necessity. The treatment of biodegradable waste varies from one waste collection scheme to another and includes in-vessel composting, windrow composting and AD [26], each presenting advantages and limitations (Table 3). AD is increasingly recognised as the most adequate and sustainable technology to tackle the significant amount of FW generated each year [26,31,32], due to its environmental, social and economic advantages. The term 'anaerobic digestion' refers to the degradation and stabilisation of organic waste in the absence of free oxygen. It is a natural biological process, dependent on an ensemble of microorganisms, the microbiota, which process the organic matter. The resulting products consist of biogas (composed of 50–70% methane (CH_4), 30–50% carbon dioxide (CO_2) and traces of other species, depending on the substrate), a valuable source of renewable energy, and digestate, a nutrient-rich sludge that can be used as natural fertiliser (Figure 1). Biogas can be used directly for renewable heat and electricity production. If used as biofuel or injected into the natural gas grid, CO_2 is removed in a process called upgrading. While focus should be placed on FW minimisation to achieve the highest savings in greenhouse gas (GHG) emissions over the lifecycle of food produce [33], the biggest advantage of AD over composting is its ability to recover the chemical energy stored in FW (alongside nutrient recovery).

Table 3. Characteristics of various waste treatment strategies for separately collected organic waste.

Technology		Process Description	Advantages	Disadvantages
Anaerobic digestion (AD)		Degradation of organic waste by microorganisms in the absence of oxygen in a closed chamber	- Allows for energy production alongside nutrient and organic matter recovery - Products are substitutes for fossil-based natural gas and synthetic fertilisers	- Capital and operational costs can be prohibitive - Highly sensitive process - CH_4 content of biogas can be low for some substrates - Digestate storage (e.g., lagoons) can be costly - Possible restrictions on digestate application timings
Composting	In-vessel composting (IVC)	Degradation of organic waste by microorganisms in the presence of oxygen in a silo or concrete-lined chamber	- High organic matter compost - Allows for food waste to be collected alongside garden waste - Simple, predictable and naturally occurring process - Relatively cheap	- Does not recover energy - Produces more CO_2 than AD (as comparatively little CH_4 is produced) - Leachate must be treated
	Windrow composting (WC)	Degradation of organic waste by microorganisms in the presence of oxygen in windrow (i.e., heaps laid out to dry outdoors)		- See disadvantages for IVC, and - Cannot be used in some countries (incl. UK) to treat wastes that contain catering and animal waste under the Animal By-Products Regulation

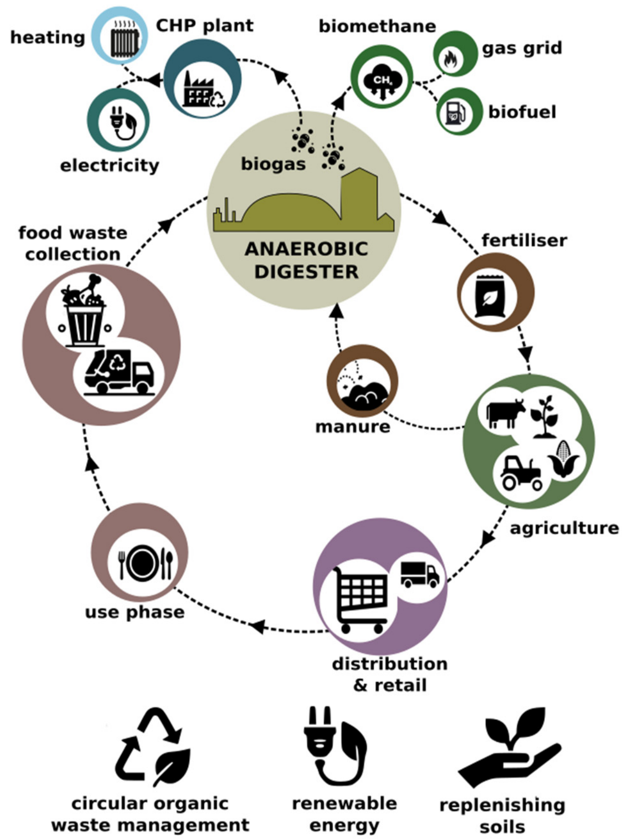


Figure 1. Anaerobic digestion: at the interface between organic waste management, renewable energy production and sustainable agriculture. Agricultural land provides food, which is distributed through the food supply chain to the consumers. The organic fraction of municipal solid waste is then treated through anaerobic digestion. The resulting biogas can be used for heating and electricity through a combined heat and power (CHP) plant or upgraded into biomethane, a substitute for natural gas. The digestate, rich in nutrients, can be used as natural fertiliser.

The physical quality of the resulting digestate is equally critical to secure a sustainable AD market [34]. This remains a challenge for municipal FW, characterised by highly heterogeneous and often contaminated feedstock, notably by plastics [32]. Plastics films are particularly present in FW because much food is wrapped in these [26]. Though packaging has played a key role in cutting down GHG emissions across complex supply chains [33], this in turn has led to a rise in food packaging waste. Plastics in digestate, resulting from inadequate de-packaging or subsequent screening, present a particular problem, both technically and economically [31] (Section 4.1). Food and its packaging must be considered as an integrated system as we explore alternatives for diverting FW from landfill and incineration [35].

2.2. Integrating Biodegradable Bioplastics into Organics Recycling

The adoption of BBPs for FW collections and some food packaging applications has provided a potential solution to help overcome the plastic contamination problem [13,26]. Studies have shown that providing households with compostable bin liners increases both the quality and quantity of FW for subsequent treatment [26,36,37]. As one of the pioneers and leaders in FW valorisation, the city of Milan, which collects FW separately at kerbside from its 1.4 million citizens, adopted compostable bin liners and has a contamination level that stays consistently below 5% of the total volume collected [26]. Further extending the use of such biodegradable materials to food packaging may allow for an even greater capture of FW, while ensuring a cleaner feedstock stream. This is particularly relevant for commercial and retail waste, where surplus food is often disposed of in its packaging (once other redistribution options have been exhausted). This holds true for households, where selective sorting of food and packaging waste can be seen as an inconvenience by consumers [38,39] (Section 4.2). Yet, most plastics—whether they are conventional, vaguely 'biodegradable' or even certified compostable—are separated at the AD process and sent to landfill or incineration [40], raising questions about the merits of a joint collection and processing system for FW and BBPs. This is because there is currently little understanding of precisely how BBPs biodegrade in an AD setting, especially with FW [21,41], which is vital to establish anaerobic co-digestion of BBPs as a reliable waste management strategy, which we delve into in the following sections.

3. Relevant Study Designs for Biodegradable Bioplastic Anaerobic Degradation

While the aerobic degradation of bioplastics has been reviewed in detail [42–44], research on BBPs in AD remains underdeveloped [21,41]. Despite increasing interest and research on the degradation of BBPs under anaerobic conditions, including dedicated reviews [11,14,20], BBPs tend to be studied in isolation. Given the recent policies aimed at FW recycling outlined in the previous sections, as well as the growing proportion of plastic packaging in the food supply chain, addressing BBP co-digestion with FW is paramount to ensure they are studied in their most appropriate context.

In this section, we build from past studies on BBP and FW co-digestion (Table S1) and discuss key parameters to consider for relevant BBP end-of-life scenarios in light of current AD practices, providing a frame of reference for further studies.

3.1. Co-Digestion Substrates

Combining feedstocks with different compositions has been promoted as a means of enhancing process stability and efficiency through the equilibration of the nutrient balance, particularly when dealing with complex types of substrates, such as manure or FW, rich in nitrogen. Yet, this question can only be addressed if the relevant co-substrates are being investigated. Further characterisation of BBP degradation in FW AD is needed to expand upon recent efforts in this field.

Commercial or household FW used as co-substrate in co-digestion studies includes FW from university canteens or catering [41,45–48], food markets [46,49], artificial household FW [50,51], OFMSW [13,21,52] and industrial food processing waste [53]. However, FW can be a challenging co-substrate to study, due to its high nitrogen content and its high heterogeneity [54], especially for municipal and household FW. Designing synthetic municipal/household FW recipes for research purposes, representative of a given geographical and societal context, can help towards more consistent system characteristics, thereby strengthening the reliability and reproducibility of the data [50,51]. Robust experimental design should also consider the compatibility of the microbial sludge inoculum with the incoming substrate. Some studies used sludge from wastewater treatment plants [21,45], despite using FW as substrate. Nevertheless, one study chose sludge from palm oil mill effluent (POME) rather than from a wastewater treatment plant because of proven more consistent data with FW as a substrate [47], arguably because of the more constant characteristics of the POME sludge since the POME digester plant treated a specialised substrate [47]. When using lab-developed inocula, feeding for a prolonged period is equally important to ensure the microbial consortium can adapt to its substrate [50,51].

3.2. Feedstock Ratios

Co-substrate ratios are often determined on a volatile solids (VS) basis (Table S1). Nevertheless, they also need to reflect current and projected rates of plastic packaging in the organic waste stream. For example, if using an FW-to-BBP VS ratio of 1:1, 2:1 and 4:1 [46,47,51], the resulting plastic content (by weight) would roughly correspond to 30%, 15% and 7.5%, respectively (based on average total solids and VS characteristics of both substrates). Yet, currently, total plastic content is between 2 and 5% of household FW [55]. Studies need to reflect that, especially when assessing the potential for methane yield enhancement, as this can be an attractive selling point for AD plant operators, but which needs to be realistic.

In some cases, existing biogas plants operate below capacity due to lack of feedstock availability, with detrimental effects on operational costs [32]. While diversifying sources of organic material is needed, the role of feedstock ratios on process performance should be carefully monitored. Ammonia is produced through biological degradation of nitrogenous matter; a high concentration of free ammonia leads to the accumulation of volatile fatty acids, which inhibits methanogenesis, resulting in low methane yields. Based on the chemical composition of BBPs and FW, a theoretical co-digestion ratio can be easily determined to achieve an optimal carbon-to-nitrogen (C:N) ratio for efficient methane production (around 20–30:1) [12]. How this then translates into practical terms is an important consideration, both in terms of actual FW and BBP proportions in waste arisings and the level of BBPs tolerated by the system to ensure biodegradation and meet the quality standards of the resulting digestate [51,52]. This was directly addressed by one study [52], in which the amount of BBPs added in the experimental assays was determined based on current and projected trends.

3.3. Hydraulic Retention Time

The hydraulic retention time (HRT), which corresponds to the average time that digester contents sit in the tank, is an important parameter to consider when assessing the real-life suitability of BBPs in AD. A number of studies have already highlighted that although some BBPs have the ability to fully biodegrade in AD, few fulfil the HRT of operating AD plants [13,20,21], with degradation times 3–6-fold longer than current industrial HRT [13]. Though it is of scientific interest to run experiments for as long as biodegradation takes place, more emphasis needs to be placed on relevant HRT [20,49,52], as well as digester operating mode [50]. A typical biogas plant treating OFMSW operates with an HRT of 15–30 days [20], though longer HRTs up to 100 days at commercial facilities treating source-separated FW have been reported [56]. Therefore, a BBP suitable for FW collection should be able to degrade within these timeframes. Some BBPs have been shown to biodegrade at an HRT usually applied at industrial scales, such as materials made of polyhydroxyalkanoate (PHA), starch, cellulose and pectin, so no possible contamination would occur [20,49], although some of these results were contested elsewhere [52].

BBP biodegradation could benefit from longer retention times typically observed in wet mesophilic AD [55,56]. Wet AD systems, in which water liquid is added or recycled to the feedstock to yield a more pumpable slurry with lower total solids (TS) concentration (TS $<$ 15%), are commonly used for the AD of organic wastes [56,57], including FW [56]. The longer HRT characteristic of FW treated in wet AD systems reinforces the suitability of FW as substrate for BBP co-digestion [51]. As the VS content of BBPs is high [22], the addition of BBPs could also increase the organic loading rate (OLR) with little effect on the overall HRT.

Dry AD (typically TS $\geq$ 20%) may offer several advantages over wet AD due to lower water use, more favourable energy balances and a more robust system [56,57]. The high solids content of FW feedstocks and the presence of additional pre- and post-treatment steps in dry AD processes [56] could make dry AD an attractive new avenue to explore for FW and BBP co-digestion, which was addressed in some recent co-digestion studies [48,52]. In any case, the systematic deployment of pre-treatment steps, such as pasteurisation or autoclaving, ahead of AD, could accelerate initial hydrolysis [40] (the rate limiting step for BBP biodegradation), thereby reducing the HRT required for effective biodegradation of further BBP materials.

3.4. Polymer Pre-Treatment

There is a growing interest in pre-treating BBP waste to enhance its biodegradability (and thus biogas recovery) in AD, including polylactic acid (PLA) [45,46,58]. A 15-day pre-treatment incubation with sodium hydroxide (NaOH) promoted PLA degradation and yielded between 97 and 99% solubilisation, effectively removing PLA aggregates left in the digestate [45]. Nevertheless, as any additional step in the process will come at a cost (both energetic and financial) to the plant operator, it is worth asking whether such a strategy is a practical option, given that BBPs represent a minor fraction of the total feedstock stream [40] (Section 4.1). Importantly, the use of corrosive agents to accelerate hydrolysis of BBPs could have environmental implications and result in the waste liquid from the pre-treated fraction to be classified as hazardous.

A number of studies looked at the effect of temperature on methane yield and BBP degradation. Operating at thermophilic (55 °C) conditions increased methane yields by 51% compared to a mesophilic range (35–37 °C) [53], although one study found no noticeable change in methane yield and only observed disintegration (as opposed to degradation) of fragments of a PLA polymer blend [48]. Hyperthermophilic treatment (80 °C) after or before thermophilic incubation further increased methane conversion and PLA transformation ratios, achieving an 80% conversion from PLA to lactic acid [50]. However, mesophilic AD currently represents the most practical and financially viable system for BBP co-digestion with FW; the characteristically high water content of FW makes it costly to operate at thermophilic ranges [56]. In addition, at thermophilic temperatures, ammonia toxicity is increased and the addition of trace elements is no longer effective in enabling metabolic pathway switching, so that other methods are necessary [59]. The longer retention times typically observed in wet mesophilic AD would also enhance further BBP biodegradation [50,56]. In one study, mesophilic conditions were indeed found to be more favourable for PHA degradation [41]. Given that pasteurisation is often a legal requirement for AD plants treating FW, moving this step at the front end could represent a compelling switch, which would allow for a thermal pre-treatment step at no extra operational cost. A recent study we conducted among British stakeholders showed that some AD plants have already successfully adopted this strategy for the treatment of source-separated FW [40].

3.5. Polymer Properties

All studies reviewed except one cut their plastics to obtain plastic fragments between 0.4 and 4 cm^2. While this is often necessary due to the lightweight nature of the materials and the limited volume of small lab-scale batch reactors, this drastically increases the number of edges available for surface erosion during microbial polymer biodegradation. While this will yield only a marginal increase on the overall surface for a single-layered plastic film, it could have more profound implications for multi-layered films. Indeed, the extra edges provide additional sites for micro-organisms to reach inner layers, which could alter the mode and rate of biodegradation, as hinted by scanning electron microscopy seen in the literature [49,55]. Thus, experimental data may not match real-life AD performance and biodegradability rates of BBPs being tested. Notably, in a recent study the BBP fragment size was set at 25 cm^2, to reflect the size used to sieve OFMSW in commercial dry AD [52], indicating that real-life conditions are being increasingly considered in study design.

On the polymer front, some BBP blends have been shown to have higher biochemical methane potential (as a proxy for ultimate biodegradability) than individual BBP polymers found to have limited biodegradability in previous experiments [13]. The synergistic effect of blending various polymers may represent a fruitful avenue to explore. In addition, a commercially available product will come with a range of additives, plasticisers and dyes, introducing further variability from the original raw material and greater uncertainties for AD plants handling these materials. It is therefore important to make the distinction between the polymer itself, i.e., its inherent physical, chemical and biochemical properties, and the product, the shape of which, alongside its thickness, number of layers, etc., will vary from one product to another, even if both products are made from the same given polymer. In practice, more data and mechanistic characterisation are needed to understand how a full plastic bag or rigid container will impact the process as well as assess the technological adjustments required to process complex mixtures of BBPs and other organic materials.

The constantly changing composition of both incoming packaging and FW itself represent a significant challenge for the AD industry [30].

3.6. Microbial Communities

Often perceived as the 'black box' of AD, the role of microbial communities has started to be increasingly recognised as a powerful indicator of AD performance [60], and the addition of specialised microorganisms could enhance FW and BBP co-digestion through 'prebiotic dosing', or bioaugmentation. Different BBPs are degraded by different microorganisms, and different microbial communities will colonise the digester depending on the composition of the waste available [20]. Among the numerous microbial species associated with BBP biodegradation, those belonging to bacterial *Pseudomonas*, *Streptomyces*, *Arthrobacter* and *Rhodococcus* and fungal *Aspergillus* and *Fusarium* genera are commonly cited [61,62]. In one study, PLA degradation increased over experimental runs, indicating an acclimatisation of the AD microbiome to PLA [50]. Despite this, very little is studied in an industrial context, including with the relevant substrates. The non-trivial, time-consuming and costly nature of microbial analysis (i.e., meta-omics techniques) is arguably a contributing factor to the paucity of microbial characterisation in the field, although the cost and complexity of genetic sequencing has dropped sharply since the early 2000s with the emergence of next-generation sequencing [63]. Nevertheless, the ability to link taxonomic data with functional insights remains limited [64], which is need before a comprehensive picture of metabolic pathways occurring within a given AD system can be drawn. Strengthening public-private partnerships could accelerate knowledge transfer to and put research into practice.

Intriguingly, in one study investigating the impact of conventional plastic contamination on FW AD performance, scanning electron microscopy results suggested that the reduction in methane yield was likely due to the interference between microorganisms and FW for effective biodegradation, and that the biological processes of AD were not affected by the plastics per se [47]. Greater reductions in methane yields were also observed when the surface areas of the plastic materials were increased [47], supporting the idea of a mechanical inhibition. It remains to be determined whether some BBPs do not present a similar barrier in an industrial AD context.

4. The Bigger Picture: Solutions beyond the Technosphere

So far, a set of study parameters were discussed in the context of BBP biodegradation and some of the major issues in experimental design were identified. While research on fundamental material properties certainly plays an important role, such studies must be clearly distinguished from those aimed at examining biodegradation within an industry-relevant fashion, reflective of real-life treatment of BBPs and in line with current and future policy. However, the ambitions of a circular economy for bioplastics cannot be fulfilled by the technosphere alone. Achieving sustainability and circularity for bioplastic packaging requires a broader, cross-disciplinary approach that expands beyond the biodegradability arena.

4.1. Legislative, Economic and Environmental Challenges

In contrast to industrial FW, characterised by highly homogenous and reliable streams, FW from municipal and commercial sources are more diverse and volatile in both feedstock quality and quantity [23,31]. While the upcoming mandate for separate FW collections [25] under the revised Waste and Landfill of Waste Framework Directives will likely boost AD and the wider organics recycling sector across Europe, ensuring the quality of the resulting digestate will be key to preserve the integrity of the AD market. Plastics in digestate are estimated to cost the industry some €90–120 million/year in Italy alone, despite exemplary low plastic contamination levels of 1.5% (on a weight basis) [40].

Legislation is still in its infancy and many countries have not yet implemented any guidelines for the production, use, or preferred waste management strategy for bioplastics. Although the EU has been promoting research and development activities in the bio-based sector, including on BBP packaging, the directions and impacts of these incentives within a circular economy framework remain unclear [65]. Individual real-life circumstances of bio-based projects need to be better understood [65]. In the case of BBPs, there is a need for stronger cohesion within the academia–policy–industry nexus to set clear priorities, including around the conventional plastics recycling versus BBP biodegradation debate [65].

BBPs certainly have a role to play in achieving a sustainable plastic economy [66], but it is important to assess carefully which applications would benefit most from a shift to biodegradable materials and support such transition with the relevant policy instruments. For example, compostable bin liners have been used for separate FW collections for over 30 years in Italy as a way of limiting non-biodegradable packaging from entering the biowaste stream [37]. To further enhance the capture of FW and to minimise the risk of substitution between conventional and compostable plastic bags, new legislation was adopted nationally in 2011, forbidding the use of conventional single-use carrier plastic bags [37]. In the future, one may see such legislation expanded onto other food packaging items.

Furthermore, standards that are fit for purpose need to be developed. Both the International Organisation for Standardisation (ISO) and the American Society for Testing Materials (ASTM) provide test methods for evaluating the anaerobic degradation of plastics under high-solid (>20% TS concentration, which would reflect dry AD processes) and low-solid (<15% TS, as is the case for wet AD, commonplace for FW treatment) conditions for thermophilic and mesophilic ranges (e.g., ISO 14853 and ASTM D5210 for aqueous mesophilic processes under low TS (<5%), or ISO 13975 for slightly higher TS (<15%)). However, to date, no certification scheme for 'AD-able' material exists, and even some of the most biodegradable EN 13432 materials (industrial composting certification scheme) were shown not to meet the physical contaminant criteria of the PAS 110 specification, the national quality standard for the digestate market in the UK [51]. This is alarming, especially in light of microplastic and plasticiser accumulation reported in agricultural soils [67,68]. Soil biodiversity and, consequently, soil fertility could be severely undermined with increasing levels of plastic pollution [68].

Plastics enter agricultural soils through deliberate introduction of plastic mulches but also compost and digestate, which can contain plastic fragments [68]. Whilst concerns over microplastic pollution have been mostly directed towards conventional, non-biodegradable plastics, some of the studies on BBPs mentioned so far seem to suggest some BBPs may also end up as microplastics in digestate. Thus, it is important to ensure BBPs do not further exacerbate the pollution crisis. The impacts of BBPs ought to be considered more holistically, as current standard methods do not consider whether post-digestion BBPs may then be fully bio-assimilated in soil and how they compare against non-biodegradable plastics.

Combining AD with downstream composting, as is common practice in Italy [37], could represent a sensible strategy to guarantee full bio-assimilation of BBPs. Indeed, this method, rooted in industrial ecology, could ensure optimal biogas production in the first step of the process, while composting phase as second step would provide longer and aerobic conditions for BBP biodegradation. This was explored by a couple of studies [48,52]. In the future, updated standardisation for materials processed alongside FW collections will be required to meet the requirements of effective operation of an AD plant [20]. This would help build trust between waste collectors, AD plant operators and the farming sector and would ensure that BBPs move from a status of contaminant to one of valuable feedstock.

A growing body of research has been investigating pre-treatment methods to increase the biodegradability of BBP waste (Section 3.5). While expanding the pool of data in this field is welcome, in practice any added processing step is likely to face a detrimental cost–benefit analysis, unless it confers a significant advantage in the overall AD operation. This might be facilitated by an increase in gate fees alongside bans on landfill (and arguably incineration) for OFMSW. It would put plant operators in the position to be able to refuse feedstocks that are too heavily contaminated, putting the pressure upstream to guarantee feedstock quality, as well as raise capital for retro-fitting plants. This could also have a positive knock-on effect on the digestate market, strengthening the resilience of the AD, which is heavily reliant on governmental subsidies [69].

4.2. Plastic Consumption and Consumer Behaviour

Given that feedstock quality is determined by how consumers dispose of and separate their waste [54], addressing consumer behaviour remains a priority and highlights the importance of the social element in ensuring feedstock quality and, by extension, a resilient AD industry. Though the use of compostable plastic bin liners for FW collections has been beneficial overall, a recent survey has shown that nearly half of the bags delivered to composting and AD plants for the treatment of FW are still manufactured from conventional, fossil-based plastics [37]. Despite a growing favourable opinion of bioplastics among consumers, consumer awareness on the relevant terminology remains poor [70–72]. The fact that consumers are most likely to recycle BBPs alongside conventional plastic packaging [70] and thus contaminate the recycling stream is a reminder of the many interdependencies in the system and the importance of accounting for those when proposing solutions.

Appropriate labelling and education will be required as the BBP market grows to prevent misplacement of BBPs at their disposal stage. Consumer behaviour psychology is still poorly understood [36] and research into how consumers are likely to correctly dispose of the final product types according to the markings and certifications used is needed. Providing clarity and minimising effort (i.e., how easy it is for one to fulfil the expected behaviour) for the consumer to assimilate knowledge, distinguish and separate various packaging materials are key steps to enable clean FW collections [40]. A notable example is the recent ban on oxo-degradable plastics in the EU under Directive 2019/904/EC due to concerns over their rate of degradation in unmanaged environment and associated false claims, thus misleading consumers [73].

In addition, there are concerns that claims of biodegradability could lead to a rise in littering among the public, with 'green' labels effectively acting as a license to dispose of bioplastic packaging in the environment, under the assumption they will break down and therefore pose no threat to the environment [61]. However, given the high perceived value of BBPs and that littering is more a cultural than individual behavioural issue [70], such a phenomenon is arguably unlikely to occur. In the context of OFMSW management, successful rollouts in complex and highly dynamic environments (e.g., the cities of Milan, Barcelona, Copenhagen and Ljubljana) [26] can help build a portfolio of case studies for future policy interventions. One common element is often the recognition that consumers are often ill-informed and ill-equipped, and facilitating the step between motivation and action through consumer awareness campaigns and harmonising waste disposal and collection schemes may lead to more effective interventions.

5. Conclusions

By addressing the topic of BBPs under the umbrella of a circular bioeconomy, this perspective aimed to provide a paradigm shift for future studies on BBP biodegradation in the biowaste management stream. Bioplastics can contribute towards building a more sustainable future, but the precautionary principle should be applied to avoid the classic situation of burden shifting. Development and use of BBPs should be targeted for niche applications where biodegradability is meaningful and compatible with targeted organic waste streams. As the BBP market share continues to grow, the study of biodegradation of BBPs urgently needs to adequately reflect their intended end-of-life under current and future waste management practices. Future work should focus on co-digestion with FW, and further research is needed to characterise the best conditions required to ensure optimal biodegradation of BBPs in FW AD.

Achieving sustainability requires a systems-thinking approach. Many operational, logistical, legislative and economic hurdles remain to be addressed before BBPs can be accommodated effectively and extensively. Without a holistic policy framework, it is unclear whether BBPs will deliver on their ambitions. Strengthening the crosstalk between manufacturers, retailers, local authorities, plant operators, farmers, consumers and policymakers will be vital to build a more sustainable and resilient supply chain.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/environments9010009/s1, Table S1: Summary of studies on biodegradable bioplastics (BBPs) and food waste (FW) anaerobic co-digestion.

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