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CASE STUDY

Composting of Algae-Derived Bioplastics from Anaerobic Digestion of Wastewater Biosolids for Sustainable Management: A Field-Scale Case Study

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Abstract

Background: The scale of environmental damage caused by plastic pollution highlights the need to implement sustainably sourced biodegradable plastics within the global economy. Microalgae biofilms cultivated on rotating algae biofilm reactors (RABRs) using anaerobically digested municipal wastewater provide a feedstock for bio-based and biodegradable bioplastic production for practical environmental management applications.

Algix, LLC, a company based in Meridian, Mississippi, specializes in manufacturing bioplastic products from microalgae suspended in aqueous environments [1]. Algix, LLC manufactures bioplastics for multiple products, including shoes and agricultural mulch films. The Sustainable Waste-to-Bioproducts Engineering Center at Utah State University (USU) in Logan, Utah collaborated with Algix, LLC and the 230,000 m3/day Central Valley Water Reclamation Facility in Salt Lake City, Utah to create a bio-based polyester using microalgae biomass cultivated on an 11.4 m3 pilot-scale rotating algae biofilm reactor (RABR). While the physicochemical properties of the bioplastics have been described [2], the biodegradation characteristics of this bio-based polyester have not been evaluated.

The purpose of this research was to investigate the biodegradation of biofilm microalgae-based bioplastic under temperature- and moisture-controlled conditions in a full-scale composting system at CVWRF.

Methods: ASTM Method D6400 was used to quantify the biodegradability of thin-film samples of the bioplastic composed of 30% algae biomass over a

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16-week period.

Results: Thin film samples of the algae-based bioplastics were reduced in mass from 5 g to less than 0.01 g and in size from 8500 mm2 to particle sizes less than 40 mm2 after 16 weeks. A polyethylene negative control showed no disintegration based on mass loss and size reduction.

Conclusions: Bioplastic samples made from RABR-cultivated algae biofilms retained no measurable mass on a 6.35 mm sieve after 16 weeks of aerobic composting. However, further studies utilizing triplicate conditions for each plastic sample are recommended to increase the statistical robustness of the resulting data.

Introduction

Plastics are versatile polymers that have become critically important materials in many industries. In 2015, 322 tonnes of plastic were manufactured worldwide; this amount was forecast to double by the year 2035 [3]. Although plastics are important and useful materials, they account for vast amounts of waste that accumulate in the environment. Plastic packaging totaled 74.8 million tons, or 31.6% of the total municipal solid waste, in the United States in 2003 [4]. Moreover, nearly 34 million tons of plastic waste are generated annually worldwide; 93% of this waste is ultimately disposed of in landfills or oceans [5].

In the United States, landfilling is the most common method of plastic waste disposal, followed by recycling, incineration, and composting [6]. While the recycling of plastic packaging materials has increased in recent years, the recycling rates for plastic packaging materials are still low [7]. According to Eurostat, 31% of plastic packaging waste was incinerated, 39% was landfilled, and only 6% was recycled [8]. The varying compositions of plastics and contamination during their use make recycling difficult, which explains the logistical preference for landfilling and incineration [9]. These plastic waste disposal practices have negative consequences for the environment; nearly 400 million tonnes of carbon dioxide are released from plastic waste to the environment per year [3].

Plastic waste has also accumulated in the environment; at least 5.25 trillion plastic particles, weighing 269,000 tonnes, was estimated to be polluting the oceans as of 2013 [10]. Both macroplastics and microplastics pollute the soil, which can be harmful to both the environment and the population [11]. The plastics that constitute these pollutants are mainly derived from crude oil [12], and although these crude oil-derived plastics, such as polyethylene (PE) and polyvinylchloride (PVC), are very useful because of their chemical stability and hydrophobicity, they do not degrade easily and tend to persist in the environment [13]. For example, PE and PVC remained almost completely unchanged after being buried in soil for 32 years [14]. Additionally, since fossil fuels are becoming increasingly scarce, petroleum-derived plastics such as PE and PVC are becoming increasingly energetically expensive to manufacture [1].

Sustainable bioproducts are becoming increasingly important in the effort to mitigate the impacts of pollution and climate change. The scale of environmental damage caused by plastic pollution highlights the need to implement sustainably sourced biodegradable plastics within the global economy. Bioplastics are promising solutions to the problems of plastic pollution in the environment and nonrenewable resource usage. Bio-based polymers reduce environmental impact by utilizing renewable carbon sources, while biodegradable plastics reduce environmental damage by easily disintegrating when discarded into the environment [15]. For example, biodegradable plastics such as polylactic acid (PLA) can degrade in approximately 1.5 years in an oceanic environment [16]. A more detailed summary of plastic degradation rates is found in table 1 However, only approximately 1% of plastics currently in production are bioplastics and about 55.5% of bioplastics are biodegradable [17].

The mechanisms of biodegradation depend on the intrinsic material properties of the plastic (including glass transition temperature, crystallinity, melting temperature, and hydrophobicity) and the environmental conditions (including UV exposure, oxidation, mechanical stress, hydrolysis, and microbial activity) [26]. Abiotic phenomena, such as UV exposure and oxidation, lead to fragmentation and disintegration of the polymer; however, only microbial activity can achieve the complete mineralization of the polymer [26]. Biodegradation by microbial activity occurs when microorganisms adhere to the surface of the plastic and subsequently form a biofilm; microbial enzymes then bind to the surface of the plastic substrate and the polymer chain length is reduced by hydrolysis [30]. Extracellular depolymerases secreted by microorganisms facilitate the hydrolytic catalysis of biodegradable polyesters [31]. A common reaction mechanism for the biodegradation of polyesters by depolymerases involves aspartate, histidine, and serine. Aspartate and histidine interact to form a hydrogen bond; the histidine ring acts as a base to deprotonate serine, which generates a very nucleophilic alkoxide group. The alkoxide group then attacks the ester bond, forming an alcohol end-group and acyl-enzyme complex; this acyl-enzyme bond is attacked by water to produce the free enzyme and a carboxyl end group [30].

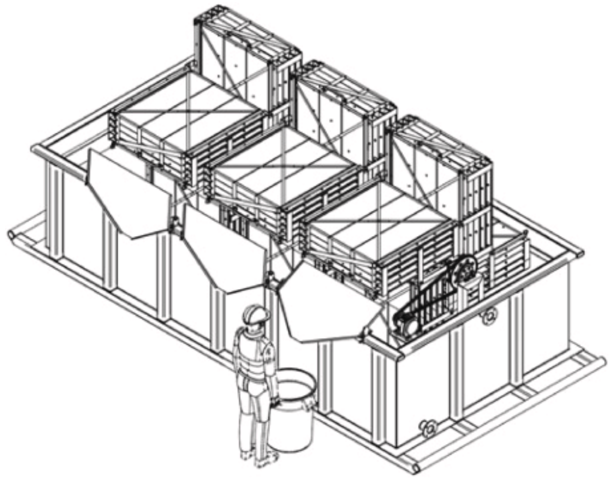

Figure 1 A diagram of the Rotating Algae Biofilm Reactor at Central Valley Water Reclamation Facility. Courtesy of WesTech Engineering [18].

Table 1: Degradation properties of various bioplastics.

Polymer type	Mineralization %	Half-life	Degradation rate
PLA	85.75% at 90 days [18]	--	0.500 day^{-1} [18]
PHB	96% at 60 days [19]	14 days [20]	--
PBS	31 % at 80 days [21] 60% at 40 days [57]	--	0.01 day^{-1} [21]
PCL	90% at 47 days [22] 12.8% at 49 days [59]	--	--
PGA	39% at 18 days [23]	--	--
PLGA	--	7-14 days [24]	--
PPDO	70.49% at 65 days [25]	--	--
PHBV	100% at 70-90 days [26]	--	--
PEA	6% at 15 days [27]	--	--
PE/Starch	11.5% at 90 days [18]	--	1.000 day^{-1} [18]
PBAT	67.3% at 45 days [28]	--	--
PLLA	100% at 28 days [29]	--	--

Microalgae biofilms cultivated on Rotating Algae Biofilm Reactors (RABRs) using municipal wastewater are a possible feedstock for bio-based bioplastic production [32]. Microalgae feedstocks for bioplastic production can be produced on non-arable land, be used to reclaim wastewater, and increase CO_2 sequestration by

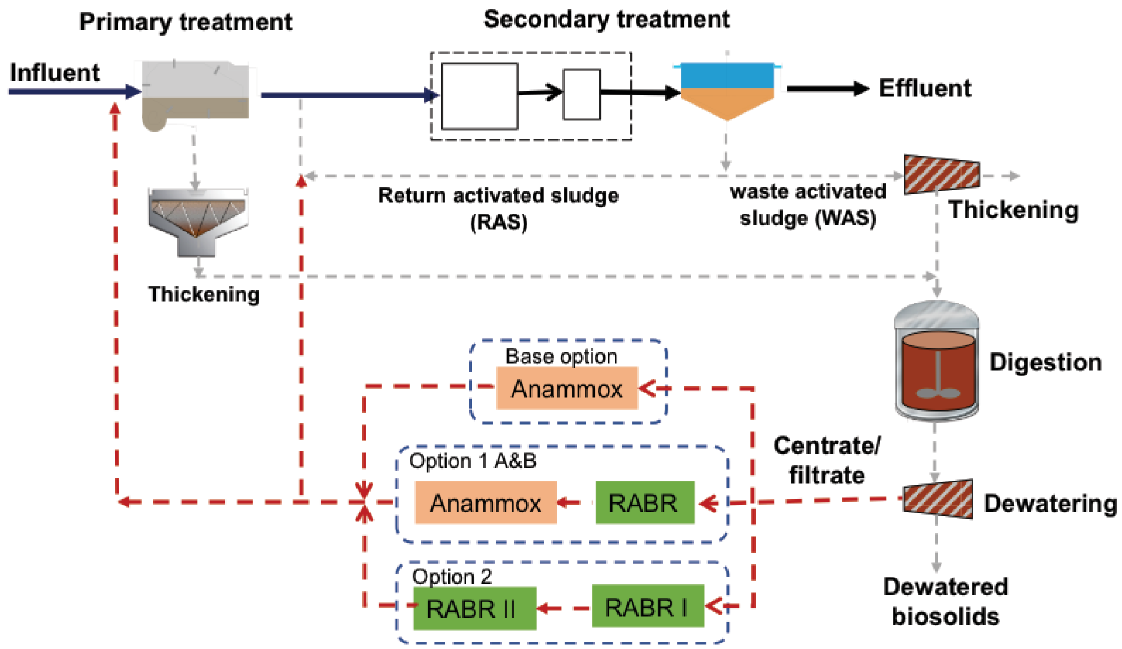

Figure 2 Schematic of the CVWRF water treatment process. The influent for the Rotating Algae Biofilm Reactor is the anaerobic digester effluent. The anaerobic digester effluent is filtered using a belt press; the filtrate from the belt press is then pumped into the RABR [19]. Diagram courtesy of CVWRF.

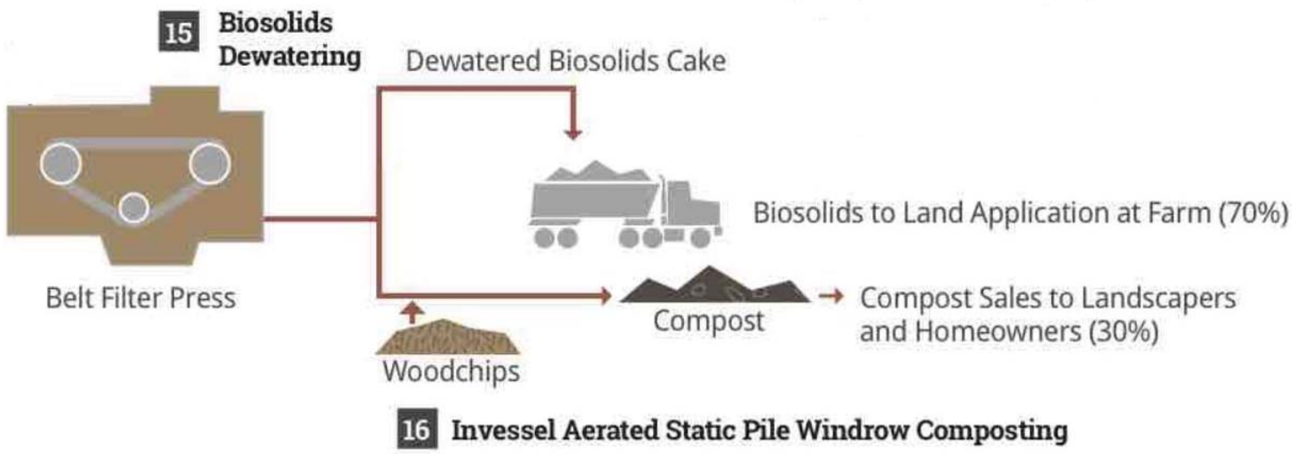

Figure 3 Schematic of the biosolids dewatering process at CVWRF. The dewatering process in Figure 1.2 is the belt filter press in this diagram. The dewatered biosolids are combined with woodchips in an aerated static pile composting process. Diagram courtesy of CVWRF.

enhancing global photosynthetic capacity [33].

The Central Valley Water Reclamation Facility (CVWRF) in Salt Lake City, Utah, was the test site for an 11.4 m^3 pilot-scale RABR. A diagram of the RABR is shown in figure 1. The RABR uses a series of stainless-steel shelves affixed to a rotating drum. Attached to the shelves are 1 m2 square sheets of recycled plastic substratum, which serve as a surface for biofilm growth. The rotating drum and shelves are centered over an 11.4 m^3 rectangular water vessel with a working volume of 11,400 L [34]. The water vessel contains clarified nitrogen and phosphorus-rich anaerobic digester effluent, which is filtered through a belt press to remove

Table 2: Dimensions and masses of all plastic film samples.

Plastic Film Samples			
Sample Name	**Dimensions (mm)**	**Mass (g)**	**Sample Description**
PE	100x85	1.1 ± 0	Polyethylene negative control
AA30	100x85	1.7 ± 0	30% commercially-sourced algae
BPE0	100x85	1.5 ± 0	0% algae biodegradable polymer
AB30	100x85	1.7 ± 0	30% RABR algae
AB30E	100x85	1.6 ± 0	30% RABR algae + biodegradation-enhancing resin

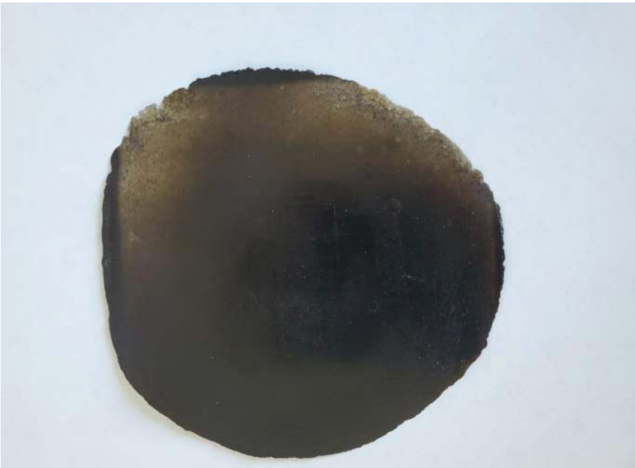

Figure 4 Bioplastic sample containing 30% RABR algae biomass (AB30).

suspended biosolids; the biosolids are combined with woodchips and placed in a composting process. The nitrogen and phosphorus in the anaerobic digester effluent are at high concentrations of approximately 45 mg/L total phosphorus and 470 mg/L total nitrogen and are utilized for algae cultivation. The anaerobic digester effluent was pumped through the RABR at 1.5 L/min using a variable-speed peristaltic pump, with a hydraulic retention time of 5 days [34]. A schematic of the RABR within the CVWRF treatment process is shown in figure 2 [35]. A diagram of the CVWRF composting process is shown in figure 3.

Struvite, a mineral composed of nitrogen, phosphorus, and magnesium at a molar ratio of 1:1:1, has been observed in the microalgae biomass on the RABR [34,36]. This mineral acts as a fertilizer and can be incorporated into bioplastics made from microalgae containing it [32]. While AD-cultivated biofilm algae containing struvite has been demonstrated to serve as an effective fertilizer [37], the biodegradation of bioplastics containing struvite has not been previously published in the refereed literature and is addressed in this research.

The incorporation of biofilm algae with high mineral (ash) content as nutrients into thermoplastic bioplastic performs as a filler that enhances the quality of a bioplastic [32]. Fillers are utilized in bioproducts production to reduce shrinkage during the settling process. Fillers are also used to improve tensile strength and hardness of bioplastic, as well as to reduce the cost of bioplastic resin per kg of product. The nutrients that comprise the ash that are then incorporated into the bioplastic.

The struvite-rich microalgae biomass cultivated on the CVWRF RABR was harvested and processed for bioplastic production. The bioplastics in this study were biodegradable polyesters produced by Algix, LLC [1]. While Algix used the struvite-rich microalgae biomass from the CVWRF RABR to produce these bioplastics, the biodegradation properties of this novel bio-based bioplastics produced from microalgae biomass must be characterized to estimate the utility of such materials.

The purpose of this study was to quantify the biodegradation characteristics of bioplastics

Table 3: Mass of plastic debris remaining on 6.35 mm (¼-in.) sieve, measured after 8 weeks and 16 weeks.

Mass retained on sieves (g)					
	AB30	AB30E	AA30	BPE0	PE
0 weeks	5.00	5.00	5.00	5.00	5.00
8 weeks	3.78	2.29	3.91	3.83	5.00
16 weeks	0.00	0.00	0.00	0.00	5.00

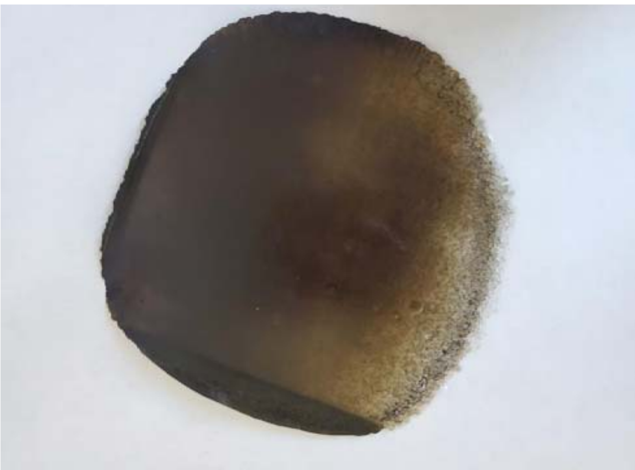

Figure 5 Bioplastic sample containing 30% RABR algae with a biodegradation-enhancing resin (AB30E).

produced from biofilm microalgae biomass containing struvite. Specifically, this study measured the reduction in mass and reduction in size of samples provided by Algix, LLC through time of composting in a full-scale municipal aerobic and controlled compost system used to produce commercially available compost.

Materials and Methods

Industry field-scale testing

The following methods were based on Section 6.2 of the ASTM D6400 standard specification for labeling of plastics designed to be aerobically composted in municipal or industrial facilities [38].

Algae collection and drying

Between June 2022 and April 2023, algae biomass was harvested weekly using mechanical scraping using a garden hoe from the pilot-scale Rotating Algal Biofilm Reactor (RABR) at Central Valley Water Reclamation Facility (CVWRF) in Salt Lake City, Utah. Simultaneously, biomass samples were collected from the trickling filters at the CVWRF facility to supplement the biomass harvested from the RABR. The wet biomass samples were taken to the Algae Processing and Products (APP) facility at Utah State University in Logan, Utah. The trickling filter and RABR biomass samples were dried at 60°C for 48 hours. A total of 20 lbs (9.07 kg) of dry algae biomass was collected, which was the minimum amount required by Algix for bioplastic production. The dry biomass was ground into a coarse powder with a particle size of approximately 1-2 mm. Analysis by Goldsberry demonstrated the presence of struvite in the microalgae biomass cultivated on anaerobic digester effluent [34].

Bioplastic production

The dry algae biomass was shipped to Algix, LLC in Meridian, Mississippi for bioplastic production. Algix, LLC provided five different thin film polymers for testing; these plastic samples are shown in figures 4-8, and their characteristics are summarized in table 2.

All samples were a biodegradable polyester blend, which were prepared for biodegradation testing using twin extrusion on a corotating screw setup for compound development. The final parts were then molded on an injection molder.

The parts provided were all 30% algae by weight except for the positive and negative controls which were 0% algae. There were 3 parts provided with 30% algae which included

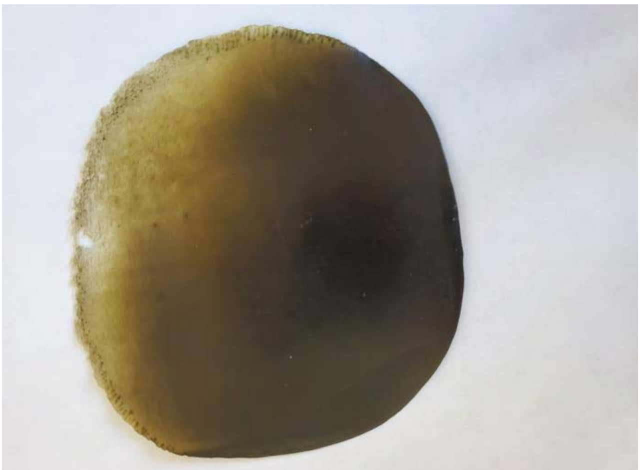

Figure 6 Bioplastic sample containing 30% algae biomass derived from commercially available sources (AA30).

Figure 7 Bioplastic sample containing 0% algae (BPE0).

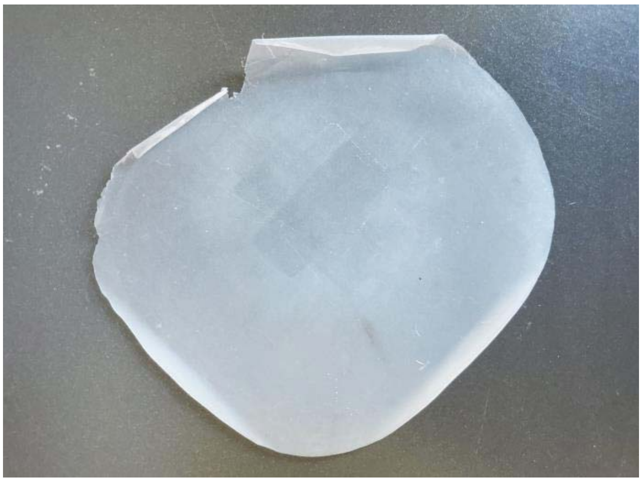

Figure 8 Negative control sample made from polyethylene (PE).

a biodegradable resin with CVWRF RABR algae, a biodegradable resin with an additive to improve biodegradation with CVWRF RABR algae, and a control sample containing the same biodegradation additive with the same biodegradable resin but with commercially available sources of algae used in industry currently. These test parts were supplied as-is for testing in biodegradation tests and were pressed on a compression molder into thin films to mimic the conditions of an agricultural mulch film. The parts were molded using 67% of the original masterbatch compounds to yield the finished 30% algae content.

Masterbatch compounding on the extruder was all conducted with a temperature range from 110-180 °C in extruder settings. The laboratory extrusion was conducted at a rate of 1.5 kg/h, which represents between 75 and 90% of the maximum throughput of the extruder. This is reflective of what could be accomplished with this composition given a skilled operator and algae appropriately prepared for production by drying and milling. The masterbatch compositions all contained 45% algae from either CVWRF or commercial sources and those compositions with a biodegradation additive at a loading of 1.5%; the remaining portion of all

Figure 9 Compost pile at CVWRF where the compost vessels were buried.

Figure 10 The five compost vessels in the CVWRF compost pile.

Figure 11 Plastic samples after the first eight-week compost period: AB30 (A), AB30E (B), AA30 (C), BPE0 (D), PE (E).

masterbatches was biodegradable resin.

Industry field-scale testing

Plastic samples AB30, AB30E, AA30, BPE0, and PE were placed in a full-scale municipal biosolids composting process at CVWRF (Figure 9). The samples were each encased in separate compost vessels with CVWRF compost inoculum. Five compost vessels were built using perforated stainless steel spherical containers, each with an approximate volume of 8 L; the vessels are shown in the compost pile in figure 10. Each vessel was filled with compost inoculum and 5 g thin film plastic sample. The containers were then buried approximately 1 m deep into the compost pile for 54 days. The samples were removed from the pile for measurement and examination, and then replaced into the stainless-steel containers and incubated in the compost pile for another 60 days at a depth of 1 m. The temperature was maintained between 60 and 70 ˚C for both compost periods.

At the end of each biodegradation period, the degradation of the materials was measured quantitatively by screening the contents of each vessel through a 12.7mm (½-in.) and 6.35 mm (¼-in.) stainless steel sieve to recover the remnants of the plastic and measuring the mass of the sample remaining in the sieve. The samples were photographed and visually examined for qualitative measurement.

Results and Discussion

Quantitative results

The contents of each compost vessel were emptied through a 12.7 mm (½-in) and 6.35 mm (¼-in) stainless steel sieve; all bioplastic particles retained on the sieves were weighed. Table 3 shows the masses of the retained bioplastic particles after the first and second compost periods. All samples except for the PE negative control retained no measurable mass on the sieves after the second compost period. These results indicate that the AB30, AB30E, AA30, and BPE0 plastics are capable of disintegration under aerobic composting conditions, in contrast to the PE control.

Qualitative results

All samples except for the negative control were significantly texturally fractured and disintegrated after the first compost period. The samples showed extreme brittleness and fragility except for the negative control. All samples excluding the negative control showed significant discoloration and fading. Figure 11 shows the contents of each vessel following the first compost period, and figure 12 shows the contents of each vessel following the second compost period. These photographs visually demonstrate the disintegration of the AB30, AB30E, AA30, and BPE0 samples.

Conclusions

Industry field-scale testing

Each plastic type except for the polyethylene negative control retained no measurable mass of sample on the 6.35 mm (1/4 in.) sieve after a total of 16 weeks retention time in the compost pile; the negative control remained intact and retained the original mass of 5 g on the sieve. The reduction of mass and particle size of the AB30, AB30E, AA30, and BPE0 samples indicates that the samples demonstrated disintegration during the controlled composting conditions.

Limitations of the study

This study has several limitations surrounding the experimental setup, results, and conclusions. Because of practical constraints of measuring the mass loss and size reduction of the plastic samples, the entire 5 g mass of each plastic sample was placed in each respective compost vessel. Therefore, there were no replicates of the compost vessels, and there were no samples run in parallel. The results and conclusions of this study should therefore be considered in the context of these experimental limitations.

Because of the large-scale nature of this study, the measurement of carbon dioxide produced as a result of plastic biodegradation was impractical. Therefore, this study cannot provide any conclusions on the mineralization of the plastic samples. The scope of this study is limited to observing the disintegration of the plastic samples measured by mass loss and particle size reduction.

Recommendations for future work

In order to overcome the aforementioned limitations, future studies could use larger initial masses of plastic samples so that each

Figure 12 Plastic samples after the second eight-week compost period: AB30 (A), AB30E (B), AA30 (C), BPE0 (D), PE (E).

condition could be tested in triplicate. A study with triplicate compost vessels for each plastic type would enable a more robust statistical analysis for the resulting data.

Furthermore, future experiments could analyze the microorganisms within the compost mixture and on the bioplastic surface. This analysis would provide insight into the mechanisms of biodegradation and could help determine if mineralization of the plastics has occurred. Additional laboratory-scale biodegradation studies could also assess mineralization of the plastics by measuring carbon dioxide production from the compost.

Additionally, further studies could assess the presence of microplastics such as polyfluoryl alkylated substances (PFAS) in the final compost mixture. This would enable the evaluation of potential accumulation of PFAs from wastewater into the algae biofilm used for bioplastic production.

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Conflicts of Interest

Ashton Zeller works for BLOOM Sustainable Materials, a technology company which converts algae biomass into thermoplastic compounds for use in consumer products. Ashton Zeller helped produce the plastic samples that were tested in this study. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethics Approval and Consent to Participate

Not applicable

Consent for Publication

Not applicable

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' Contributions

- **Clayton Lords**: Writing – original draft, Writing – review and editing, Methodology, Resources, Investigation, Data curation.
- **Ronald Sims:** Writing -- review and editing, Resources, Methodology, Conceptualization, Supervision, Project administration, funding acquisition.
- **Philip Heck:** Resources, Methodology. Ashton Zeller: Writing – original draft, Methodology, Resources.
- **Tansley Mazurkiewicz:** Writing – original draft, Writing – review and editing, Methodology

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