Compost
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Compostable Plastics

LITERATURE REVIEW

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Compostable Plastics Literature Review

The Compostable Plastics Literature Review focused on the following questions:

1. Formation and fate in the environment of microplastics derived from compostable bioplastics under industrial-scale composting conditions.

2. Factors that optimize the disintegration and biodegradation of compostable bioplastics during industrial-scale composting, including additives.

3. Analysis and/or comparison of biodegradation under anaerobic and aerobic conditions.

Section I. Formation and Fate of Microplastics

Accinelli, C., et.al., "Persistence in soil of microplastic films from ultra-thin compostable plastic bags and implications on soil *Aspergillus flavus* population", Waste Management Volume 113, 15 July 2020, Pages 312-318, https://www.sciencedirect.com/science/article/pii/S0956053X20303214

> An increasing number of states and municipalities are choosing to reduce plastic litter by replacing plastic items, particularly single-use ones, with same-use products manufactured from compostable plastics. This study investigated the formation and persistence of compostable film microplastic particles (CFMPs) from ultra-thin compostable carrier bags in soil under laboratory conditions, and the potential impact of CFMPs on *Aspergillus flavus* populations in the soil.
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> During a 12-month incubation period, compostable film samples in soils with small, medium or large populations of indigenous *A. flavus*, underwent 5.9, 9.8, and 17.1% reduction in total surface area, respectively. Despite the low levels of deterioration, the number of CFMPs released increased steadily over the incubation period, particularly fragments with size < 0.05 mm. Up to 88.4% of the released fragments had associated *A. flavus* and up to 68% of isolates from CFMPs produced aflatoxins. *A. flavus* levels associated with CFMPs increased rapidly during the initial part of the 12-month incubation period, whereas the percent aflatoxigenicity continued to increase even after *A. flavus* density leveled off later. During 12 months incubation, *A. flavus* DNA amounts recovered from CFMPs increased in soils with all levels of indigenous *A. flavus*, with the largest increases (119.1%) occurring in soil containing the lowest indigenous *A. flavus*. These results suggest that burying compostable film in soil, or application of compost containing CFMPs, may reduce soil quality and increase risk of adverse impacts from elevated aflatoxigenic *A. flavus* populations in soil.

Agarwal, S., "Biodegradable Polymers: Present Opportunities and Challenges in Providing a Microplastic-Free Environment", Macromolecular Chemistry and Physics, Vol. 221, No. 6, March 2020, https://onlinelibrary.wiley.com/doi/full/10.1002/macp.202000017

> The stability of polymers against environmental factors, chemicals, microorganisms, and hydrolysis has challenged society with the accumulation of plastic waste and its management worldwide. Large amounts of plastic litter accumulate in the environment and disintegrate into microplastics (small pieces less than 5 mm in size), a topic of real concern especially for products and applications where the plastics are used for a short time before becoming waste, and where they are difficult to recover after use and remain in the environment. Whether biodegradable polymers can be one of the solutions to the problem of plastic waste is a question very often raised in this context. Although the use of biodegradable polymers appears to be highly promising based on recent and past studies, several aspects need to be considered further regarding environmental sustainability, acceptability, and degradability in the complex natural environment. Intensive efforts need to be invested in developing new environmentally biodegradable polymers and smart mechanisms of degradation after use in the environment. The present viewpoint article discusses the present scenario of the environmental acceptability of biodegradable polymers and the opportunities and challenges they offer regarding solving the problem of microplastics and their impact on the environment.

Mendez, H., et.al., "Investigation on the Behaviour of Plastics during the Biological Treatment of Organic Wastes", http://uest.ntua.gr/heraklion2019/proceedings/pdf/112_HERAKLION2019_Mendez_etal.pdf

> Microplastics (MP) (plastics <5 mm) are increasingly seen as a burden. Most MP entering the aquatic systems are often disposed on land, but little is known about their possible accumulation in terrestrial ecosystems. Organic fertilizers produced from organic waste might be a potential entry of MP into the soil. This research aim is to understand the behaviour of PE, PBAT, and PLA during the degradation of organic waste to assess their disintegration and to formulate recommendations for fermentation and composting practices. The mechanical, thermal and biological properties of the plastics will be determined in static and dynamic systems with different temperature ranges as well as retention times. For that, laboratory scale reactors for fermentation and composting processes were installed. A composting preliminary experiment was carried out during seven weeks to test the performance of the tumbler and to investigate possible physical changes on low-density polyethylene (LDPE) and high-density polyethylene (HDPE). After seven weeks, microscopic changes were observed on the surface of the HDPE films as scratches. The results from the preliminary experiment provided an insight on the performance of the compost tumbler and the quality of the compost. Preliminary fermentation tests will be carried out in the future and therefore results are not included here.

Shruti, V.C. and G. Kutralam-Muniasamy, "Bioplastics: Missing link in the era of Microplastics", Science of The Total Environment, Volume 697, 20 December 2019, 134-139, https://www.sciencedirect.com/science/article/abs/pii/S0048969719341166

> Concerns about microplastics (MPs) environmental behavior and accumulation are growing at global scale and meanwhile, the attention to employ bioplastics for replacing conventional plastics is increasing. The research priority for a better understanding of the fate and potential impacts of MPs from bioplastics is of utmost importance. However, the investigations on the effects of bioplastics in terms of MPs are still limited and largely unknown. In this discussion, the current knowledge of MPs is timely highlighted to incorporate biodegradable MPs in the ongoing researches. Recent studies have identified that some biodegradable MPs exhibit same effect as conventional type MPs. Furthermore, we performed a simple degradation experiment and found that polyhydroxyalkanoate films formed MPs in water environment alike other biodegradable and conventional plastics sharing common research interests. In an effort to promote investigations, we recommend the knowledge gaps identified on bioplastics MPs: understanding the timeframe of disintegration and degradation of developing bioplastics; ensuring degradability and less persistence; promoting toxicity tests and potential effects on a wide variety of organisms; promoting attempts to assess the impacts on ecosystems; evaluating the interaction of microorganisms and MPs; working towards identifying novel disposal and collection methods from public to ease recycling and degradation processes.

Smith, M., "Do Microplastic Residuals in Municipal Compost Bioaccumulate in Plant Tissue?" Master's Thesis, January 2018, https://fido.nrk.no/6e41301a36fb4dc3ffd8d26cfe45c223ab76709b3648b84883e2126a42192e33/Smith2018.pdf

> Conventional and biodegradable polymers present in residential and commercial organic waste have a propensity to fragment during the composting process. This research explores whether microplastic residuals present in industrially produced compost bioaccumulate in plant tissue grown in this medium. The experimental design was modeled on methodologies used in aquatic research of microplastics in bivalves to determine whether these marine research methodologies can be adapted for terrestrial applications. Of the 30 plant tissue samples grown in the industrially produced compost, the presence of suspected microplastics was observed in 57% of the samples through histological staining. Additional phytotoxicity testing and heavy metal analysis of the compost samples showed no evidence of ecotoxicity in the industrial compost. Further observation of the plant tissue and compost samples through infrared spectrometry needs to be conducted to identify the observed foreign bodies in the plant tissue as microplastics of non-organic polymer origin.

Sun, Y., et.al., "The degradation performance of different microplastics and their effect on microbial community during composting process", Bioresource Technology, Vol. 332, July 2021 at https://www.sciencedirect.com/science/article/abs/pii/S0960852421004727

> The objectives of this study were to investigate the degradation characteristics of different microplastics (polyethylene (PE), polyvinyl chloride (PVC), polyhydroxyalkanoates (PHA) and their effect on the bacterial community during composting. In this study, 0.5% PE, 0.5% PVC and 0.5% PHA microplastics were individually added to the mixture of cow manure and sawdust and then composted for 60 days. The treatment without microplastics was regarded as control. Results indicated that the abundance and smaller size (0–800 μm) of microplastics in all treatments obviously decreased after composting, except PVC treatment. The surface morphology of all microplastics occurred obvious erosions and cracks and the carbon content of PE, PVC and PHA microplastics were reduced by 30, 17 and 30%, respectively. After composting, all microplastics were significantly oxidized and the functional groups O–H, C=O and C–O increased. Furthermore, all microplastics exposure reduced the richness and diversity of bacteria community at thermophilic phase, especially PVC microplastics.

Section II. Degradation of Compostable Plastics, Effects of Additives

Al Hosni, A., et.al., "Microbial degradation of four biodegradable polymers in soil and compost demonstrating polycaprolactone as an ideal compostable plastic", Waste Management, Vol. 97, Sept. 2019, p. 105-114 at https://www.sciencedirect.com/science/article/abs/pii/S0956053X19305124

> Plastics are an indispensable material but also a major environmental pollutant. In contrast, biodegradable polymers have the potential to be compostable. The biodegradation of four polymers as discs, polycaprolactone (PCL), polyhydroxybutyrate (PHB), polylactic acid (PLA) and poly(1,4 butylene) succinate (PBS) was compared in soil and compost over a period of more than 10 months at 25°C, 37°C and 50°C. Degradation rates varied between the polymers and incubation temperatures but PCL showed the fastest degradation rate under all conditions and was completely degraded when buried in compost and incubated at 50°C after 91 days. Furthermore, PCL strips showed a significant reduction in tensile strength in just 2 weeks when incubated in compost >45°C. Various fungal strains growing on the polymer surfaces were identified by sequence analysis. *Aspergillus fumigatus* was most commonly found at 25°C and 37°C, while *Thermomyces lanuginosus*, which was abundant at 50°C, was associated with PCL degradation.

Castro-Aguirre, E., et.al., "Enhancing the biodegradation rate of polylactic acid film and PLA bio-nanocomposites in simulated composting through bioaugmentation", Polymer Degradation and Stability, Vol. 154, August 2018, p. 46-54 at https://www.sciencedirect.com/science/article/pii/S0141391018301708

> Biodegradable polymers provide an opportunity to divert plastic waste from landfills, with composting as an alternative disposal route. However, some biodegradable polymers, such as poly (lactic acid) (PLA), do not biodegrade as fast as other organic wastes during composting, affecting their general acceptance in industrial composting facilities. Bioaugmentation, the addition of specific microbial strains, is a promising technique to accelerate the biodegradation of compostable plastics, so that they biodegrade in comparable time frames with other organic materials. In this study, we evaluated the effect of bioaugmentation on the biodegradation of PLA and PLA bio-nanocomposites (BNCs) in simulated composting conditions. PLA, PLA with 5% organo-modified montmorillonite (PLA-OMMT5), and PLA with 0.4% surfactant (PLA-QAC0.4) films were produced and fully characterized. PLA-degrading bacteria were isolated through an enrichment technique with PLA as the sole carbon source at 58°C. Isolates were identified as *Geobacillus* using 16 S rRNA gene sequencing and the NCBI database, and further used to study the effect of bioaugmentation on the biodegradation rate of PLA and BNCs in solid environments. The biotic and abiotic degradation was assessed in compost, inoculated vermiculite, and uninoculated vermiculite at 58°C by analysis of evolved CO_2 using an in-house built direct measurement respirometer. Size exclusion chromatography was also used to measure and to monitor the change in molecular weight of the film samples retrieved every week during the biodegradation test. The microbial attachment on the surface of PLA of the isolated microbial strain and other microorganisms present in the compost was evaluated by a biofilm forming assay in wells incubated at 58°C. Bioaugmentation with *Geobacillus* increased the evolution of CO_2 and accelerated the biodegradation phase of PLA and BNCs when tested in compost and inoculated vermiculite with compost mixed culture. Bioaugmentation could commercially be used to accelerate the biodegradation of PLA in compost environments.

Del Campo, A., et.al., "Accelerated disintegration of compostable Ecovio polymer by using zinc oxide particles as filler", Polymer Degradation and Stability, Vol. 185, March 2021, https://www.sciencedirect.com/science/article/pii/S0141391021000215

> Zinc oxide (ZnO) compounds exert a catalytic effect on the degradation of polyesters and could affect the biodegradability of such polymers. Herein, composites of 2% wt. of ZnO particles and biodegradable commercial Ecovio polymer, a blend of poly(lactic acid) (PLA) and a copolyester, are prepared by melt extrusion process to further study the effect of the incorporation of ZnO particles on the biodegradability of this polyester under composting conditions. Different nano- and micro-sized ZnO particles are employed to investigate the effect of the size, morphology, and surface charge of ZnO on the physicochemical properties of the polymeric composite and nanocomposite by differential scanning calorimetry (DSC) and thermogravimetric analyses (TGA). The influence of such compounds on the compost

disintegradability is further investigated by different techniques including, gel permeation chromatography (GPC), confocal Raman microscopy and energy dispersive x-ray spectrometer (EDX). The results demonstrate that the ZnO particles significantly accelerate the disintegration process of the Ecovio polymeric blend under a composting environment.

DelRe, C., et. al., "Near-complete depolymerization of polyesters with nano-dispersed enzymes", *Nature*, April 2021. https://www.nature.com/articles/s41586-021-03408-3

Successfully interfacing enzymes and biomachinery with polymers affords on-demand modification and/or programmable degradation during the manufacture, utilization and disposal of plastics, but requires controlled biocatalysis in solid matrices with macromolecular substrates. Embedding enzyme microparticles speeds up polyester degradation, but compromises host properties and unintentionally accelerates the formation of microplastics with partial polymer degradation. Here we show that by nanoscopically dispersing enzymes with deep active sites, semi-crystalline polyesters can be degraded primarily via chain-end-mediated processive depolymerization with programmable latency and material integrity, akin to polyadenylation-induced messenger RNA decay. It is also feasible to achieve processivity with enzymes that have surface-exposed active sites by engineering enzyme–protectant–polymer complexes. Poly(caprolactone) and poly(lactic acid) containing less than 2 weight percent enzymes are depolymerized in days, with up to 98 percent polymer-to-small-molecule conversion in standard soil composts and household tap water, completely eliminating current needs to separate and landfill their products in compost facilities. Furthermore, oxidases embedded in polyolefins retain their activities. However, hydrocarbon polymers do not closely associate with enzymes, as their polyester counterparts do, and the reactive radicals that are generated cannot chemically modify the macromolecular host. This study provides molecular guidance towards enzyme–polymer pairing and the selection of enzyme protectants to modulate substrate selectivity and optimize biocatalytic pathways. The results also highlight the need for in-depth research in solid-state enzymology, especially in multi-step enzymatic cascades, to tackle chemically dormant substrates without creating secondary environmental contamination and/or biosafety concerns.

Kalita, N.K., et.al., "Demonstrating an ideal compostable plastic using biodegradability kinetics of polylactic acid based green biocomposite films under aerobic composting conditions", Environmental Challenges, Vol. 3, April 2021, at https://www.sciencedirect.com/science/article/pii/S2667010021000093

This study demonstrates the kinetics of aerobic biodegradation of melt-extruded poly(lactic acid) (PLA) based biocomposite films by online monitoring of CO_2 using gas chromatography technique following ASTM International D 5338–15 protocol. Biodegradation studies of PLA and its biocomposites were carried out in the presence of compost microbes, without the addition of any external inoculum. The first-order kinetics model was modified by incorporating a linear lag phase for each test sample. Bacterial identification by 16S rRNA gene sequencing

showed *Bacillus flexus* as one of the microbes responsible for biodegradation of the exposed films at thermophilic temperatures. Neat PLA (NPLA) and PLA/Chitosan composite films were found to evolve high amounts of C–CO_2 (carbon-to-carbon dioxide). C–CO_2 conversion was found to be very low in PLA/cellulose nanocrystals and PLA/gum arabic biocomposites, expressing the presence of only 4% and 6% slowly hydrolysable carbon, respectively, as compared to NPLA and PLA/chitosan samples. The C-CO_2 evolution rate was the highest for PLA/chitosan sample at 1.13 day^{-1}. Experimental data of all the test samples showed a good fit (R^2 ~ 99.99) with the kinetic model. Morphological analysis by FESEM confirmed the erosion of polymer during composting.

Karamanlioglu, M. & U. Alkan, "Influence of Degradation of PLA with High Degree of Crystallinity on Fungal Community Structure in Compost", Compost Science & Utilization, April 2021 at https://www.tandfonline.com/doi/full/10.1080/1065657X.2020.1864514

Degradation rate of poly(lactic acid) (PLA), a compostable plastic, is affected by its physical properties and environmental conditions. Since PLA with different physical properties enter composting systems, investigation of degradation of PLA with strong physical properties in compost at different temperatures and its influence on compost fungal community structure are the main concerns of this study. To determine the effect of slow PLA degradation on fungal communities, PLA granules with high degree of crystallinity, 60%, were incubated in compost at 25°C and 50°C for 4 months at 0, 10, 25 and 50% (w/w) concentrations; their degradation rates were compared and impact of PLA degradation on compost fungal communities was examined by terminal restriction fragment length polymorphism (TRFLP). PLA granules in compost at 25°C showed no physical changes but at 50°C physical disintegration occurred after 4 months. TRFLP revealed that fungal community profiles in compost were affected by PLA, particularly at 50°C where PLA degraded. Compost fungal communities in the presence of PLA at 50°C had more variation, 63%, than at 25°C (52%). Incubation time affected fungal community structure as during 2nd month, community structure changed specifically at 50°C and at 50% (w/w) PLA, however, became similar to that in the absence of PLA at the end of fourth month at both temperatures indicating PLA with a high degree of crystallinity causes a temporal perturbation in compost fungal communities. In compost containing PLA at 50°C, abundance of certain TRFs representing fungal populations increased to 30% which may involve in PLA utilization.

Moraczewski, K., et.al., "Composting of Polylactide Containing Natural Anti-Aging Compounds of Plant Origin", Polymers, 11 (10), 2019, p. 1582 at https://www.mdpi.com/2073-4360/11/10/1582

The paper presents the effects of biodegradation of polylactide containing natural anti-aging compounds. Polymer containing 0.5; 5 and 10 wt % of coffee, cocoa or cinnamon extracts were subjected to industrial composting for 7, 14, 21 or 28 days. The effect of the composting process on polylactide properties was examined based on visual assessment, scanning electron microscopy, average molecular weight, differential scanning calorimetry, thermogravimetry,

and tensile strength. The impact of the tested extracts on the effects of the composting process was compared with the impact of a commercially available anti-aging compound. It was found that the tested extracts in most cases did not adversely affect the effects of the composting process compared to pure polylactide, often resulting in intensification of biodegradation processes. As a result of the composting process, changes in the macro- and microscopic appearance of the samples and a decrease in molecular weight, phase transition temperatures, thermal resistance, and thermal strength were observed on a scale close to or greater than the reference anti-aging compound.

Muniyasamy, S., et.al., "Thermal-chemical and biodegradation behaviour of alginic acid treated flax fibres/poly(hydroxybutyrate-*co*-valerate) PHBV green composites in compost medium", Biocatalysis and Agricultural Biotechnology, Volume 22, November 2019, at https://www.sciencedirect.com/science/article/abs/pii/S187881811930725X

In this study, thermal-chemical and biodegradation behaviour of green composites based on flax fibres untreated and treated with alginic acid treated, and poly hydroxybutyrate-*co*-valerate (PHBV) were studied under composting conditions. The biodegradability of PHBV composites and neat PHBV were assayed by monitoring CO_2 production from polymeric carbon under controlled aerobic composting conditions as per ASTM D5338 standard. During the biodegradation process, PHBV composites thermal-chemical and morphology properties were characterized by thermogravimetric analysis (TGA), Fourier transform infra-red (FT-IR) and scanning electron microscopy (SEM) techniques. The ultimate biodegradation (mineralization) study results showed alginic acid treated flax/PHBV composites has higher rate of degradation than untreated flax/PHBV composite and neat PHBV. TGA analysis indicated that an increased t-onset temperature for alginic acid treated flax fibers/PHBV composites which was mainly due to the influence of 2% sodium alginate treated with flax fibers. FTIR results showed the increased degradation of PHBV composites was due to the hydrolytic chain scission mechanisms influenced by presence of alginic acid and flax fibers as compared to neat PHBV matrix. Morphological SEM analysis showed PHBV composites biodegradation were readily attacked by fungus but rather PHBV degradation by bacteria. This study found that the incorporation of flax fibers into PHBV matrix provides a benefit to the green composites with enhanced biodegradability.

Qi, X., et.al., "New advances in the biodegradation of polylactic acid", International Biodeterioration and Biodegradation, Vol. 117, Feb. 2017, p. 215-223, at https://www.sciencedirect.com/science/article/abs/pii/S0964830517300100

Poly(lactic) acid (PLA) is currently a most potential and popular polymeric material, which will play a key role in building of a sustainable bioeconomy. Knowledge of biodegradation of PLA is crucial for treating plastic wastes and easing the serious energy crisis. The biodegradability of PLA based on microorganisms (actinomycetes, bacteria, fungus) and biochemical processes of degradation have been advanced in recent years, but the high efficient

methods of PLA biodegradation are still inadequately addressed. With the development of the modern molecular biological techniques, some studies have detected specific groups of microorganisms involved in the biodegradation process of PLA. Nevertheless, few studies were conducted to establish the simulated system based on aerobic biodegradation of PLA due to the lack of available information on process parameters. In this review, PLA is treated according to its synthesis mechanisms, applications, biochemical processes in degradation, degrading microorganisms and enzymes. In addition, the simulated system based on aerobic microorganism is also presented for acceleration of PLA degradation.

Rose, R-S., et.al., "Microbial Degradation of Plastic in Aqueous Solutions Demonstrated by CO_2 Evolution and Quantification", International Journal of Molecular Sciences, Vol. 21, No. 4, p. 1176, Feb. 2020 at https://www.mdpi.com/1422-0067/21/4/1176

The environmental accumulation of plastics worldwide is a consequence of the durability of the material. Alternative polymers, marketed as biodegradable, present a potential solution to mitigate their ecological damage. However, understanding of biodegradability has been hindered by a lack of reproducible testing methods. We developed a novel method to evaluate the biodegradability of plastic samples based on the monitoring of bacterial respiration in aqueous media via the quantification of CO_2 produced, where the only carbon source available is from the polymer. *Rhodococcus rhodochrous* and *Alcanivorax borkumensis* were used as model organisms for soil and marine systems, respectively. Our results demonstrate that this approach is reproducible and can be used with a variety of plastics, allowing comparison of the relative biodegradability of the different materials. In the case of low-density polyethylene, the study demonstrated a clear correlation between the molecular weight of the sample and CO_2 released, taken as a measure of biodegradability.

Sednickova, M., et.al., "Changes of physical properties of PLA-based blends during early stage of biodegradation in compost", International Journal of Biological Macromolecules, Vol. 113, July 2018, p. 434-442 at https://www.sciencedirect.com/science/article/abs/pii/S0141813017333561

Three biodegradable plastics materials, namely pure poly(l-lactide) (PLA), PLA with plasticizer triacetine (TAC) and the mixture PLA/polyhydroxybutyrate (PHB) and TAC were investigated concerning changes of physical properties due to biodegradation in compost at 58°C up to 16 days. With rising time of degradation in compost, both number and weight molecular masses were decreasing progressively, but only marginal change of the polydispersity index was observed which indicates that biodegradation is not random process. FTIR spectroscopy revealed that in spite of the extensive decrease of molecular weight, no substantial change in chemical composition was found. The most significant modification of the spectra consisted in an appearing of the broad band in region 3100–3300 cm^{-1}, which was assigned to a formation of biofilm on the sample surfaces. This effect appeared for all three materials, however, it was much more pronounced for samples containing also triacetine. Measurement of changes in crystalline portion confirmed that amorphous phase degrades substantially faster compared to crystalline part. The plasticizer

triacetine is disappearing also rather fast from the sample resulting besides other effect also in a temporary increase of Tg, which at the beginning grows almost to the value typical for PLA without plasticizer but later the Tg is decreasing due to substantial changes in molecular weight. Generally during composting, the samples keep shape for up to 8 days, after that time the material disintegrates to rough powder.

Tolga, S., et.al., "Progress of Disintegration of Polylactide (PLA)/Poly(Butylene Succinate) (PBS) Blends Containing Talc and Chalk Inorganic Fillers under Industrial Composting Conditions", Polymers, 13 (1), 2021 at https://www.mdpi.com/2073-4360/13/1/10

> Biodegradable plastics are experiencing increasing demand, in particular because of said property. This also applies to the two biopolyesters poly(lactic acid) (PLA) and poly(butylene succinate) (PBS) covered in this study. Both are proven to be biodegradable under industrial composting conditions. This study presents the influence of mineral fillers on the disintegration process of PLA/PBS blend systems under such conditions. Chalk and talc were used as fillers in PLA/PBS (7:3) blend systems. In addition, unfilled PLA/PBS (7:3/3:7) blend systems were considered. Microscopic images, differential scanning calorimetry and tensile test measurements were used in addition to measuring mass loss of the specimen to characterize the progress of disintegration. The mineral fillers used influence the disintegration behavior of PLA/PBS blends under industrial composting conditions. In general, talc leads to lower and chalk to higher disintegration rates. This effect is in line with the measured decrease in mechanical properties and melting enthalpies. The degrees of disintegration almost linearly correlate with specimen thickness, while different surface textures showed no clear effects. Thus, we conclude that disintegration in a PLA/PBS system proceeds as a bulk erosion process. Using fillers to control the degradation process is generally regarded as possible.

Wilfred, O., et.al., "Biodegradation of Polylactic Acid and Starch Composites in Compost and Soil", International Journal of Nano Research, Vol. 1, No. 2, 2018 at https://research.bangor.ac.uk/portal/files/22767119/2018_Biodegradation_of_Polyactic_Acid_and_Starch_Composites_in_Compost_and_soil.pdf

> The use of biodegradable polymers and their composites have wide applications and high demands because they can be ideal alternatives to non-biodegradable polymers due to the growing global environmental concerns. The biodegradation of PLA and starch-based plastic composites by the use of enzymes was studied in a commercial compost and soil. The composites were prepared from two biopolymers, *i.e.* polylactic acid (PLA) and starch, using Brabender 30 EHT mixer at the composition of 10:90, 25:75, 50:50, 75:25 and 90:10 (weight ratio) respectively, and then their degradability was investigated under controlled compost and soil burial laboratory conditions for 14 and 28 days. The degradation was measured throughout the period of the experiment by visual inspection, gel permeation chromatography (GPC), thermal gravimetric analysis (TGA), scanning electron microscopy (SEM), Fourier transform infrared (FTIR), titration and gas chromatography (GC). GPC analysis

confirmed that the molecular weight of PLA decreased due to degradation, while TGA analysis showed a lower thermal stability for the composites containing more starch. The visual inspection and SEM analysis revealed that the size of polymer composites reduced while the shape became less regular owing to the biodegradation. FTIR spectra of polymer composites showed strong carbonyl bands between 1750.9 cm-1-1760.2 cm-1 that became broader with a slight shift to higher wave number to 1756.1 cm-1-1763.7 cm-1 after degradation. Moreover, the addition of lipase into the compost and soil promoted the degradation rate of polymer composites, leading to the generation of more CO_2 gas and more weight loss, compared to the experimental results obtained without the use of lipase. To conclude, the degradation rate of PLA/starch composites can be tailored by changing the composition and environmental conditions (such as temperature and the addition of enzymes).

Zhang, H., et.al., "Disintegration of compostable foodware and packaging and its effect on microbial activity and community composition in municipal composting", International Biodeterioration & Biodegradation, Vol. 125, November 2017, p. 157-165 at https://www.sciencedirect.com/science/article/abs/pii/S0964830517302354

Despite the compostability certification of compostable foodware and packaging (CFP) in lab conditions, composting facilities are reluctant to accept CFP. Certified CFP at 10 and 20% by volume were examined in four types of composting practices in British Columbia, Canada to assess disintegration. Laboratory studies were conducted to determine CFP amended with compost feedstocks at 1 and 2% by weight effects on microbial activity and community structure. Results showed disintegration varied significantly by CFP and facility type. Nearly 90% of poly-lactic acid based CFP completely disintegrated in the in-vessel and static pile, followed by turned windrow (63%) but only 30% of CFP in the anaerobic digestion operation. The disintegration of fibre based CFP was significantly lower than other CFP across composting practices. Increased concentration of CFP enhanced disintegration only in the static pile. Doubling the concentration of CFP (2 vs.1%) in laboratory conditions significantly increased microbial activity (150% of CO_2 respiration) and abundance of microbial community groups, i.e., total phospholipid fatty acids, and those of gram-positive bacteria and fungi by 45, 330 and 28%, respectively. These results indicate that under ideal composting conditions CFP products are likely to disintegrate completely and higher concentrations may enhance their biodegradation.

Section III. Biodegradation Under Anaerobic and Aerobic Conditions

Bandini, F., et.al., "Fate of Biodegradable Polymers Under Industrial Conditions for Anaerobic Digestion and Aerobic Composting of Food Waste", Journal of Polymers and the Environment, Vol. 28, p. 2539-2550, June 2020 https://www.researchgate.net/publication/342320273_Fate_of_Biodegradable_Polymers_Under_Industrial_Conditions_for_Anaerobic_Digestion_and_Aerobic_Composting_of_Food_Waste

Biodegradable polymers were introduced in the past decades in order to address the issue of plastic pollutions, and these materials have thus required the development of methodologies to understand and evaluate their disintegration. The aim of this study was to simulate the organic fraction of municipal solid waste (OFMSW) treatment in laboratory-scale and to assess the biodegradation of poly(lactic acid) (PLA) water bottles and starch-based bags under real industrial conditions of anaerobic digestion and aerobic composting. Methane production and loss of mass were determined to estimate the anaerobic degradation; whereas phytotoxicity tests were carried out to provide an evaluation of the compost quality. To visualize the effects on the materials, SEM analyses, differential scanning calorimetry (DSC) and FT-IR/ATR spectroscopy were performed. Different outcomes were found for the tested bioplastics products. PLA bottles didn't biodegrade under anaerobic conditions and the pieces appeared wrap up at the end, while starch-based bioplastic bags performed 85.79% of disintegration degree. CH_4 production was between 40 and 50% for both the products. Phytotoxicity test on the final composts highlighted negative effects on both selected seeds for PLA solutions. Water-soluble lactic acid from degraded PLA bottle significantly reduced the pH of compost affecting seed germination and germination indexes. Both bioplastics showed chemical modification according to DSC and FT-IR/ATR analyses.

Ruggero, F., et.al., "Methodologies to assess biodegradation of bioplastics during aerobic composting and anaerobic digestion: A review", Waste Management & Research, Vol. 37, No. 10, 2019, https://journals.sagepub.com/doi/full/10.1177/0734242X19854127

Bioplastics are emerging on the market as sustainable materials which rise to the challenge to improve the lifecycle of plastics from the perspective of the circular economy. The article aims at providing a critical insight of research studies carried out in the last 20 years on the degradation of bioplastics under aerobic composting and anaerobic digestion conditions. It mainly focuses on the various and different methodologies which have been proposed and developed to monitor the process of biodegradation of several bioplastic materials: CO_2 and CH_4 measurements, mass loss and disintegration degree, spectroscopy, visual analysis and scanning electron microscopy. Moreover, across the wide range of studies, the process conditions of the experimental setup, such as temperature, test duration and waste composition, often vary from author to author and in accordance with the international standard followed for the test. The different approaches, in terms of process conditions and monitoring methodologies, are pointed out in the review and highlighted to find significant correlations between the results obtained and the experimental procedures. These observed correlations allow critical considerations to be reached about the efficiency of the methodologies and the influence of the main abiotic factors on the process of biodegradation of bioplastics.

Ruggero, F., "Bioplastics in the organic fraction of MSW: influence of composting process conditions on biotic and abiotic degradation and fate of residues", Doctoral degree dissertation, University of Firenze, October 2020, https://flore.unifi.it/retrieve/handle/2158/1232623/584858/PhD%20Thesis%20Federica%20Ruggero.pdf

The worldwide market of bioplastic products, both film (e.g. biobags) and rigid (e.g. cutleries, dishes, coffee capsules), underwent a significative increase in the last decade. Bioplastics have been considered a suitable alternative to conventional plastics for their cleaner life cycle. They can derive from renewable resources and be treated with the organic waste, to become compost and enter in the chain of food and agriculture. Thus, they are posed as virtuous example of circular economy. Compostable bioplastics, meaning those materials certified to be treatable in aerobic and anaerobic biological processes, should be collected with the organic waste and conferred to aerobic composting possibly preceded by anaerobic digestion. However, some issues have risen in the last years about bioplastic waste management in the industrial treatments for the organic waste. In fact, the conditions set during the tests for standard certifications can largely differ from those of the biological industrial aerobic and anaerobic plants, referring to temperature, humidity and times of the processes.

This research aims to stress the effect of the operative conditions on bioplastics degradation, particularly in aerobic composting. It started from the observation of the industrial composting plants in Italy and Europe to carry out lab scale tests with various operative conditions, and developed a synergic approach of methodologies to monitor their effect on the degradation of Mater-Bi®, polybutylene adipate terephthalate, polylactic acid and polyethylene. The study considered different aspect of the degradation, including chemical and physical analyses to assess the level of deterioration at different times of the tests, and microbiological analyses to investigate how the bacterial community can become more specialized in degrading polymers.

The obtained results disclosed that some critical operative conditions cannot ensure a complete degradation of the complex bioplastics, raising the issue of microplastics release as part of compost in soil and definitively in water environments. Therefore, lab scale tests were carried out in soil, sand, fresh and saltwater, to explore the behaviour of bioplastic residues derived from incomplete degradation in composting. Unfortunately, it was demonstrated that the outside conditions are not favourable for the degradation process to continue. Finally, it was stressed an important question related to microplastics monitoring in compost and sludge, derived from both aerobic and anaerobic biological treatments. The current legislation set a threshold size of 2 mm for plastics quantification in these matrices, basically for a lack of a standardized protocol allowing to identify and recover items smaller than this size. Therefore, an extraction method was tested on microplastics derived from both conventional plastics and bioplastics, with the objective to make a step more towards the capability to properly monitor and characterize compost and sludge quality.