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SAMMENDRAG/SUMMARY:

Summary

Food waste collection in Norway is mostly done using plastic bags, made either of polyethylene or, more recently, of biodegradable plastics, which are materials that can be degraded by microorganisms under certain environmental conditions and time frames. Most of the biodegradable plastic bags used in Norway for food waste collection are labelled as compostable, i.e. degradable under composting conditions, but end up in biogas plants and only rarely in composting plants. The present work provides answers to the following questions. First, to what extent are biodegradable plastic bags deteriorated during anaerobic digestion of food waste. Secondly, is the situation different under mesophilic (37°C) and thermophilic (55°C) conditions. Finally, does thermal hydrolysis (THP) pretreatment of food waste containing biodegradable plastic change the results.

In tests offering optimal conditions for microorganisms involved in anaerobic digestion, limited deterioration of biodegradable plastics (Mater-Bi® certified as compostable under industrial (ICP) and home (HCP) composting conditions, representative of what is used in Norway for food waste collection for biogas production) was observed, as shown by limited mass loss (14-21 % for ICP and 22-33 % for HCP) and limited changes in the chemical composition after 22 d, a relevant hydraulic retention time for industrial biogas plant operations. Higher mass loss was observed under thermophilic conditions compared to mesophilic conditions. The effect of THP pretreatment of food waste containing

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biodegradable plastics offered unexpected results: while a small, non-significant increase in mass loss was observed for ICP, THP led to a significantly reduced mass loss for HCP during anaerobic digestion. The biogas process itself was not significantly affected by ICP and HCP present in food waste at a 4 % plastic to food waste ratio. The present research shows that the majority (79-86 % of ICP and 67-78 % of HCP) of biodegradable plastic residues left after initial pretreatment of food waste, will withstand anaerobic conditions, both under mesophilic and thermophilic conditions, also when subjected to THP pretreatment (5 bars, 160°C, 20 min). This strongly suggests that post-treatment of digestate is required to avoid the spread of biodegradable plastics to agricultural soils, for digestates intended for agricultural use.

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FYLKE/COUNTY:	Akershus
KOMMUNE/MUNICIPALITY:	Ås
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Innhold

Norsk sammendrag

Matavfall samles inn i Norge hovedsakelig i plastposer laget av enten polyetylen eller av bionedbrytbar plast, en felles betegnelse for plasttyper som lar seg bryte ned av mikroorganismer under visse forhold og tidsrammer. De fleste bionedbrytbare plastposene som brukes i Norge til innsamling av matavfall er sertifisert som komposterbare (nedbrytbare under komposteringsforhold), men havner for det meste i biogassanlegg og kun sjelden i komposteringsanlegg. Målet med dette arbeidet var å få svar på det følgende: 1) I hvilken grad brytes bionedbrytbar plast ned under anaerob utråtning av matavfall? 2) Er situasjonen forskjellig under mesofile (37°C) og termofile (55°C) forhold? 3) Er resultatene annerledes når matavfall som inneholder bionedbrytbar plast forbehandles med termisk hydrolyse (THP)?

Etter 22 dager under optimale forhold for mikroorganismer involvert i anaerob utråtning, ble det observert begrenset nedbrytning av bionedbrytbar plast (Mater-Bi® sertifisert som industrielt komposterbar «ICP» eller hjemmekomposterbar «HCP»), som vist ved begrenset massetap (14-21 % for ICP og 22-33 % for HCP) og begrensede endringer i deres kjemiske sammensetning. Høyere massetap ble målt under termofile forhold sammenlignet med mesofile forhold. Effekten av THP-forbehandling (5 bar, 160°C, 20 min) av matavfall med bionedbrytbar plast ga uventede resultater: Mens THP førte til en liten, ikke-signifikant, økning i massetap av ICP, førte THP til statistisk signifikant lavere massetap av HCP etter anaerob utråtning, sammenlignet med ikke THP-behandlet HCP. Selve biogassprosessen ble ikke påvirket av at det var 4 % (på tørrvektbasis) bionedbrytbar plast i matavfall. Resultatene viser at det meste (79-86 % av ICP og 67-78 % av HCP) av plasten i biosubstrat (dvs. plast som ikke ble fjernet av forbehandling av våtorganisk avfall) ikke påvirkes av anaerob utråtning, selv under termofile forhold, og selv med THP-forbehandling. Dette tyder sterkt på at etterbehandling av biorest, f.eks. med kompostering, er nødvendig for å unngå tilførsel av bionedbrytbar plast på landbruksjord.

1 Introduction

Food waste is a sizeable issue in the EU, with over 59 million tonnes generated annually, from which 54 % comes from households, accounting for 72 kg per inhabitant each year (Eurostat, 2024). Norwegian households generated 219 000 tonnes food waste in 2023, accounting for 40 kg per inhabitant (SSB, 2024). Since 2024, EU member states are obliged by the Waste Framework Directive to introduce separate collection for bio-waste (i.e. green waste (from park and gardens) and food waste), and similarly, the Norwegian Waste Regulation was revised in 2023, requiring from all municipalities to sort green waste and food waste from households at the source. **Most (77 %) food waste in Norway goes to biogas production**, with the remaining going to composting facilities (SSB, 2024).

Biogas is a renewable energy source produced through the anaerobic digestion of organic materials such as agricultural waste, sewage, and food waste. This process involves the breakdown of organic matter by microorganisms, resulting in the release of methane and carbon dioxide. Biogas is a versatile and sustainable fuel that can be used for electricity generation, heating, and as a vehicle fuel, contributing to both waste management and reduced greenhouse gas emissions. Food waste is an attractive biogas substrate, as it is energy rich, with ca. 20-30 % dry matter content, ca. 90 % organic matter content, and relatively balanced in terms of nutrient composition.

Food waste collection in Norway is mostly done using plastic bags made of polyethylene or, more recently, of biodegradable plastic, with some municipalities also using paper bags. **Biodegradable plastics are materials that can be degraded by microorganisms**. Under favourable conditions of temperature, humidity and nutrients, and variable time frames, microorganisms colonize the surface of biodegradable plastics, release enzymes able to depolymerize biodegradable polymers, and use the monomers as food source, eventually leading to the production of new microbial biomass, water and CO_2 (and methane under anaerobic conditions). Biodegradable plastic bags used for food waste collection in Norway are commonly labelled as home compostable or compostable in industrial facilities, which guarantees that these materials should be degraded within one year at 20-30 °C (under home composting conditions) and within six months at 60 °C (under industrial composting conditions). It is obvious that **the time frame, biological and physicochemical conditions** required for a satisfactory degradation of these materials are **not compatible with those occurring in biogas plants**. Yet, increasing numbers of biodegradable plastic bags are used in Norway to collect food waste, which as we saw above, end up mostly in biogas plants, and seldom in composting plants. While the majority is removed from food waste through pretreatment steps (e.g. sieving), a small fraction of biodegradable plastic residues follows the biological substrate treated by anaerobic digestion.

The questions answered in this study

- To what extent are biodegradable plastic bags degraded during anaerobic digestion of food waste?
- Is the situation different under mesophilic (37 °C) and thermophilic (55 °C) conditions?
- Does thermal hydrolysis pretreatment of food waste containing biodegradable plastic affect the results?

The way we answered these questions

- Mass loss and changes in chemical composition of biodegradable plastics were assessed under all treatment conditions (mesophilic and thermophilic, with and without thermal hydrolysis pretreatment, and for both home compostable and industrially compostable plastics).
- Physicochemical parameters of the digestate, as well as biogas production and composition were analysed.

The ultimate aim is to increase our understanding and awareness of potential risks posed by **materials entering other waste treatment plants than those for which they are intended**.

2 Materials and methods

2.1 Biodegradable plastic bags

The test materials were biodegradable plastic bags purchased from BioBag® (Askim, Norway) and made of Mater-Bi® (Novamont S.p.A.), which according to the manufacturer is produced from starches, cellulose, vegetable oils and their combinations (Fig. 1). These bags are **extensively used for food waste collection** in Norway. The first material, referred to as **ICP** for industrially compostable plastic, had the TUV Austria certification "**OK compost industrial**", which should guarantee that the material is biodegradable in an industrial composting plant, according to the European standard EN 13432:2000. The second material, referred to as **HCP** for home compostable plastic, had the TUV Austria certification "**OK compost home**", which is not based on a standard, but is the basis of standards AS 5810:2010, NF T 51800:2015 and EN 17427:2022.

The bags were cut into squares of 25 × 25 mm, with an individual mass of 13.5 ± 0.3 mg (mean ± standard variation, SD) for ICP and 11.5 ± 0.2 mg for HCP. Biodegradable plastic bits were weighed at the beginning and the end of the experiment, using a Mettler-Toledo XSR204DR weighing scale (Mettler-Toledo GmbH, Switzerland).

Figure 1. The two types of plastic bags used in the study: Industrially compostable (ICP, left) and home compostable (HCP, right).

2.2 Food waste and inoculum

Food waste, collected from our research institute's canteen, was composed of vegetables, pasta, fruits, eggshells, bread, and meat to a lesser extent. It was homogenized, ground into a slurry, sieved at <1 cm, and kept at -18°C until use in the experiments.

Food waste was characterized (Table 1) with respect to total solids (TS), volatile solids (VS), chemical oxygen demand (COD), pH, ammonium (NH_4), and FOS/TAC (an indicator of the fermentation process, where FOS is a measure of volatile organic acids and TAC of buffer capacity, i.e. calcium carbonate). TS (%) was determined after 24 h at 105 °C, and VS (% of TS) after another 15 h at 550 °C. COD was measured spectrophotometrically after oxidation with potassium dichromate at 220 °C for 3 h. NH_{4+} was determined as total ammonium and measured spectrophotometrically. FOS/TAC was determined by auto titration with sulfuric acid (modified Norman method, Hashemi et al., 2023).

The mesophilic inoculum (37 °C) was collected from a lab scale continuously stirred tank reactor (CSTR, 10 L effective volume), with cow manure as substrate and hydraulic retention time (HRT) of 25 d. The thermophilic inoculum (55 °C) was established by transferring 5 L of the above-mentioned mesophilic inoculum to another CSTR (10 L effective volume) set to 55 °C, and adapted to thermophilic operation over a period of 20 d. The reactors were not fed during the adaptation time. Inoculums were characterized with respect to TS, VS, COD, pH, NH_4 and FOS/TAC (Table 1).

Table 1. Total solids (TS), volatile solids (VS), chemical oxygen demand (COD), pH, ammonium (NH_4) and fermentation indicator FOS/TAC characteristics of food waste and inoculums used in anaerobic digestion tests with industrially compostable (ICP) and home compostable (HCP) plastics. Results are provided as mean ± standard deviation (SD).

		TS (%)	VS (%TS)	COD (g/L)	pH	NH_4 (g/L)	FOS/TAC
Food waste	ICP	24.0 ± 0.1	82.7 ± 0.1	273.7 ± 1.8	n/a	6.4 ± 0.1	12.5
	HCP	23.1 ± 0.1	82.0 ± 0.6	270.9 ± 1.4	n/a	6.2 ± 0.1	12.2
Mesophilic inoculum	ICP	3.4 ± 0.2	64.6 ± 0.3	22.3 ± 0.4	7.4	7.7 ± 0.1	0.4
	HCP	3.6 ± 0.1	69.8 ± 0.2	25.4 ± 0.1	7.4	6.8 ± 0.2	0.3
Thermophilic inoculum	ICP	2.8 ± 0.5	66.1 ± 2.5	25.1 ± 0.3	7.9	7.0 ± 0.2	0.1
	HCP	4.5 ± 0.1	75.3 ± 0.1	36.4 ± 0.1	7.8	7.6 ± 0.1	0.2

2.3 Thermal Hydrolysis Process

Plastic bags were subjected to thermal hydrolysis process (THP, Fig.2) using a steam explosion unit (Cambi, Asker, Norway, see Sahu et al. (2022) for more details), consisting of a 20 L pressure reactor connected to a 200 L steam boiler and a flash tank with removable bucket to collect THP treated materials. The THP system was operated at **5 bars (160°C) for 20 min**, **to represent conditions relevant to full-scale biogas production plants treating food waste**. Biodegradable plastic bags, in 25 × 25 mm squares, were subjected to THP both alone and together with food waste, in which case the **plastic bag to food waste ratio was 4 % on dry matter basis** (similar to that used in the anaerobic digestion experiment). The plastic to food waste ratio was chosen as to represent the proportion of biodegradable plastic in municipal organic waste (Calabrò and Grosso, 2018; Cucina et al., 2021; Gadaleta et al., 2022). After being submitted to THP in presence of food waste, biodegradable plastic bits were recovered with tweezers, washed with water and air dried before use in the anaerobic digestion experiment.

Figure 2. Thermal hydrolysis process (THP) unit used for pretreatment of biodegradable plastics, either on their own or mixed with food waste (as shown on the right picture).

2.4 Anaerobic digestion in batch mode

The biochemical methane potential (BMP) in food waste with and without plastics was studied in batch mode using 500 mL glass bottles. The experimental setup featured **28 bottles per biodegradable plastic type** (Fig. 3): four treatments with plastic, each in four replicates (mesophilic and thermophilic digestion with pristine plastic; mesophilic and thermophilic digestion with THP treated plastic), and for both inoculum types, negative controls (in triplicates, microbial inoculum only, to assess background biogas production of the inoculum) and positive controls (in triplicates, microbial inoculum and cellulose, for process validation).

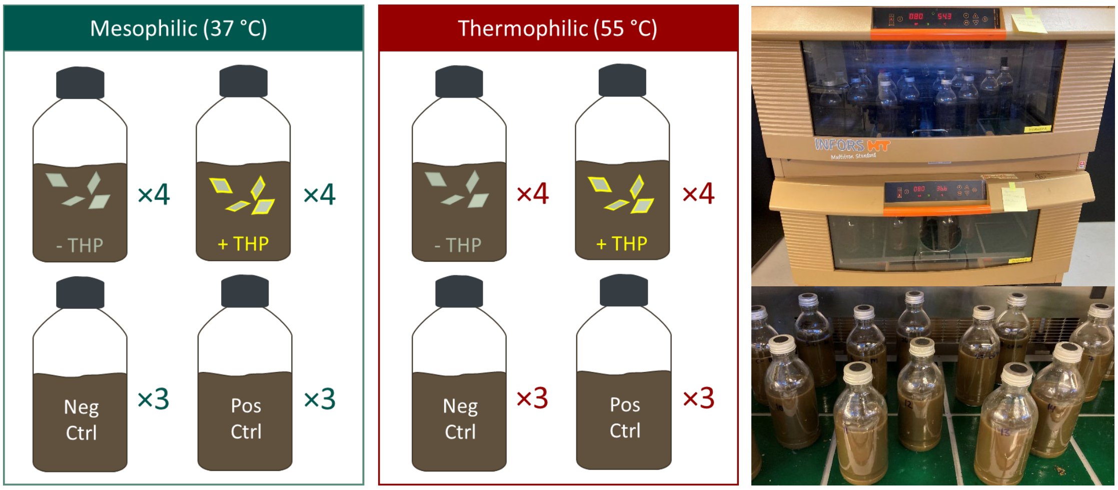


Figure 3. Experimental setup conducted for both biodegradable plastic types. Thermal hydrolysis (THP) pretreatment was applied to half of the plastic treatments, the other half was tested without THP. The actual BMP bottles and incubation cabinets are shown on the right.

Food waste and inoculum were added to the bottles at an **Inoculum Substrate Ratio of 2**, i.e. 2 g VS inoculum and 1 g VS food waste. This corresponded to 52-107 g wet weight (ww) inoculum (depending on VS content shown in Table 1) and 5 g ww food waste. Negative controls received 2 g VS inoculum and no other carbon source, and positive controls received 2 g VS inoculum and 1 g cellulose (microcrystalline, Thermo Scientific) instead of food waste. **Four 25×25 mm squares of pristine plastic or their equivalent mass for THP treated plastic** were added per bottle, corresponding to 54 ± 2 mg ICP and 45 ± 2 mg HCP, and a **plastic to food waste ratio of approx. 4 %** (4.4 % and 3.7 % for ICP and HCP, respectively). Tap water was then added to the bottles to reach a total volume of 400 mL, leaving a headspace of 125 mL. The bottles were sealed using rubber stoppers tightened with metal screw caps. The headspace was flushed with N_2 after sealing, to remove oxygen. All bottles were incubated in Methrom cabinets at their respective temperatures (37 °C and 55 °C). Gas pressure in the bottles was recorded and released daily during the first 11 d, thereafter every 2-3 d, and the total gas volume produced was calculated and reported at standard temperature and pressure. **The experiment lasted for 22 d** (HRT 22 d).

At the end of the experiment, **CH_4, CO_2, and H_2S concentrations** were analysed by gas chromatography (Agilent 990 Micro GC), the **chemical composition of the digestate** (pH, TS, VS, COD, pH, NH_4, NH_3, and FOS/TAC) was determined in each bottle (as described in section 2.3), and degradation rate and mass balance in terms of **mL biogas produced per g VS** added were calculated.

2.5 Biodegradable plastic analysis

At the end of the experiment (day 22), biodegradable plastics were recovered with tweezers by careful inspection of the whole bottle content, small volumes at a time, to keep the liquid transparent and easy to inspect. **Due to limited plastic deterioration during the experiment, recovery was simple**: the plastic squares from the treatments without THP were seemingly intact with the naked eye, and so were the more irregularly shaped plastic fragments in the THP treatments. Plastic samples were washed in tap water, and gently but thoroughly dried with blotting paper, to remove any remaining biofilm and organic matter that could influence the final mass (Fig. 4). Finally, the **plastics samples were weighed** using a Mettler-Toledo XSR204DR weighing scale (Mettler-Toledo GmbH, Switzerland) and pictured.

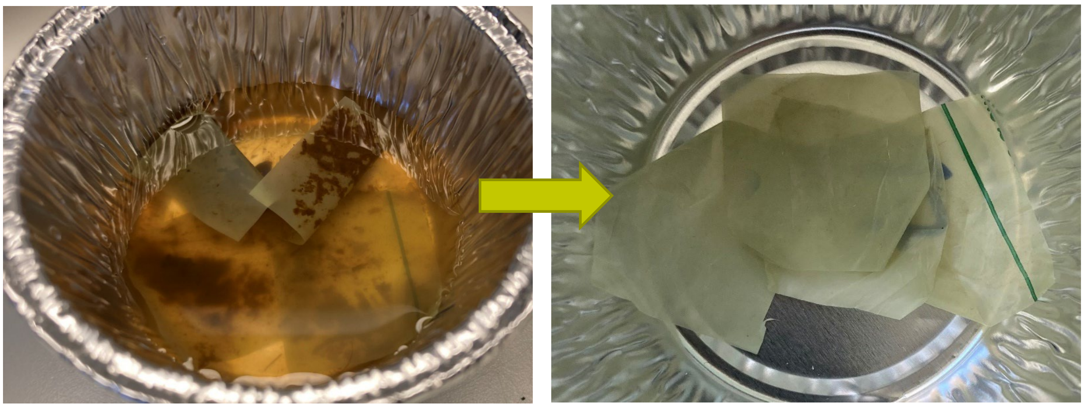


Figure 4. Recovery of plastic samples followed by washing, drying, weighing and FTIR analysis.

The influence of THP pretreatment and anaerobic digestion on the chemical composition of ICP and HCP was determined by **Fourier-transform infrared spectroscopy** (FTIR, PerkinElmer Spotlight 200i connected to a PerkinElmer Spectrum Two spectrometer unit). The analytical settings were as follows: ATR mode, wavenumber range 4000–650 cm^{-1}, resolution 4 cm^{-1}, accumulation of 16 scans, aperture opening 100×100 µm. The following materials were analysed: ICP and HCP before and after THP treatment, ICP and HCP after mesophilic and thermophilic anaerobic digestion, both for THP treated and untreated materials. For each of these materials, measurements were done on three positions across the plastic surface. Processing of spectral data included a baseline correction using Spectrum 10 software and peak area normalization in R. Peak assignment was based on the Infrared Spectroscopy Absorption Table by LibreTexts (2024) and Rampazzo et al. (2023).

2.6 Data analysis

The effects of temperature (mesophilic *vs.* thermophilic) and THP pretreatment on mass loss was analysed using one-way analysis of variance, for ICP and HCP. As variance was not homogenous across treatments, the Welch's test was used, followed by Games-Howell pairwise comparisons to identify differing treatments. The level of significance was set to 0.05.

The influence of biodegradable plastics on the biogas process (total amount of biogas produced, final CO_2, CH_4 and H_2S concentrations) under various conditions (mesophilic, thermophilic, with and without THP) was also analysed by one-way analysis of variance. When variance was homogenous across treatments, differing treatments were identified using a Tukey test, otherwise, the Welch's test followed by Games-Howell pairwise comparisons was applied.

3 Results and discussion

3.1 THP pretreatment

THP had different effects on biodegradable plastic depending on whether food waste was present or not (Fig. 5). When submitted to THP on its own, ICP ended up as small particles, whereas in presence of food waste (at a plastic to food waste ratio of 4 % on dry matter basis) larger plastic fragments were recovered. This qualitative assessment is interesting and suggests that **food waste may protect plastic from degradation during THP**. HCP was only submitted to THP in presence of food waste (using the same 4 % ratio), since the exposure without food waste is not relevant to real-life situations, and we needed three THP batches to collect enough HCP for the BMP experiment (compared to one THP batch for ICP). It was beyond the scope of the study to quantify the effect of THP on biodegradable plastics' mass loss, but this gives a qualitative indication that HCP was, as expected, more affected by THP than ICP.

Figure 5. Left: Effect of THP on ICP alone (top) and in presence of food waste (bottom). Right: Recovered HCP together with food waste elements after THP (mesh size 2.5 mm).

3.2 Plastic mass loss during anaerobic digestion

The visual aspect of ICP and HCP before and after anaerobic digestion was very similar (shown in Fig. 6 for ICP) and was reflected by a **limited mass loss**. Mass loss ranged from **14 % to 21 % for ICP**, and from **22 % to 33 % for HCP**, with statistical differences among treatments in both cases (Fig. 7). As expected, mass loss of untreated plastics was significantly **higher under thermophilic conditions (55 °C), with 30 % and 14 % increase in mass loss for ICP and HCP**, respectively, compared to mesophilic conditions (37 °C).

The effect of THP pretreatment on the other hand was different for ICP and HCP. **For ICP, THP marginally increased mass loss** (by 6 % and 14 %, for mesophilic and thermophilic conditions, respectively, but without statistical significance), compared to pristine ICP. Contrastingly for HCP, **THP significantly reduced mass loss by 25 % under mesophilic** conditions, and **by 35 % under thermophilic** conditions. This is a surprising and unexpected result, which raises the question as to whether THP could have induced physicochemical changes in HCP, rendering them more resistant to degradation, compared to their pristine (not THP treated) counterparts. An element supporting this is provided in the next section. Finally, it is interesting to note that THP treated ICP and HCP displayed a variable behaviour under thermophilic conditions, as denoted by the high standard deviation.

BMP tests are reliable, quick and powerful tools to evaluate biodegradability under anaerobic digestion, and as they are designed to offer optimal conditions to microorganisms, BMP tests can lead to an **overestimation of biodegradation of biodegradable plastics**, compared to what would happen at industrial scale (Cazaudehore et al., 2022). Our results are in line with those of Calabrò et al. (2020), who found 23 and 28 % mass loss of Mater-Bi® after 15 d of anaerobic digestion under mesophilic and thermophilic conditions, respectively. Cazaudehore et al. (2022) reviewed the published literature on anaerobic digestion of biodegradable plastics and found that **HRT required to attain significant biodegradation of biodegradable plastics are by far exceeding those relevant to industrial biogas plants**. Many studies reported in the review used HRT of 60-100 d (and up to 280 d), still resulting in variable, and often limited, percentage of methane conversion of biodegradable plastics. The review is highly recommended to anyone interested in having a comprehensive understanding of the current situation and challenges with anaerobic digestion of biodegradable plastics.

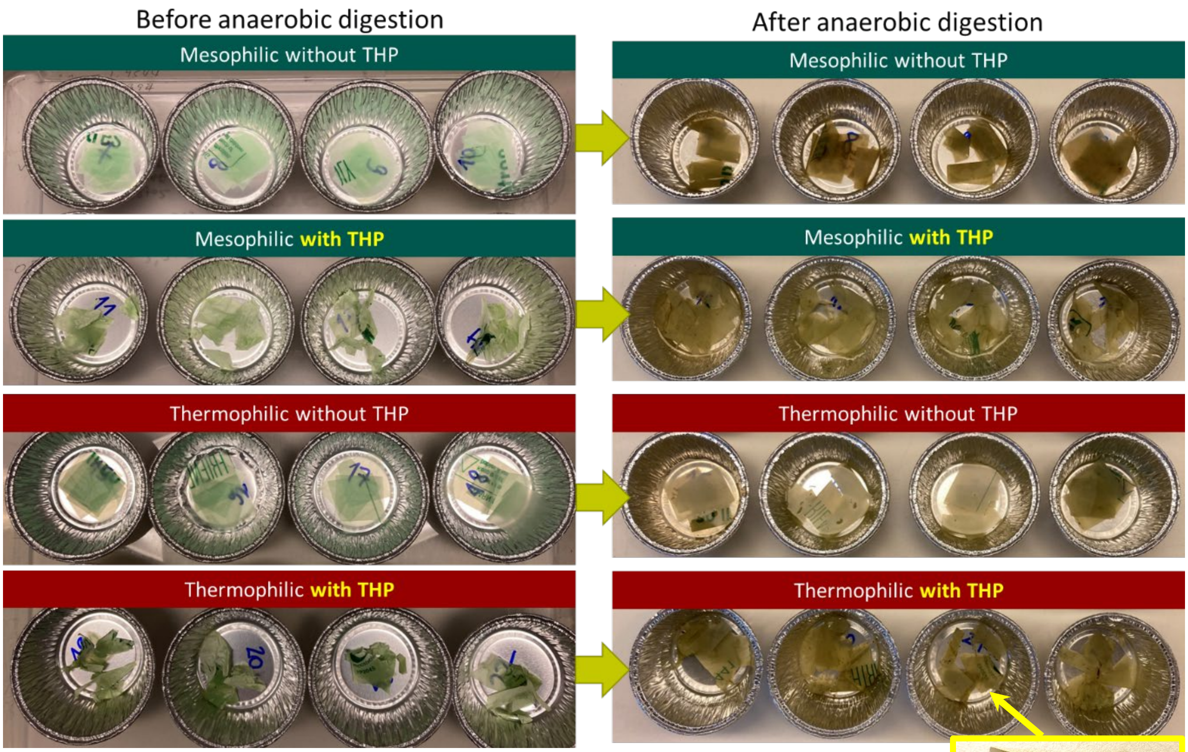


Figure 6. Visual overview of industrially compostable plastic before and after anaerobic digestion under mesophilic and thermophilic conditions, and with and without thermal hydrolysis (THP) pretreatment. The insert shows an enlargement of one of plastic piece where "compostable" is still legible after 22 d under the harshest test conditions.

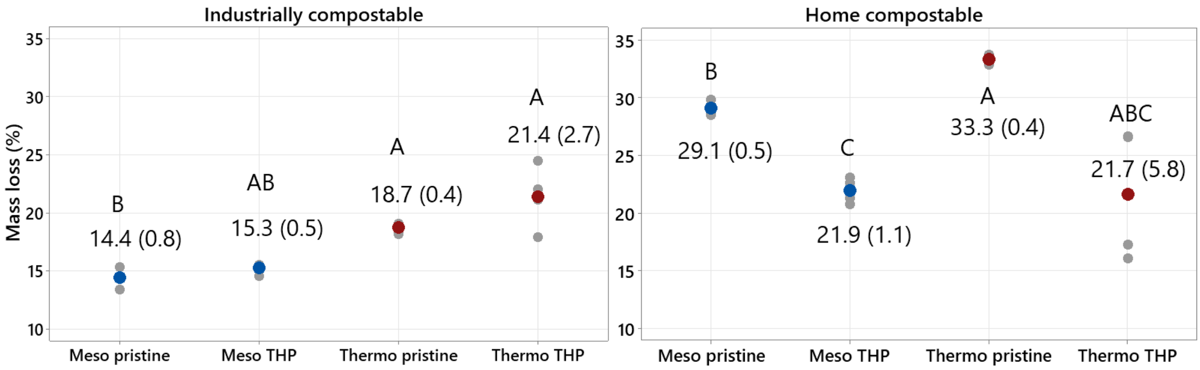


Figure 7. Mass loss (%) of industrially compostable and home compostable plastic after 22 d under mesophilic and thermophilic anaerobic digestion, without and with thermal hydrolysis (THP) pretreatment. Individual data points (in grey) and means (blue or red) are indicated (with SD in parentheses), different letters indicate statistical differences.

3.3 Influence of anaerobic digestion on FTIR spectra of biodegradable plastics

The overall influence of anaerobic digestion (mesophilic and thermophilic) and THP on ICP and HCP was very limited, as shown by mostly overlapping spectra in Fig. 7. **The chemical composition of these biodegradable plastics was therefore little affected anaerobic digestion, even under thermophilic conditions, and after thermal hydrolysis pretreatment.**

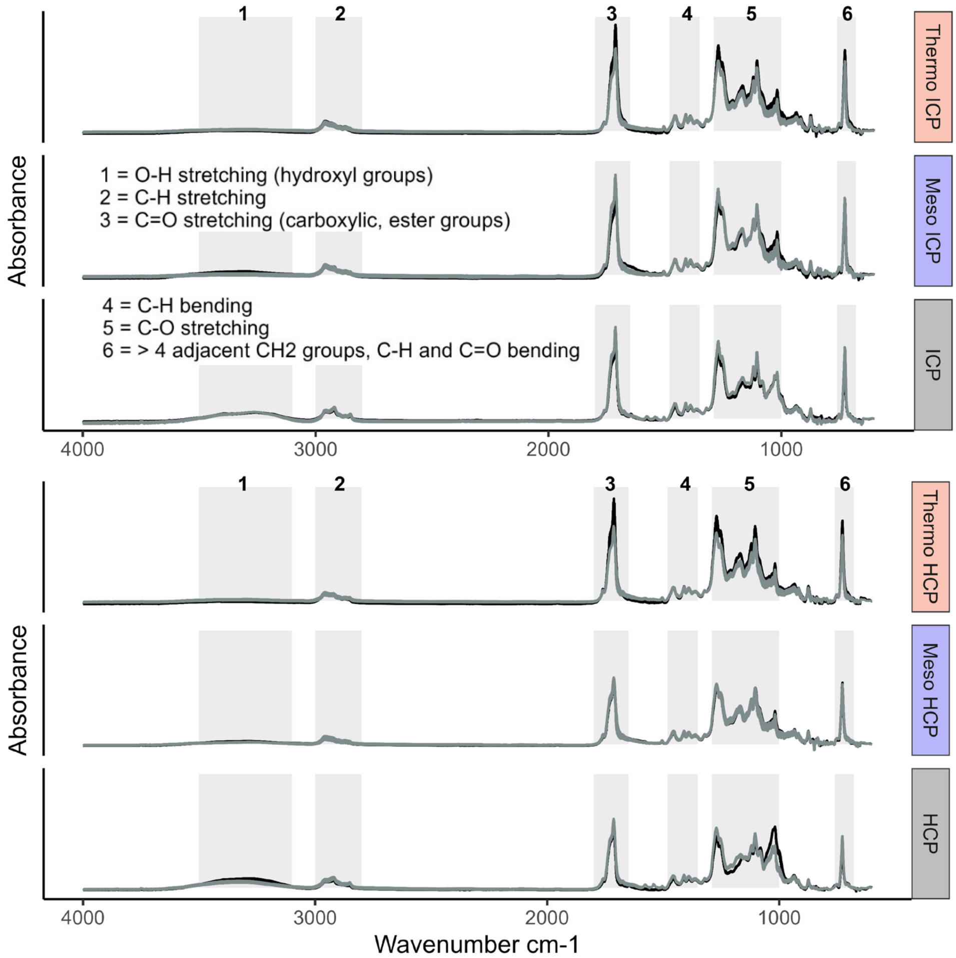
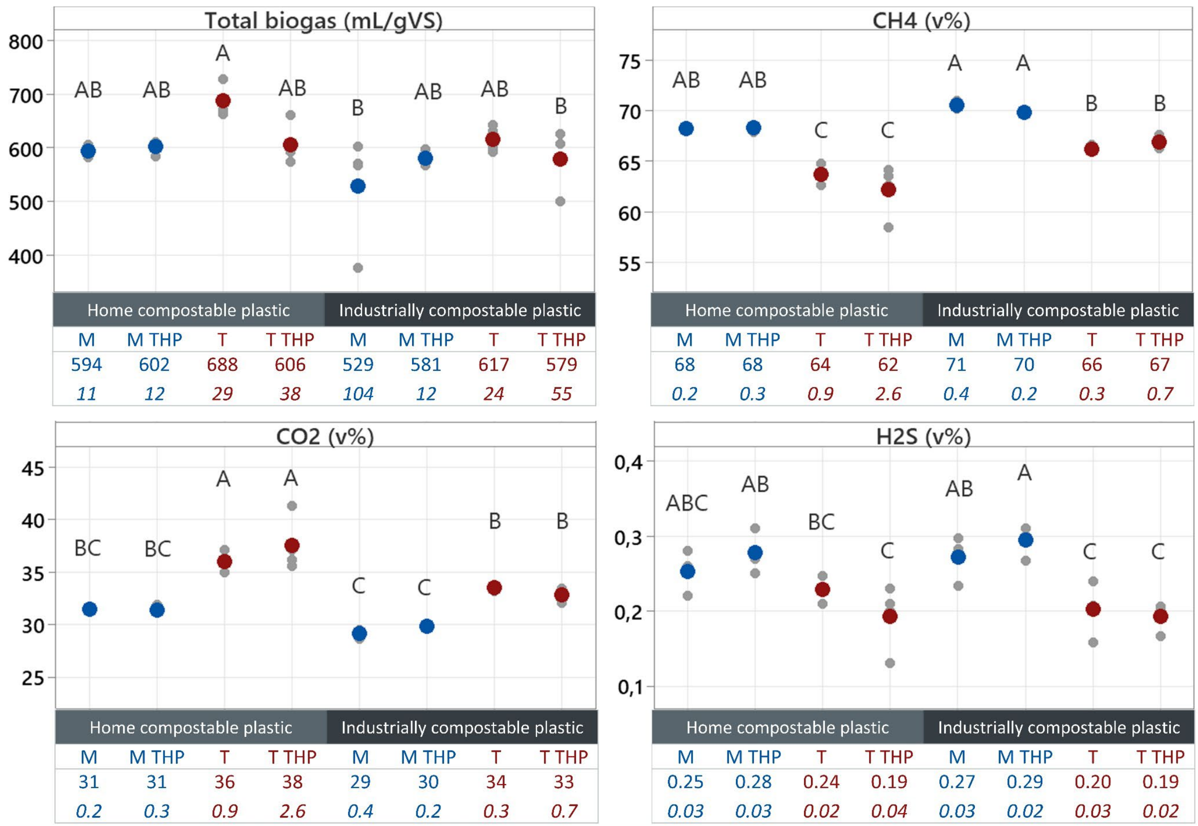


Figure 7. Normalised FTIR spectra of industrially compostable (ICP, top panel) and home compostable (HCP, bottom panel) plastics before and after thermophilic and mesophilic anaerobic digestion, and for both untreated (black lines) and THP pretreated (grey lines) plastics.

Among the limited changes that could be observed, we note the following: 1) before anaerobic digestion, both ICP and HCP showed a broad weak peak in the region 1 (3500-3100 cm⁻¹), corresponding to O-H stretching in starch (one component of Mater-Bi®), which became less visible after mesophilic and thermophilic anaerobic digestion; 2) For HCP before anaerobic digestion (the lowest part of Fig. 7), the peak at 1000 cm^{-1} (in the C-O stretching region, 5) was weaker after THP. This latter point indicates that THP had an impact of the chemical composition of HCP, which may be linked to the higher resistance to degradation (mass loss) under anaerobic digestion mentioned in the previous section, and would deserve more scrutiny.

3.4 Influence of biodegradable plastic on anaerobic digestion

The presence of plastics did not markedly impact the process performance and biogas yields in the BMP experiment. **Biogas yields were in line with what is expected from anaerobic digestion of food waste** (Bong et al., 2018; Kumar et al., 2016), ranging from 529 (untreated ICP under mesophilic conditions) to 688 mL/g VS (untreated HCP under thermophilic conditions), with few statistical differences across treatments (Fig.8, top left panel). Likewise, **CH_4 and CO_2 concentrations were in line with what is commonly found for anaerobic digestion of food waste**, with CH_4 ranging from 62 to 71 v% (Fig. 8, top right panel) and CO_2 from 29 to 38 v% (Fig. 8, bottom left panel). Regardless of plastic type and pretreatment, CH_4 concentrations were significantly higher under mesophilic conditions, and CO_2 concentrations significantly higher under thermophilic conditions. H_2S concentrations were generally very low compared to concentrations of other gases, ranging from 0.19 to 0.29 v% (Fig. 8, bottom right panel), with higher concentrations under mesophilic conditions (statistically significant for ICP with and without THP, and for THP treated HCP).



Total biogas (mL/gVS):

	Home compostable plastic				Industrially compostable plastic			
	M	M THP	T	T THP	M	M THP	T	T THP
Letters	AB	AB	A	AB	B	AB	AB	B
Mean	594	602	688	606	529	581	617	579
SD	*11*	*12*	*29*	*38*	*104*	*12*	*24*	*55*

CH4 (v%):

	Home compostable plastic				Industrially compostable plastic			
	M	M THP	T	T THP	M	M THP	T	T THP
Letters	AB	AB	C	C	A	A	B	B
Mean	68	68	64	62	71	70	66	67
SD	*0.2*	*0.3*	*0.9*	*2.6*	*0.4*	*0.2*	*0.3*	*0.7*

CO2 (v%):

	Home compostable plastic				Industrially compostable plastic			
	M	M THP	T	T THP	M	M THP	T	T THP
Letters	BC	BC	A	A	C	C	B	B
Mean	31	31	36	38	29	30	34	33
SD	*0.2*	*0.3*	*0.9*	*2.6*	*0.4*	*0.2*	*0.3*	*0.7*

H2S (v%):

	Home compostable plastic				Industrially compostable plastic			
	M	M THP	T	T THP	M	M THP	T	T THP
Letters	ABC	AB	BC	C	AB	A	C	C
Mean	0.25	0.28	0.24	0.19	0.27	0.29	0.20	0.19
SD	*0.03*	*0.03*	*0.02*	*0.04*	*0.03*	*0.02*	*0.03*	*0.02*

Figure 8. Total biogas production (in mL/g VS) and composition (in v% CH_4, CO_2 and H_2S) for both biodegradable plastic types and under various conditions: mesophilic (M), mesophilic with THP (M THP), thermophilic (T), and thermophilic with THP (T THP). Individual data points (in grey) and means (blue or red) are shown on the graphs, different letters indicate statistical differences, and tables contain mean and *SD*.

The chemical composition of the digestate was consistent with what is common for BMP tests, i.e. diluted systems (Table 3). Verification of the methodology was confirmed by COD/VS ratios between 1 and 3 in all samples (ratio based on values provided in g/L, not shown here). VS and COD contents were reduced after anaerobic digestion and reflected the gas yields. The ammonium content (NH_4) was reduced in the digestate compared to those in the inoculum and substrate, and the share of ammonia (NH_3) was typically <5 %. FOS/TAC ratios in the digestate ranged from 0.09 to 0.3, which is within typical FOS/TAC ratios in operating biogas systems, and pH levels were between 6.7 and 7.5, which is also normal for biogas reactors.

Table 3. Digestate quality in terms of total solids (TS), volatile solids (VS), chemical oxygen demand (COD), pH, ammonium (NH_4), ammonia (NH_3) and fermentation indicator FOS/TAC, for industrially and home compostable plastics, under mesophilic and thermophilic conditions, with and without thermal hydrolysis (THP). Results are provided as mean ± SD.

	TS (%)	VS (%TS)	COD (g/L)	pH	NH_4 (g/L)	NH_3 (g/L)	FOS/TAC
Industrially compostable plastic							
Meso	0.70 ± 0.00	64.9 ± 0.2	28.2 ± 0.1	7.2 ± 0.1	1.1 ± 0.01	0.023	0.11
Thermo	0.80 ± 0.00	67.4 ± 0.7	30.5 ± 0.4	7.2 ± 0.1	1.0 ± 0.04	0.052	0.09
Meso+THP	0.70 ± 0.00	65.9 ± 0.5	28.4 ± 0.1	7.1 ± 0.0	1.1 ± 0.02	0.017	0.11
Thermo+THP	0.78 ± 0.04	67.1 ± 1.2	29.0 ± 0.2	7.3 ± 0.1	1.0 ± 0.03	0.071	0.15
Control meso	0.60 ± 0.00	66.3 ± 0.4	31.1 ± 0.1	7.5 ± 0.0	0.9 ± 0.04	0.036	0.15
Control thermo	0.73 ± 0.05	67.2 ± 1.2	24.9 ± 0.2	7.1 ± 0.0	0.8 ± 0.01	0.036	0.15
Home compostable plastic							
Meso	0.58 ± 0.01	60.6 ± 0.7	27.3 ± 0.2	7.1 ± 0.0	1.0 ± 0.02	0.016	0.12
Thermo	0.42 ± 0.02	61.3 ± 0.4	30.2 ± 0.5	7.0 ± 0.1	1.1 ± 0.04	0.040	0.22
Meso+THP	0.52 ± 0.07	53.4 ± 11.1	30.8 ± 0.4	7.1 ± 0.0	1.1 ± 0.02	0.017	0.19
Thermo+THP	0.46 ± 0.02	61.6 ± 1.3	37.9 ± 0.2	7.0 ± 0.1	1.0 ± 0.08	0.043	0.19
Control meso	0.58 ± 0.01	63.9 ± 0.2	30.6 ± 0.5	6.7 ± 0.0	0.8 ± 0.02	0.005	0.30
Control thermo	0.41 ± 0.00	63.6 ± 0.3	31.4 ± 0.1	6.9 ± 0.3	0.8 ± 0.02	0.024	0.18

4 Conclusions

In BMP tests offering optimal conditions for microorganisms involved in anaerobic digestion, **limited degradation of biodegradable plastics** (Mater-Bi® certified as compostable under industrial (ICP) and home (HCP) composting conditions, representative of what is used in Norway for food waste collection for biogas production) was observed, as shown by limited mass loss (14-21 % and 22-33 % for ICP and HCP, respectively) and limited changes in the chemical composition (assessed by FTIR) after 22 d, a relevant hydraulic retention time for industrial biogas plant operations. As expected, **higher mass loss was observed under thermophilic conditions** compared to mesophilic conditions. The effect of THP pretreatment of food waste containing biodegradable plastics, on the other hand, offered unexpected results: while a small, non-significant increase in mass loss was observed for ICP, **THP led to a significantly reduced mass loss for HCP** during anaerobic digestion.

The biogas process in itself was not significantly affected by ICP and HCP present in food waste at a 4 % plastic to food waste ratio, as shown by biogas production and composition, and digestate composition in line with what has been reported for anaerobic digestion of food waste.

The present research shows that **the majority** (79-86 % and 67-78 % for ICP and HCP, respectively) of biodegradable plastic residues left after the initial pre-treatment steps (e.g. sieving) of food waste, **will withstand anaerobic conditions**, not only under mesophilic but also under thermophilic conditions, and also when THP pretreatment (5 bars, 160 °C, 20 min) of food waste is applied.

This strongly suggests that **post-treatment of digestate is required** to avoid the application of biodegradable plastics to agricultural soils, for digestates intended for agricultural use. It is important to understand that the **biodegradability of these materials is conditional to specific environmental conditions and time frames**, which in the present case are one year at 20-30 °C (under home composting conditions) and six months at 60 °C (under industrial composting conditions), conditions that are not fulfilled in soil under Norwegian field conditions. Post-treatment of digestate using composting should offer optimal conditions for complete degradation of biodegradable plastic residues.

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