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Chemical composition and mesophilic anaerobic digestion of commercial compostable food packaging: Implications for bio-waste management[☆]

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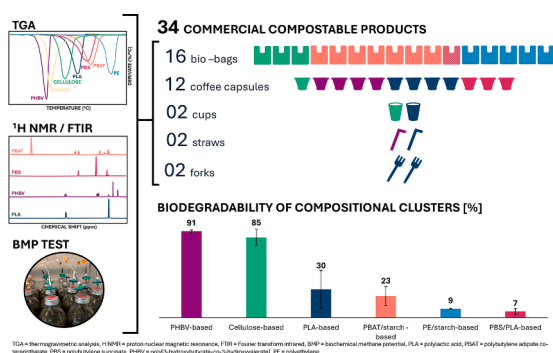
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HIGHLIGHTS

- Study of chemical composition of 34 compostable food packaging.
- Investigation of mesophilic anaerobic digestion of 34 compostable food packaging.
- Only PHBV and select cellulose-based products were anaerobically degraded over 80%.
- Biodegradability of PBS/PLA-based and PBAT/starch items was low (6% to 30%).
- Presence of conventional polymer PE (> 70 %) in some certified compostable bags.

GRAPHICAL ABSTRACT



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ABSTRACT

This study assessed the chemical composition and mesophilic anaerobic biodegradability (BI) of 34 commercial compostable food packaging products, including sixteen bags, twelve coffee capsules, and six other products (cups, forks and straws). Thermogravimetric analysis and spectroscopy techniques allowed to determine the proportions of polymers (PLA, PBAT, PBS, PHBV, PE, cellulose, and starch) and additives (inorganic and organic). Six compositional clusters were identified: PHBV-based products (BI = 92 ± 1 %), cellulose-based products (BI = 85 ± 9 %), PLA-based products (BI = 30 ± 20 %), PBAT/starch-based bags (BI = 25 ± 8 %), PE/starch-based bags (BI = 9.5 ± 0.5 %), and PBS/PLA-based capsules (BI = 6.6 ± 3.0 %). Only select cellulose-based products (three bags, one cup, and one capsule) and the PHBV-based products (five capsules and one straw) exhibited a biodegradability over 80 %. Analyzing product composition reveals components that affect

1. Introduction

As part of its sustainable bio-waste management strategy, the EU has mandated the separate collection of bio-waste to promote its recycling into organic fertilizers (e. g., compost or digestate) through composting or anaerobic digestion (AD) (EU, 2018). A significant challenge is bio-waste contamination with conventional plastics from food packaging (USEPA, 2021), which necessitates costly and energy-intensive pre-separation processes that often fail to completely remove plastic, compromising the quality of compost and digestate while also leading to inadvertent bio-waste loss in the reject stream (Do Carmo Precci Lopes et al., 2019). A promising solution is to replace conventional plastics with biodegradable alternatives, such as bio-based cellulose, starch, polylactic acid (PLA), and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) or fossil-based polybutylene adipate co-terephthalate (PBAT), polybutylene succinate (PBS) and polycaprolactone (PCL) (Afshar et al., 2024; Cheng et al., 2024).

Currently, the EU allows the collection of plastic waste alongside selective bio-waste collection if compliant with biodegradability standards (EU, 2022, 2018). Therefore, effective biodegradation of these plastics is of utmost importance if they are to contribute to the organic recycling of bio-waste and achieve their most sustainable end-of-life options (Ali et al., 2023). While there are established test method standards for assessing plastic biodegradability in composting (e. g., EN ISO 14855) and AD (e. g., EN ISO 13975), specification standards only exist to certify a plastic as home compostable (e. g., NF T51-800) or compostable in industrial conditions (e. g., EN 13432) (Afshar et al., 2024; Cazaudehore et al., 2022a). Despite the well-established biodegradability of compostable plastics, there remains a significant knowledge gap regarding their biodegradability in AD (Álvarez-Méndez et al., 2023; Calabro et al., 2020; Cazaudehore et al., 2022a). This gap is crucial to address, especially as AD—particularly mesophilic AD (35 °C to 38 °C)—gains importance in bio-waste management due to its energy and environmental benefits (Ali et al., 2023; Cazaudehore et al., 2022a; Dolci et al., 2021; Mu et al., 2021).

Research on the AD of biodegradable plastics has predominantly focused on pure polymers or laboratory-synthesized plastics rather than commercial products, which are more complex since they consist of blended polymers combined with various additives (e. g., plasticizers, stabilizers, fillers) tailored to specific cost, processing, and functional requirements (Afshar et al., 2024; Cazaudehore et al., 2022a). Recent studies on the mesophilic AD of commercial compostable food packaging have demonstrated significant variability in degradation, even among products made from the same main polymer. For instance, methane production from cellulose-based products has been reported to range from 225 to 347 NmLCH₄/g VS (Battista et al., 2021; Calabro et al., 2020; Dolci et al., 2021; Üveges et al., 2023; Zhang et al., 2018; Zaborowska et al., 2023). In comparison, starch-based products exhibit even greater variability in methane production, with values ranging from 12 to over 300 NmLCH₄/g VS (Bandini et al., 2022; Battista et al., 2021; Calabro et al., 2020; Cazaudehore et al., 2021; Cucina et al., 2021; Dolci et al., 2021; Zaborowska et al., 2021; Zhang et al., 2018). Additionally, PLA-based products show varying levels of biodegradability, with reported values ranging from 2.1 % to 33 % (Bouchalová et al., 2023; Cucina et al., 2021; Mu et al., 2021; Üveges et al., 2023; Zaborowska et al., 2021).

Although this variability can be attributed to several factors, such as product type or differences in reported test parameters, it may also stem from a frequently underexplored reason: the presence of components other than the main polymer (Afshar et al., 2024; Bracciale et al., 2023, 2024). For example, Bracciale et al., 2023 found that a PLA-based plate

with a higher additive content exhibited slower degradation compared to another PLA-based plate. Similarly, Bracciale et al., 2024 reported limited degradation of a MaterBi® product containing PBS and elevated levels of additives among three MaterBi® tableware products. Unfortunately, manufacturers often do not disclose specific compositional information (Afshar et al., 2024; Zaborowska et al., 2023) and very few studies on anaerobic biodegradability have verified the presence of the claimed main polymer or determined the presence or quantity of other components in the investigated products (Álvarez-Méndez et al., 2023; Bracciale et al., 2023, 2024; Cucina et al., 2022b, 2021; Falzarano et al., 2024; Peng et al., 2024; Yu et al., 2023). The ambiguity surrounding the composition of these products poses a significant risk of misclassification and complicates data comparisons across different studies, an issue further exacerbated by variability in test parameters (Afshar et al., 2024; Cazaudehore et al., 2022b). Furthermore, the lack of thorough compositional analysis limits the understanding of biodegradability and its environmental impact, ultimately preventing progress in the development of sustainable food packaging. (Afshar et al., 2024; Bracciale et al., 2023; Falzarano et al., 2024).

To address these challenges, this study aimed to elucidate the mesophilic anaerobic biodegradability of compostable food packaging products through a comprehensive analysis of their chemical composition using a multi-technique approach. By maintaining consistent test conditions, this research enables direct comparisons among up to 34 commercially available products and offers compositional data that is infrequently reported in the existing literature. Ultimately, this study seeks to offer insights that could lead to the improved eco-design of anaerobically digestible food packaging, ensuring that it maintains its functional properties while effectively degrading through mesophilic AD and contributing to sustainable bio-waste management strategies.

2. Material and methods

2.1. Compostable plastic food packaging

A total of 34 compostable food packaging products found in commerce were analyzed, including sixteen bags, twelve coffee capsules, two cups, two straws, and two forks. The majority of the products were certified as either home compostable (HC) under specification standard NF T51-800 or compostable in industrial conditions (IC) under specification standard EN 13432, while a subset was described as compostable without any certification, as seen in Table 1. For confidential reasons, the trademarks and certificate holders are not disclosed. In the case of coffee capsules, the coffee was removed, and the capsules were washed with deionized water and then dried at 38 °C.

2.2. Analytical methods

The thickness of the food packaging products was measured in triplicate using a micrometer (IP65 Digimatic, Mitutoyo, JP). Total Solids (TS) and Volatile Solids (VS) were determined in triplicate by loss on drying at 105 °C and loss on ignition at 550 °C (APHA, 2023), respectively. The contents of organic carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) were measured in duplicate with an elemental analyzer (Vario Micro Cube, Elementar, DE), while the oxygen content (O) was estimated as the difference between VS and C, H, N and S contents. The chemical composition was determined using a combination of thermogravimetric analysis (TGA) and liquid-state proton nuclear magnetic resonance spectroscopy (¹H NMR), complemented with Fourier transform infrared spectroscopy (FTIR) in certain cases, similar to the approach of Elfehri Borchani et al., 2015.

TGA was performed on 10 mg of sample using a thermal analyzer (TGA2, Mettler Toledo, US) with a temperature range from 25 to 800 °C at a rate of 10 °C/min under a N₂ atmosphere (50 mL/min). After reaching 800 °C, the temperature was held constant for 20 min under air (50 mL/min) to estimate remaining mineral content (considered as inorganic additives). ¹H NMR spectra were obtained using an NMR spectrometer (Avance III 400 NMR, Bruker, US), equipped with a 5 mm ¹H/X BBFO probe, operating at 400.13 MHz and 298 K. The spectra were acquired with a zg-1D pulse sequence, 128 number of scans, 64 k time domain and 30 s relaxation delay (4.9 s acquisition time). The free induction decay (FID) was weighted by exponential function without line broadening factor. All data were processed with Bruker Topspin 3.6.2 software. ¹H NMR analyses were performed on 20 mg samples that were preliminarily solubilized in 1 mL of deuterated chloroform (CDCl₃) at 55 °C under stirring for 24 h to ensure the complete solubilization of all chloroform-soluble components. The non-chloroform-soluble residue, if present in a large proportion, was subsequently analyzed with an FTIR spectrometer (Vertex 70v, Bruker, US) equipped with a diamond prism and employing ATR (Attenuated Total Reflection) mode with a resolution of 4/cm with 64 scans between 600/cm and 4000/cm.

TGA curves and their respective derivatives were employed to quantify the mass concentration of each component in the sample. ¹H NMR and FTIR spectra were analyzed to confirm the chemical nature of chloroform-soluble components (i.e., PLA, PBAT, PBS, PHBV) and non-chloroform-soluble components (i.e., cellulose, starch, and polyethylene [PE]), respectively. For products containing a mixture of PLA, PBAT, and starch, the overlapping thermal degradation profiles of PLA and starch prevented direct calculation of their individual mass concentrations

from the TGA curves. In these cases, the PLA mass concentration was determined using the PBAT mass concentration obtained from TGA—feasible due to its distinct degradation profile—and relating it to the relative molar ratio (expressed in monomer units) of PLA ([C₃H₄O₂]_{LA}) to PBAT ([C₁₂H₁₂O₄]_{BT}-[C₁₀H₁₆O₄]_{BA}) determined by ¹H NMR (Álvarez-Méndez et al., 2023):

$$w_{PLA} = w_{PBAT} \times \frac{\left(\frac{I_{4.4ppm}}{4} + \frac{I_{4.0ppm}}{4}\right) \times M_{BT-BA}}{\left(\frac{I_{5.2ppm}}{1}\right) \times M_{LA}}$$

where, w_{PLA} is the PLA mass concentration [%], w_{PBAT} is the PBAT mass concentration obtained by TGA [%], $I_{4.4ppm}$ is the integrated area of the peak at $\delta = 4.4$ ppm which corresponds to the 4 protons of —OCH₂ in repeating unit BT (butylene terephthalate) [relative mol], $I_{4.0ppm}$ is the integrated area of the peak at $\delta = 4.0$ ppm which corresponds to the 4 protons of —OCH₂ in repeating unit BA (butylene adipate) [relative mol], M_{BT-BA} is the average molecular mass of repeating units BT (220 g/mol) and BA (200 g/mol) according to their proportion in PBAT, $I_{5.2ppm}$ is the integrated area of the peak at $\delta = 5.2$ ppm which corresponds to the one proton of —CH in repeating unit LA (lactide) [relative mol], and M_{LA} is the molecular mass of repeating unit LA (72 g/mol). Finally, the mass concentration of starch was calculated by subtracting the sum of the mass concentrations of PLA, PBAT, and other constituents (including additives) from the total mass of the blend.

Table 1
Thickness, proximate and ultimate composition of compostable food packaging.

Food Packaging	BIC	Thickness [μm] ^a	TS [%ww] ^a	VS [%TS] ^a	C [%TS] ^b	H [%TS] ^b	O [%TS] ^c	N [%TS] ^b	S [%TS] ^b
Bag-01	C	199 ± 9	93 ± 0	100 ± 0	43 ± 0	6 ± 0	50 ± 0	0.0 ± 0.0	—
Bag-02	C	63 ± 8	94 ± 0	98 ± 0	42 ± 0	7 ± 0	49 ± 0	1.3 ± 0.0	0.06 ± 0.01
Bag-03	IC	116 ± 3	92 ± 0	90 ± 0	41 ± 0	6 ± 0	43 ± 0	0.2 ± 0.0	0.03 ± 0.00
Bag-04	IC	13 ± 2	97 ± 0	100 ± 0	54 ± 0	7 ± 0	38 ± 1	1.1 ± 0.3	—
Bag-05	IC	23 ± 1	97 ± 0	100 ± 0	55 ± 0	7 ± 0	36 ± 0	2.0 ± 0.1	0.02 ± 0.04
Bag-06	IC	23 ± 1	97 ± 0	92 ± 0	53 ± 0	7 ± 0	32 ± 0	1.3 ± 0.1	—
Bag-07	HC	25 ± 2	97 ± 0	99 ± 0	54 ± 0	7 ± 0	37 ± 0	1.2 ± 0.0	—
Bag-08	IC	34 ± 2	97 ± 0	99 ± 0	55 ± 0	7 ± 0	36 ± 0	0.9 ± 0.0	—
Bag-09	C	31 ± 1	98 ± 0	97 ± 0	54 ± 0	7 ± 0	35 ± 0	1.2 ± 0.1	—
Bag-10	HC	13 ± 2	99 ± 1	99 ± 0	55 ± 0	7 ± 0	37 ± 0	0.0 ± 0.0	—
Bag-11	HC	22 ± 1	96 ± 0	99 ± 0	70 ± 0	12 ± 0	15 ± 0	2.1 ± 0.2	—
Bag-12	HC	16 ± 1	96 ± 1	98 ± 0	69 ± 0	12 ± 0	16 ± 0	1.2 ± 0.1	—
Bag-13	C	14 ± 1	96 ± 0	98 ± 0	70 ± 0	11 ± 0	16 ± 0	1.5 ± 0.0	—
Bag-14	HC	23 ± 1	97 ± 0	98 ± 0	68 ± 0	11 ± 0	17 ± 0	1.1 ± 0.1	—
Bag-15	C	15 ± 3	96 ± 0	99 ± 0	70 ± 0	12 ± 0	16 ± 1	0.9 ± 0.0	—
Bag-16	C	48 ± 2	99 ± 0	100 ± 0	61 ± 0	7 ± 0	30 ± 0	1.2 ± 0.1	—
Cap-01	IC	654 ± 59	98 ± 2	95 ± 3	53 ± 0	7 ± 0	34 ± 3	1.0 ± 0.1	—
Cap-02	HC	687 ± 45	98 ± 0	98 ± 0	52 ± 0	7 ± 0	39 ± 0	0.8 ± 0.1	—
Cap-03	HC	579 ± 11	99 ± 0	100 ± 0	57 ± 0	7 ± 0	35 ± 0	0.5 ± 0.1	—
Cap-04	HC	588 ± 19	99 ± 0	100 ± 0	57 ± 0	7 ± 0	36 ± 0	0.3 ± 0.0	—
Cap-05	HC	550 ± 20	95 ± 0	97 ± 0	42 ± 0	7 ± 0	47 ± 0	1.5 ± 0.2	0.16 ± 0.03
Cap-06	IC	556 ± 24	98 ± 0	100 ± 0	50 ± 0	6 ± 0	43 ± 0	0.5 ± 0.1	—
Cap-07	IC	304 ± 65	99 ± 0	99 ± 0	50 ± 0	6 ± 0	43 ± 0	0.5 ± 0.0	—
Cap-08	IC	601 ± 25	98 ± 0	89 ± 0	47 ± 0	6 ± 0	36 ± 0	0.5 ± 0.1	—
Cap-09	IC	465 ± 15	99 ± 0	81 ± 0	44 ± 0	6 ± 0	31 ± 0	0.6 ± 0.1	—
Cap-10	IC	569 ± 24	99 ± 0	82 ± 0	45 ± 0	6 ± 0	31 ± 0	0.4 ± 0.1	—
Cap-11	IC	757 ± 39	99 ± 0	99 ± 0	54 ± 0	6 ± 0	37 ± 0	0.9 ± 0.2	—
Cap-12	IC	715 ± 72	99 ± 0	83 ± 0	44 ± 0	5 ± 0	33 ± 0	0.0 ± 0.0	—
Cup-01	IC	311 ± 3	94 ± 0	96 ± 0	41 ± 0	6 ± 0	47 ± 0	1.4 ± 0.0	—
Cup-02	C	238 ± 1	99 ± 0	100 ± 0	50 ± 0	6 ± 0	43 ± 0	1.2 ± 0.1	—
Straw-01	HC	177 ± 7	99 ± 0	78 ± 0	47 ± 0	6 ± 0	25 ± 0	1.0 ± 0.0	—
Straw-02	IC	181 ± 5	100 ± 0	88 ± 0	46 ± 0	5 ± 0	37 ± 0	0.0 ± 0.0	—
Fork-01	IC	1 009 ± 32	99 ± 0	98 ± 0	50 ± 0	6 ± 0	40 ± 0	1.1 ± 0.1	—
Fork-02	IC	5 111 ± 3	100 ± 0	71 ± 0	36 ± 0	4 ± 0	29 ± 0	1.3 ± 0.3	—

(BIC = biodegradability claim, TS = total solids, VS = volatile solids, Cap = capsule, C = compostable [not certified], IC = compostable under industrial conditions [certified], HC = home compostable [certified]).

^a = average of triplicates.

^b = average of duplicates.

^c = estimated as the difference between VS and C, H, N and S contents.

2.3. Biochemical methane potential tests

The mesophilic anaerobic degradation of the food packaging products was studied by means of biochemical methane potential (BMP) tests. The BMP tests were designed and calculated according to the guidelines of the German Institute for Biomass Research (DBFZ) (DBFZ, 2024) and validated according to criteria of the DBFZ and standard EN ISO 13975 (ISO, 2019). Three BMP series, each assessing eleven or twelve products, were performed sequentially in the course of a year. The inocula for the three series came from the same industrial anaerobic digester treating bio-waste and agricultural waste. Prior to each series, the inoculum was sampled and maintained in a pilot reactor at 38 °C until no biogas production was observed. Average inoculum parameters were pH = 8.0 ± 0.1, TS = 6.5 ± 1.0 %w/w, VS = 58 ± 3 %TS, FOS/TAC = 0.16 ± 0.01 and N-NH₄⁺ = 2.7 ± 0.2 g/L, throughout the three series. Bags were assessed as pieces of 2 x 15 cm, coffee capsules and cups as pieces of 1 x 1 cm, and straws and forks as pieces of 0.5 x 2 cm.

For each product assessed in the series, three replicate 500 mL serum bottles were prepared with product and inoculum at a ratio of 0.37 gVS_{product}/gVS_{inoculum} (Cazaudehore et al., 2022b). Approximately 12 mL of a buffer solution (50 gNaHCO₃/L), 10 mL of a macroelement solution (22.4 gNa₂HPO₄, 10.6 gNH₄Cl, 5.4 gKH₂PO₄, 2.0 gMgCl₂, 1.5 gCaCl₂, 0.4gFeCl₂ /L) and 0.2 mL of a microelement solution (1.0 gNa₂HPO₄COCl₂, 0.5 gMnCl₂, 0.1 gNiCl₂, 0.05 gZnCl₂, 0.05 gH₃BO₃, 0.05 gNa₂SeO₃, 0.03 gCuCl₂, 0.01 gNa₂MO₄ /L) were added to ensure good bacterial development. Distilled water was added to achieve a working volume of around 200 mL and an organic loading of 30–40 gVS/L. Each series included duplicate blank control bottles (with no substrate) to determine endogenous methane production, and duplicate positive control bottles (with AcrosOrganics cellulose microcrystalline [CMC] as substrate) to validate the results according to the DBFZ guidelines (DBFZ, 2024) and the requirements of EN ISO 13975 (ISO, 2019).

Bottles were flushed with N₂ gas, sealed, and incubated (New Brunswick Innova 44, Eppendorf, DE) under mesophilic conditions (38 °C) and continuous stirring (75 rpm) for 105 days. The pressure and composition of the headspace of each bottle were periodically measured to determine methane production. The pressure was measured with a manometer (LEO 2, Keller, CH). After venting, the headspace composition was analyzed with a gas chromatograph (MicroGC 990, Agilent, US) equipped with two columns and a thermal conductivity detector. The first column (CP-Molesieve 5 Å 10 m, Agilent J&W, US) operated at 80 °C and 200 kPa using Ar as carrier gas to separate H₂, O₂, N₂, and CH₄. The second column (CP-PoraPLOT U 10 m, Agilent J&W, US) operated at 80 °C and 150 kPa using He as carrier gas to separate CO₂ and H₂S. The injection and detection temperatures were 80 °C. At the end of each series, the pH of the bottles was measured.

The cumulative methane production was expressed under standard conditions of temperature and pressure (0 °C, 101325 Pa). The experimental BMP (BMP_{exp}) corresponded to the maximum methane production yielded during the 105 days of BMP test. The methane production rate was calculated as the first derivative of cumulative methane production data using the differentiation function (centered difference method) of OriginPro® software. This approach was selected to identify the maximum methane production rate (R_m [NmLCH₄/gVS/day]) and facilitate comparisons across all products, as a single kinetic model struggles to accurately represent the kinetics of biodegradable plastics with diverse compositions (Ebrahimzade et al., 2022).

The biodegradability (BI) was calculated as the ratio between the BMP_{exp} and the theoretical BMP (BMP_{th}) of the product. The BMP_{th} for all products and CMC was calculated based on their elemental composition using the Buswell equation modified by Boyle (Achinis and Euverink, 2016). To compare the products across the three series, a normalized BI and BMP were calculated. The BMP_{exp} of each product was normalized against the BMP_{exp} of CMC from the same series and the BMP_{th} of CMC. The normalized BI was then calculated as the ratio

between the normalized BMP_{exp} and the BMP_{th} of each product:

$$BI_i^* = \frac{BMP_{exp,i}^*}{BMP_{th,i}} = \frac{BMP_{exp,i,n} \times \frac{BMP_{exp,CMC,n}}{BMP_{th,CMC}}}{BMP_{th,i}}$$

where, BI_i^* is the normalized BI of product i [NmLCH₄/gVS], $BMP_{exp,i}^*$ is the normalized BMP of product i [NmLCH₄/gVS], $BMP_{th,i}$ is the theoretical BMP of product i [NmLCH₄/gVS], $BMP_{exp,i,n}$ is the BMP_{exp} of product i in series n [NmLCH₄/gVS], $BMP_{exp,CMC,n}$ is the BMP_{exp} of CMC in the same series n [NmLCH₄/gVS] and, $BMP_{th,CMC}$ is the BMP_{th} of CMC [NmLCH₄/gVS].

2.4. Statistical analysis

A hierarchical agglomerative clustering analysis was performed using the group average linkage method and the Euclidean distance metric, aiming to categorize the food packaging based on their compositional similarities. Descriptive statistics and comparisons among the resulting compositional clusters were conducted using the Kruskal-Wallis ANOVA test at a significance level of $p < 0.05$, followed by Dunn's test for post-hoc analysis. All statistical analyses were performed in OriginPro® software.

3. Results and discussion

3.1. Composition of compostable food packaging

The thickness, proximate and ultimate composition of the compostable food packaging products are presented in Table 1, while the chemical composition and dendrogram from the hierarchical agglomerative clustering analysis are detailed in the supplementary materials. The thickness and chemical composition of all the products are visually depicted in Fig. 1, arranged according to product type.

TGA, ¹H NMR and FTIR revealed the presence of several polymers, including PLA, PBAT, PBS, PHBV, PE, cellulose (CELL), and thermoplastic starch (STAR), along with organic additives (O.ADD) and inorganic additives (I.ADD). Six compositional clusters were identified through hierarchical clustering analysis: cellulose, PBAT/starch, PE/starch, PLA, PBS/PLA, and PHBV-based products. The majority of products (25 out of 34) contained a maximum of two polymers in their composition. Inorganic additives were found in all products and exhibited a varying distribution, ranging from 0.4 % to 28 %, even among products of the same type and compositional cluster. On the other hand, organic additives were limited to only eight products (Bag 01, 03, and 06; Cap 02, 03, 04, and 10; and Cup 01).

The PLA-based cluster was the most heterogeneous, displaying diversity both in products (Cap 06–08 and 12; Cup 02; Straw 02; and Fork 01 and 02;) and in polymers (i.e., PLA with PBAT, PHBV, PBS or cellulose), with PLA concentrations ranging from 42 % to 99.6 %. In contrast, the cellulose-based cluster, which also included several products (Bag 01–03, Cap 05, and Cup 01), exhibited a less heterogeneous composition, with a high cellulose content at 88 ± 8 %. The PHBV-based cluster was more homogeneous, comprising fewer product types (Cap 01–04 and Straw 01), with PHBV as the only polymer at 88 ± 7 %. Both the PBAT/starch-based (Bag 04–10) and PE/starch-based clusters (Bag 11–15) consisted exclusively of bags and demonstrated a uniform composition, particularly the PE/starch-based bags. Lastly, the PBS-based cluster (Cap 09, 10, and 12), was a small group of three coffee capsules with a relatively uniform composition.

3.1.1. Composition of compostable plastic bags

Compostable bags presented four types of composition, as seen in Fig. 1: cellulose-based (Bag 01–03), PBAT/starch-based (Bag 04–10), PBAT/PHBV-based (Bag 16), and PE/starch-based (Bag 11–15).

Cellulose-based bags contained cellulose concentrations ranging

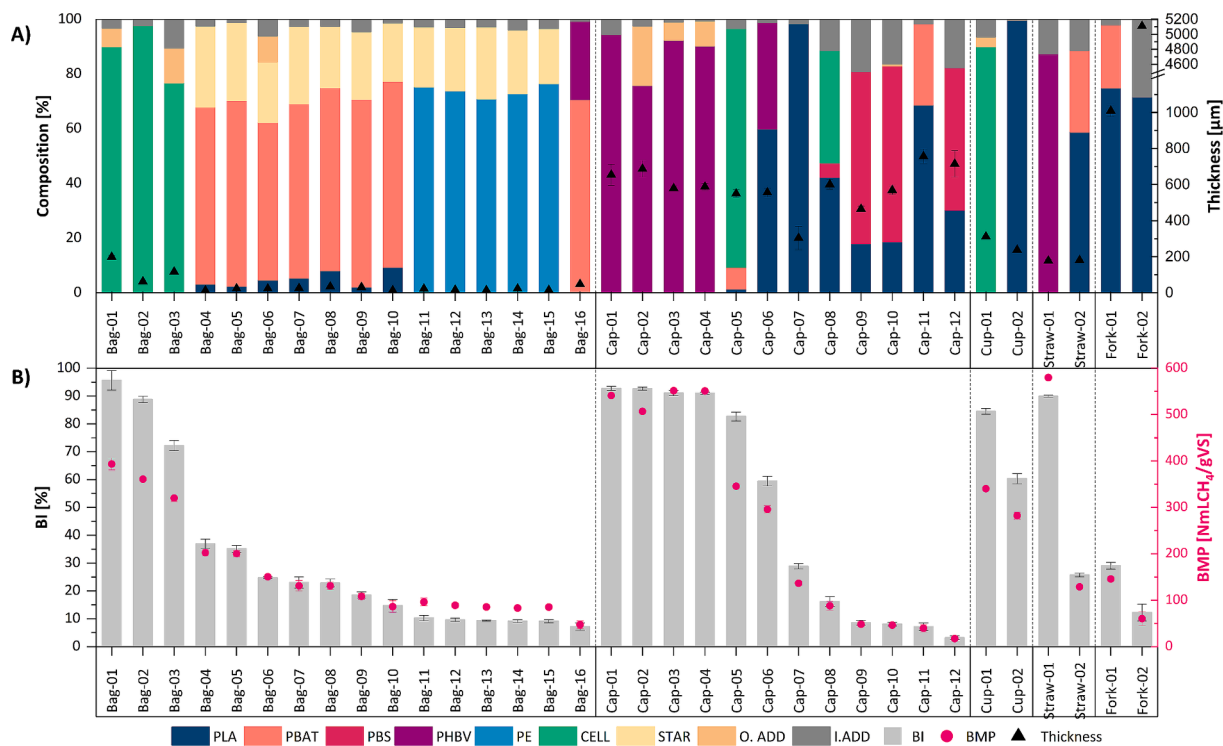


Fig. 1. A) Chemical composition, thickness, B) anaerobic biodegradability and biochemical methane potential of compostable food packaging categorized according to product type. (BI* = biodegradability [normalized], BMP*exp = experimental biochemical methane potential [normalized], VS = volatile solids, Cap = capsule, PLA = polylactic acid, PBAT = polybutylene adipate co-terephthalate, PBS = polybutylene succinate, PHBV = poly[3-hydroxybutyrate-co-3-hydroxyvalerate], PE = polyethylene, CELL = cellulose, STAR = starch, O.ADD = organic additive, I.ADD = inorganic additive).

from 77 % in Bag 03 to 98 % in Bag 01, and an average carbon content of 42 ± 1 % TS, closely aligning with the theoretical carbon content of cellulose (41 %TS). Bag 03 had the highest additive (both organic and inorganic) concentration at 11 %, while Bag 01 had the lowest concentration at 2.3 %. Cellulose-based bags were generally thicker (125 ± 68 μm) than the PBAT/starch-based (23 ± 8 μm) and PE/starch-based bags (18 ± 4 μm). Unlike flexible PBAT and PE, the low flexibility of cellulose requires thicker, heavier bags to enhance their structural integrity. Additionally, cellulose-based bags exhibited a lower TS content (93 ± 1 %w/w) compared to PBAT/starch-based (97 ± 1 %w/w) and PE/starch-based bags (96 ± 0 %w/w). Cellulose possesses higher moisture retention than PBAT and PE which enhances breathability, as noted by (Dolci et al., 2021), but leads to poorer barrier properties (Cheng et al., 2024).

PBAT/starch-based bags exhibited a relatively uniform composition, consisting of 66 ± 4 % PBAT and 25 ± 4 % starch. However, they also contained PLA, with concentrations ranging from 2.1 % in Bag 09 to 9.3 % in Bag 10, and inorganic additives varying from 1.1 % in Bag 05 to 6.1 % in Bag 06. PBAT, a copolyester of butylene terephthalate and butylene adipate (De Luca et al., 2023; Shaikh et al., 2021), is flexible, ductile, and tear-resistant, making it an excellent alternative to conventional PE used in bags (Afshar et al., 2024; Dammak et al., 2020; De Luca et al., 2023). PBAT is normally blended with thermoplastic starch to enhance cost-effectiveness (Dammak et al., 2020), while also benefiting from its bio-based origin and superior biodegradability (Cheng et al., 2024). Before blending with PBAT, starch must be modified to thermoplastic starch by adding plasticizers like glycerol to enhance its processability (Cazaudehore et al., 2022a). Nevertheless, the differing surface properties (PBAT being hydrophobic and starch being hydrophilic) limit interfacial adhesion between the two phases, restricting the amount of starch that can be effectively incorporated into the blend (Dammak et al., 2020). The starch content of MaterBi®, a commonly used blend in compostable bags, has been cited to range from 20 % to 60 % (Calabro

et al., 2020; Dolci et al., 2022). Elfehri Borchani et al., 2015 determined a specific composition of 70 % PBAT, 20 % starch, and 10 % additives for MaterBi® grade NF803, which closely resembles the composition of the PBAT/starch-based bags examined in this study. While recent studies have confirmed the presence of polyesters and starch in commercial compostable bags (Clagnan et al., 2023; Cucina et al., 2022b, 2021; Dolci et al., 2022), the specific content or proportions of these materials remained unassessed. PLA, the other polyester present in these bags, may enhance tensile strength and reduce stiffness, as demonstrated by Bouzidi et al., 2022 in their study on blending PLA with MaterBi® grade YI0140. PLA has been previously identified and quantified in relation to PBAT in bags by Álvarez-Méndez et al., 2023 and Peng et al., 2024 using ^1H NMR. The PLA to PBAT molar ratios from 0.03 in Bag 09 to 0.14 in Bag 10, were found to be at the lower end of the 0.15 to 0.91 ratio range reported by Álvarez-Méndez et al., 2023 for five different commercial compostable bags.

In Bag 16, the inclusion of PHBV instead of starch is a less common practice due to the higher cost and the low melt strength and viscosity of PHBV, which make it less suitable for blown film extrusion, a common method for producing flexible films for bags (Le Delliou et al., 2024; Teixeira et al., 2020). The greater thickness of Bag 16 (48 ± 2 μm) compared to the PBAT/starch-based bags may be attributed to the inclusion of PHBV, as implied by Teixeira et al., 2020, who found that reducing the proportion of PHB was essential for achieving thinner PBAT/PHB films.

The PE/starch-based bags exhibited a homogeneous composition consisting of 74 ± 2 % PE, 22 ± 2 % starch, and 3.1 ± 0.4 % inorganic additives. The presence of this cluster was unexpected, as PE is one of the conventional polymers that current research seeks to replace with biodegradable alternatives. Initially, the high carbon content (69 ± 1 % TS) and hydrogen content (11 ± 0 %TS) of these bags suggested the presence of a hydrocarbon like PE, a finding that was later confirmed by FTIR analysis. Notably, among the sixteen bags, five contained PE: three

were certified for home composting under the same certification holder (Bag 11, 12 and 14), while two others claimed to be compostable but were not certified (Bag 13 and 15).

3.1.2. Composition of compostable plastic coffee capsules

Compostable coffee capsules exhibited a more diverse composition, as shown in Fig. 1, categorized into cellulose-based (Cap 05), PHBV-based (Cap 01–04), PLA-based (Cap 06–08 and 11), and PBS/PLA-based clusters (Cap 09, 10 and 12).

The cellulose-based capsule incorporated PBAT (8 %) and PLA (1 %), probably to provide sufficient mechanical strength and hydrophobicity for improved barrier properties (Cheng et al., 2024). PHBV-based capsules presented PHBV in concentrations ranging from 76 % in Cap 02 and 95 % in Cap 01. Notably, Cap 02 presented a high proportion of organic additives (22 %). PHBV, a copolyester made of hydroxybutyrate and hydroxyvalerate units, is the most common polyhydroxyalkanoate (PHA) favored in food packaging for its balanced flexibility and toughness, and excellent barrier properties (Afshar et al., 2024; Shaikh et al., 2021).

The PLA-based coffee capsules were the primary contributors to the compositional diversity within the PLA cluster. Specifically, Cap 06 contained PHBV; Cap 08 included cellulose, PBS, and a high content of inorganic additives (11 %); Cap 11 featured PBAT; and Cap 07 was composed solely of PLA. PLA is recognized as one of the most promising biodegradable polymers for packaging due to its high strength, transparency, and ease of processing (Cheng et al., 2024; De Luca et al., 2023). Its blending with various polymers, as shown in the studied coffee capsules, is common and primarily aimed at improving its brittleness, low toughness, and processability at lower temperatures (De Luca et al., 2023). While Cazaudehore et al., 2021 and Shrestha et al., 2020 cited PLA as a component in the compostable coffee capsules they studied, the composition of the capsules remained unassessed up to date.

The PBS/PLA coffee capsules presented an average composition of 60 ± 7 % PBS, 22 ± 7 % PLA, and 18 ± 1 % of inorganic additives. The relatively high values of inorganic additives may be intended to improve miscibility between the polymers, which has been reported to decrease with larger proportions of PBS (De Luca et al., 2023). Interestingly, Cap 09 and Cap 10, which contained a higher proportion of PBS relative to PLA than Cap 12, were particularly prone to fracture upon touch compared to all the other coffee capsules.

3.1.3. Composition of compostable cups, straws and forks

Compostable cups, straws and forks were present in three clusters: cellulose-based, PHBV-based, and primarily PLA-based, as illustrated in Fig. 1. Cellulose-based Cup 01 had a similar composition to Bag 01; however, they differed in thickness, measuring 311 ± 3 µm and 199 ± 9 µm, respectively. Similarly, PHBV-based Straw 01 exhibited a comparable composition to the PHBV-based capsules, but its thickness was significantly lower at 177 ± 7 µm, compared to 627 ± 52 µm for the capsules.

Cup 02, Straw 02, Fork 01, and Fork 02 were all made from PLA, a widely used material for disposable tableware and cutlery (Bracciale et al., 2023). While PLA-based commercial tableware and cutlery have been studied, only Bracciale et al., 2024, 2023 and Falzarano et al., 2024 have confirmed the presence of PLA in these products, either as the sole polymer or in combination with starch, PBAT, or PBS. Among the aforementioned products, Cup 02 and Fork 02 presented PLA as a sole polymer, with Cup 02 showing an almost identical composition and a slightly lower thickness compared to Cap 07, while Fork 02 distinguished itself by having the highest proportion of inorganic additives at 28 % and the greatest thickness of 5111 ± 3 µm among all the products.

3.2. Mesophilic anaerobic biodegradability of compostable food packaging

The CMC used as a positive control for the BMP tests yielded BMP_{exp}

values of 386 ± 1 (Series 1), 372 ± 6 (Series 2), and 359 ± 5 NmLCH₄/gVS (Series 3) all of which met the validation criteria established by the DBFZ (DBFZ, 2024). Additionally, CMC achieved a degradation rate of 70 % within 15 days across all three series, satisfying the validation criteria outlined in standard EN ISO 13975 (ISO, 2019). Methane production curves for selected products (Bag 02, 06, 14 and 16; Cap 03, 04, 07, 10 and 11, Cup 01 and 02, Straw 01 and 02, and Fork 01) are detailed in supplementary materials, while normalized BI, normalized BMP_{exp} and R_m of all products are presented in Table 2.

Fig. 1 compares the normalized BI and normalized BMP_{exp} in relation to the composition and thickness of each product, arranged according to product type. Fig. 2 illustrates the R_m and the peak production time, corresponding to the day the R_m was achieved. PHBV-based (BI = 92 ± 1 %; BMP = 546 ± 26 NmLCH₄/gVS) and cellulose-based products (BI = 85 ± 9 %; BMP = 352 ± 27 NmLCH₄/gVS) exhibited a significantly higher BI and BMP than the other products, which had a BI below 30 % and a BMP under 242 NmLCH₄/gVS. Notably, PLA-based products demonstrated considerable variability in BI (7.1 % to 60 %) and BMP (40 NmLCH₄/gVS to 296 NmLCH₄/gVS), likely due to their heterogeneous composition. Additionally, as seen in Fig. 2, PLA and PBS/PLA-based products tended to present a lower R_m (< 5 NmLCH₄/gVS/day) compared to the other types of products.

3.2.1. Mesophilic anaerobic digestion of compostable bags

As shown in Fig. 1, cellulose-based bags (BI = 86 ± 8 %; BMP = 358 ± 37 NmLCH₄/gVS) significantly outperformed both PBAT/starch-based bags (BI = 25 ± 8 %; BMP = 132 ± 53 NmLCH₄/gVS) and PE/starch-based bags (BI = 9.5 ± 0.5 %; BMP = 88 ± 5 NmLCH₄/gVS). This superior performance aligns with the known degradability of cellulose under AD conditions. Overall, studies on compostable bags under mesophilic AD, excluding cellulose-based variants, have consistently reported low BMP values (less than 200 NmL CH₄/g VS) and limited BI (Álvarez-Méndez et al., 2023; Battista et al., 2021; Bouchalová et al., 2023; Calabro et al., 2020; Cucina et al., 2021; Dolci et al., 2021; Peng et al., 2024; Zaborowska et al., 2021). Among the cellulose-based products, Bag 03, which contained a larger proportion of additives, exhibited the lowest BI (72 ± 2 %) and BMP (320 ± 7 NmLCH₄/gVS).

The kinetics of methane production from PBAT/starch and PE/starch-based bags showed a rapid increase at the beginning of the test, followed by a significant decline that stabilized at a low, constant level of methane production (see supplementary materials). As illustrated in Fig. 2, the R_m of these bags occurred within the first five days of the test. These observations indicate that an easily degradable component undergoes initial degradation, followed by the subsequent degradation of a more recalcitrant component. Under varying test conditions, Clagnan et al., 2023; Cucina et al., 2022b; Cucina et al., 2021; Cucina et al., 2022a and Yu et al., 2023 confirmed through spectroscopic analysis of polyester/starch-based bags before and after AD that the starch component was preferentially degraded compared to the polyester component. In addition to starch, organic additives such as glycerol—acting as a plasticizer in the conversion of starch into thermoplastic starch for blending with PBAT—could also influence methane yield. For example, Vasmara et al., 2024 found that one type of PLA yielded 20 mL CH₄/gVS, while another yielded only 1 mL CH₄/gVS, with the higher yield attributed to the presence of acetic acid as an additive.

Bag 16, containing PBAT and PHBV, exhibited the lowest BI (7.2 ± 1.3 %) and BMP (47 ± 9 NmLCH₄/gVS) among all bags, including the PE/starch-based bags. This result is unexpected, considering that PHBV is known to be highly degradable in mesophilic AD conditions (Cazaudehore et al., 2022b), and its presence should theoretically improve BI. By considering a BMP_{th} of 605 NmLCH₄/gVS for PHBV (Cazaudehore et al., 2023) along with the PHBV content in the bag, the theoretical contribution of the PHBV content in Bag-16 is estimated at 173 NmLCH₄/gVS, a value that was far from being attained. This suggests that the PHBV in Bag 16 may have been inaccessible to microorganisms, possibly due to its encapsulation between layers of PBAT, as

Table 2

Biochemical methane potential, anaerobic biodegradability and maximum methane production rate of compostable food packaging.

Product	BIC	Cluster	Test Series	BMP _{th} [NmLCH ₄ /gVS] ^a	BMP* _{exp} [NmLCH ₄ /gVS] ^b	BI* [%] ^c	R _m [NmLCH ₄ /gVS/day] ^d
Bag-01	C	Cellulose	3	411 ± 1	394 ± 13	96 ± 3	32 ± 11
Bag-02	C	Cellulose	2	407 ± 1	361 ± 4	89 ± 1	41 ± 7
Bag-03	IC	Cellulose	3	444 ± 0	320 ± 7	72 ± 2	27 ± 15
Bag-04	IC	PBAT/starch	3	549 ± 2	203 ± 7	37 ± 1	21 ± 6
Bag-05	IC	PBAT/starch	3	570 ± 1	200 ± 6	35 ± 1	19 ± 3
Bag-06	IC	PBAT/starch	2	607 ± 1	150 ± 2	25 ± 0	11 ± 0
Bag-07	HC	PBAT/starch	2	570 ± 0	131 ± 11	23 ± 2	12 ± 1
Bag-08	IC	PBAT/starch	2	573 ± 0	131 ± 8	23 ± 1	9.0 ± 1.5
Bag-09	C	PBAT/starch	2	585 ± 1	108 ± 6	18 ± 1	10 ± 0
Bag-10	HC	PBAT/starch	2	585 ± 1	86 ± 13	15 ± 2	7.3 ± 3.4
Bag-11	HC	PE/starch	2	935 ± 1	96 ± 8	10 ± 1	9.5 ± 3.5
Bag-12	HC	PE/starch	2	924 ± 1	89 ± 5	10 ± 1	8.8 ± 0.7
Bag-13	C	PE/starch	2	917 ± 1	85 ± 2	9.3 ± 0.2	8.2 ± 1.0
Bag-14	HC	PE/starch	2	910 ± 0	83 ± 4	9.1 ± 0.5	9.9 ± 0.8
Bag-15	C	PE/starch	2	933 ± 1	85 ± 4	9.1 ± 0.5	8.7 ± 2.7
Bag-16	C	PBAT/PHBV	3	656 ± 1	47 ± 9	7.2 ± 1.3	1.2 ± 2.3
Cap-01	IC	PHBV	1	584 ± 8	541 ± 3	93 ± 1	21 ± 7
Cap-02	HC	PHBV	1	547 ± 1	507 ± 2	93 ± 0	18 ± 1
Cap-03	HC	PHBV	1	605 ± 1	551 ± 4	91 ± 1	45 ± 6
Cap-04	HC	PHBV	1	605 ± 0	551 ± 2	91 ± 0	44 ± 16
Cap-05	HC	Cellulose	3	418 ± 1	346 ± 5	83 ± 1	23 ± 9
Cap-06	IC	PLA	1	497 ± 1	296 ± 8	59 ± 2	6.5 ± 6.5
Cap-07	IC	PLA	1	473 ± 0	137 ± 4	29 ± 1	3.1 ± 2.0
Cap-08	IC	PLA	1	543 ± 1	88 ± 9	16 ± 2	2.4 ± 6.5
Cap-09	IC	PBS/PLA	1	564 ± 1	48 ± 5	8.5 ± 0.9	1.1 ± 2.4
Cap-10	IC	PBS/PLA	1	571 ± 1	46 ± 4	8.1 ± 0.7	0.85 ± 2.51
Cap-11	IC	PLA	1	556 ± 1	40 ± 8	7.1 ± 1.4	1.3 ± 6.1
Cap-12	IC	PBS/PLA	1	545 ± 1	17 ± 4	3.2 ± 0.7	0.90 ± 2.51
Cup-01	IC	Cellulose	3	403 ± 0	340 ± 4	84 ± 1	28 ± 4
Cup-02	C	PLA	3	468 ± 0	282 ± 7	60 ± 2	4.3 ± 1.7
Straw-01	HC	PHBV	3	644 ± 0	580 ± 1	90 ± 0	2.4 ± 1.3
Straw-02	IC	PLA	3	500 ± 1	129 ± 3	26 ± 1	1.6 ± 3.9
Fork-01	IC	PLA	3	502 ± 1	146 ± 6	29 ± 1	15 ± 2
Fork-02	IC	PLA	3	494 ± 1	60 ± 15	12 ± 3	2.2 ± 0.6

(BIC = biodegradability claim, BMP_{th} = theoretical biochemical methane potential, BMP*_{exp} = experimental biochemical methane potential [normalized], BI* = biodegradability [normalized], R_m = maximum methane production rate, VS = volatile solids, Cap = capsule, C = compostable [not certified], IC = compostable under industrial conditions, HC = home compostable).

^a = estimated according to the Buswell equation modified by Boyle.

^b = average of triplicates.

^c = estimated as the ratio between BMP_{exp} and BMP_{th}.

^d = estimated as maximum first derivative of methane production in function of time.

the multilayer films described by Cheng et al., 2024. Furthermore, as illustrated in Fig. 2, Bag 16 exhibited a significantly lower R_m (< 5 NmLCH₄/gVS/day) compared to the other bags, suggesting a high recalcitrance of PBAT. In fact, Álvarez-Méndez et al., 2023 and Peng et al., 2024 determined via ¹H NMR that the PBAT component in PBAT/PLA bags suffered an insignificant degradation compared to the PLA component after mesophilic and thermophilic AD, probably due to its complex structure containing aromatic bonds in the BT unit. In support to this, Yu et al., 2023 found that the PBAT-based bags in their study presented a lower methane production rate compared to a PLA-based bag and a PBAT/PLA/starch-based bag.

3.2.2. Mesophilic anaerobic digestion of compostable coffee capsules

As seen in Fig. 1, cellulose-based Cap 05, which contained a minor proportion of PBAT and PLA, exhibited a BI of 83 ± 2 % and a BMP of 346 ± 5 NmLCH₄/gVS. PHBV-based coffee capsules (Cap 01–04) exhibited the highest BI among all products at 92 ± 1 %. Their BMP ranged from 507 ± 2 NmLCH₄/gVS (Cap 02) to 551 ± 4 NmLCH₄/gVS (Cap 03 and 04). The lower BMP observed in Cap 02 can be attributed to its higher proportion of additives. While the BI and BMP values of PHBV-based capsules were relatively consistent, there were notable differences in their R_m (Fig. 2). Cap 03 (45 ± 6 NmLCH₄/gVS/day) and Cap 04 (44 ± 16 NmLCH₄/gVS/day) had a substantially higher R_m compared to Cap 01 (21 ± 7 NmLCH₄/gVS/day) and Cap 02 (18 ± 1 NmLCH₄/gVS/day) that may be attributed to a higher proportion of hydroxyvalerate in PHBV, which has been associated with lower crystallinity and faster

degradation rates (De Luca et al., 2023).

PLA-based Cap 06, characterized by a substantial content of PHBV, demonstrated a BI of 59 ± 2 % and a BMP of 296 ± 8 NmLCH₄/gVS, significantly surpassing the performance of the other PLA-based capsules (Cap 07, 08 and 11), all of which had a BI of less than 29 % and a BMP below 137 NmLCH₄/gVS after 105 days. Cap 07, which exclusively contained PLA as polymer, exhibited the highest performance (BI = 29 ± 1 %; BMP = 137 ± 4 NmLCH₄/gVS) among these three capsules, outpacing both Cap 08 (BI = 16 ± 2 %; BMP = 88 ± 9 NmLCH₄/gVS), which included a significant amount of cellulose, and Cap 11 (BI = 7.1 ± 1.4 NmLCH₄/gVS; BMP = 40 ± 8 NmLCH₄/gVS), which contained PBAT. Although the cellulose in Cap 08 should theoretically enhance BI and BMP, it appears that a phenomenon similar to that observed in Bag 16 may be occurring, where the cellulose is trapped between hydrophobic polyesters, rendering it inaccessible to microorganisms. Additionally, both Cap 08 and Cap 11 were thicker than Cap 07 and contained recalcitrant PBAT. While few capsules have been studied in the literature, Cazaudehore et al., 2021 reported similar values (BI = 12–8 %; BMP = 67–127 NmLCH₄/gVS) after 100 days of mesophilic AD for three capsules stated to contain polyesters. Additionally, Shrestha et al., 2020 found that a PLA-based capsule exhibited less than 50 % degradation under thermophilic conditions.

Lastly, the PBS/PLA-based coffee capsules displayed the lowest biodegradability (6.6 ± 3.0 %) and BMP (37 ± 17 NmLCH₄/gVS). PBS has been reported to produce low or no methane under AD, even after long digestion times (Cazaudehore et al., 2022b, 2022a), likely due to its

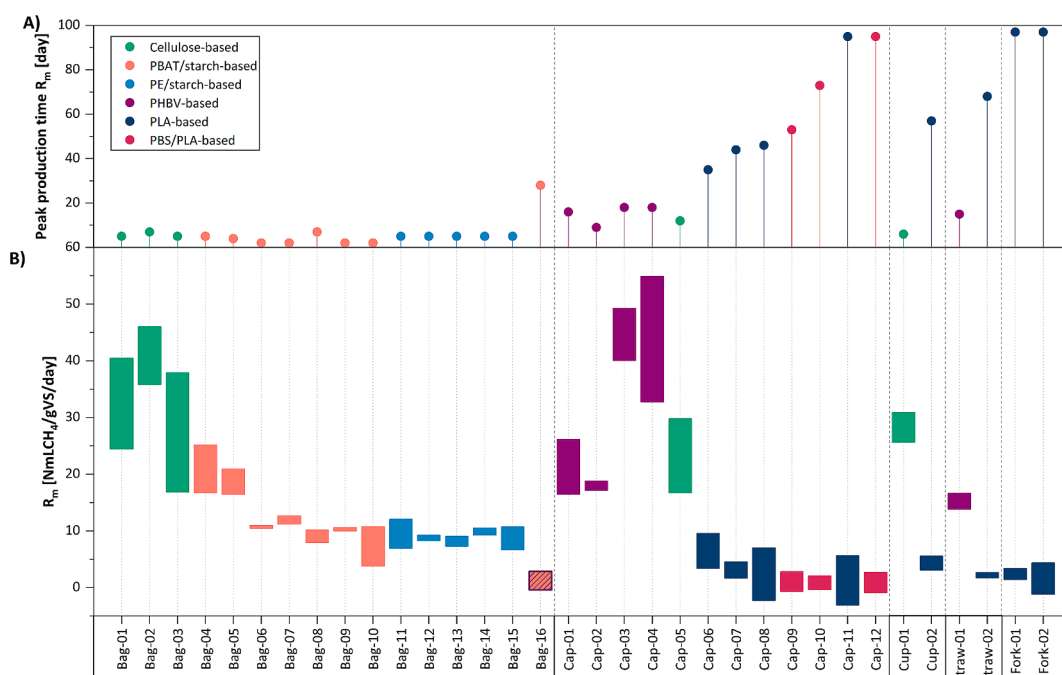


Fig. 2. A) Peak production time and B) maximum methane production rate of compostable food packaging categorized according to product type. (R_m = maximum methane production rate, VS = volatile solids, Cap = capsule, PBAT = polybutylene adipate co-terephthalate, PE = polyethylene, PHBV = poly[3-hydroxybutyrate-co-3-hydroxyvalerate, PLA = polylactic acid, PBS = polybutylene succinate]).

inherent resistance to hydrolysis. The high concentration of additives found in these capsules may further impede the AD process by interfering with microbial activity. In agreement with this, Bracciale et al., 2024 determined that the MaterBi® tableware containing high levels of PBS and inorganic additives exhibited a limited degradation (BI = 40 – 60 %) during thermophilic AD compared to the MaterBi® tableware composed mainly of PLA (BI = 70 %). The R_m of these capsules was also relatively low (< 5 NmLCH₄/gVS/day) (Fig. 2), comparable to Bag 16, and could have probably been affected by the inorganic additives. Oliver et al., 2024 determined that the higher concentrations of CaCO₃ filler in their laboratory-made starch film samples slowed down biogas production, from 30 NmL/gVS/day for the sample without filler to 23 NmL/gVS/day for the sample with 5 % filler.

3.2.3. Mesophilic anaerobic digestion of compostable cups, straws and forks

Cellulose-based Cup 01 (BI = 84 ± 1 %; BMP = 340 ± 4 NmLCH₄/gVS) had a slightly lower performance than its compositional analog, Bag 01, possibly due to its greater thickness. In contrast, PHBV-based Straw 01 showed a high BI (90 ± 0 %), and BMP (580 ± 1 NmLCH₄/gVS), similar to the PHBV-based coffee capsules, despite their difference in thickness.

PLA-based Cup 02 (BI = 60 ± 2 %; BMP = 282 ± 7 NmLCH₄/gVS) doubled its performance in relation to its compositional analog, Cap 07. This difference, along with the lower performance of Fork 02 (BI = 12 ± 3 % and BMP = 60 ± 15 NmLCH₄/gVS), may be attributed to variations in material thickness. Bracciale et al., 2023 observed that thicker stiffer PLA cups degraded 12 % to 16 % slower in the initial stages and 18 % to 21 % slower in the final stages compared to thinner PLA cups. While no significant differences were observed among the R_m of these three products and other PLA-based products (ranging from 1.3 to 6.5 NmLCH₄/gVS), as illustrated in Fig. 2, it is noteworthy that Fork 01, Fork 02 and Cap 11—being the thickest in the group—achieved their R_m values much later, toward the end of the test. The R_m values align with findings by Cazaudehore et al., 2022b who reported that PLA had a particularly low R_m (1.23 NmLCH₄/gVS/day), comparable to non-degraded PBAT and PBS, and significantly lower than starch (34 NmLCH₄/gVS/day) and PHB (46 NmLCH₄/gVS/day).

The performance of PLA-based Fork 01 containing PBAT (BI = 29 ± 1 %; BMP = 146 ± 6 NmLCH₄/gVS), was similar to its compositional analog Straw 02 (BI = 26 ± 1 %; BMP = 129 ± 3 NmLCH₄/gVS), but twice as high as Cap 11, which also shared a similar composition. When comparing these three products with similar compositions, the lower performance of Cap 11 relative to Straw 02 could be linked to its higher thickness. However, the performance difference between Cap 11 and Fork 01 is less clear and may be influenced by factors such as varying PLA/PBAT ratios (Álvarez-Méndez et al., 2023; Peng et al., 2024), the crystallinity of PLA, which is related to its enantiomeric form, or even the aromatic content in PBAT (Álvarez-Méndez et al., 2023).

3.3. Considerations for integrating food packaging into mesophilic AD plants

The diversity of polymers and blends found in the compostable food packaging examined in this study underscores the complexity of their formulation and, consequently, their biodegradation process in the mesophilic AD process. General observations suggest a connection between anaerobic biodegradability and the predominant polymer, with PHBV and cellulose exhibiting higher biodegradability than PLA, followed by PBAT and PBS, consistent with findings of the individual polymers in mesophilic AD (Cazaudehore et al., 2022a). However, relying solely on the knowledge of the main polymer is insufficient to explain differences in biodegradation. The limitation it poses is particularly evident when examining the biodegradation of PLA-based products, which often contained other polymers (i.e., PHBV, PBAT, PBS, and cellulose) that can significantly affect biodegradability. A limitation that is further exacerbated by the broad range of additive concentrations and the tendency to label products based on their most effective biodegradable polymer, rather than the polymer present in the highest proportion. For example, many products, particularly bags, are marketed and reported as starch-based; however, this study, which examined a range of bags, did not identify starch as a predominant component. Additionally, it is essential to acknowledge that while understanding the general chemical composition (i.e., primary polymers) provides valuable insights into biodegradability, it does not fully explain all observed

differences. Alongside this, a more detailed analysis of the chemical composition (including the nature of additives), as well as morphological factors (such as phase distribution, and layer arrangement), and other physical properties (crystallinity, accessible surface area, porosity) of the materials, can offer critical insights into variations in biodegradation that chemical composition alone cannot elucidate.

Considering this complexity, the present study demonstrated that most commercially available compostable food packaging—PBAT/starch-based bags, PE/starch-based bags, PLA-based products, and PBS/PLA-based coffee capsules—exhibit only partial degradation in mesophilic AD, with a BI below 60 % after 105 days, as illustrated in Fig. 3. In contrast, PHBV-based products containing over 70 % PHBV achieved at least 90 % degradation in mesophilic AD within 50 days. Similarly, cellulose-based products with over 80 % cellulose reached at least 80 % degradation, although they required longer retention times of at least 70 days. These findings support the use of cellulose-based products and particularly PHBV-based products, as effective anaerobically digestible biodegradable plastics under acceptable retention times in mesophilic AD plants. Currently, bio-waste is treated in biogas plants operating with a hydraulic retention time (HRT) between 15 to 30 days (Bátori et al., 2018) but can also be incorporated into agro-industrial biogas plants that operate with a longer HRT of around 100 days (Ruile et al., 2015).

These results also underscore the need for strategies to enhance the mesophilic anaerobic biodegradability of food packaging. Such strategies may include pretreatments to improve the hydrolysis of biodegradable polymers (Battista et al., 2021; Calabro et al., 2020; Mu et al., 2021) and/or post-treatments of digestate (e. g., composting) containing partially degraded food packaging (Bandini et al., 2022; Cucina et al., 2021). Implementing these strategies can mitigate the negative impacts of partial degradation of food packaging, such as the environmental leakage of biodegradable microplastics and additives during the application of digestate to soil (Afshar et al., 2024; Cazaudehore et al., 2022a). Another approach involves the eco-design of new biodegradable polymers that maintain essential properties, such as tensile strength and water resistance; however, this necessitates a thorough understanding of the physicochemical properties that impede the anaerobic biodegradability of polymers and also requires significant development time.

Finally, the lack of specification standards for AD, stemming from the

relatively recent emergence of organic valorization pathways and the inherent variability of AD processes, presents a significant challenge to establishing a unified specification standard (Cazaudehore et al., 2022a). Additionally, the presence of conventional polymers, such as PE, in certified products raises critical concerns regarding manufacturer transparency and the reliability of certification systems. This situation highlights the urgent need to develop or strengthen standards that assess the traceability of food packaging compositions and their biodegradability within AD processes or integrated facilities, such as those combining AD with industrial composting.

4. Conclusion

The 34 compostable food packaging presented a diverse mesophilic anaerobic biodegradability in relation to their also diverse chemical composition. Cellulose-based, PBAT/starch, PE/starch, PLA, PBS/PLA, and PHBV-based products were identified. Only PHBV and cellulose-based products achieved a biodegradability exceeding 80 %, with PHBV products reaching this level in under 50 days, making them promising candidates for integration into mesophilic AD plants. All other products presented a biodegradability below 30 %, with PBS/PLA-based products exhibiting the lowest values (< 10 %). Accurate characterization of plastic products' chemical composition enhances understanding of their biodegradability, enabling manufacturers to eco-design more sustainable food packaging for mesophilic biogas plants processing bio-waste.

CRediT authorship contribution statement

Juliana Catalina Suarez Murcia: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gaël Huet:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Julie Lamarque:** Writing – review & editing, Visualization, Investigation, Data curation, Conceptualization. **Emmanuelle Gastaldi:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Cecilia Sambusiti:** Writing – review & editing, Supervision, Project administration, Funding

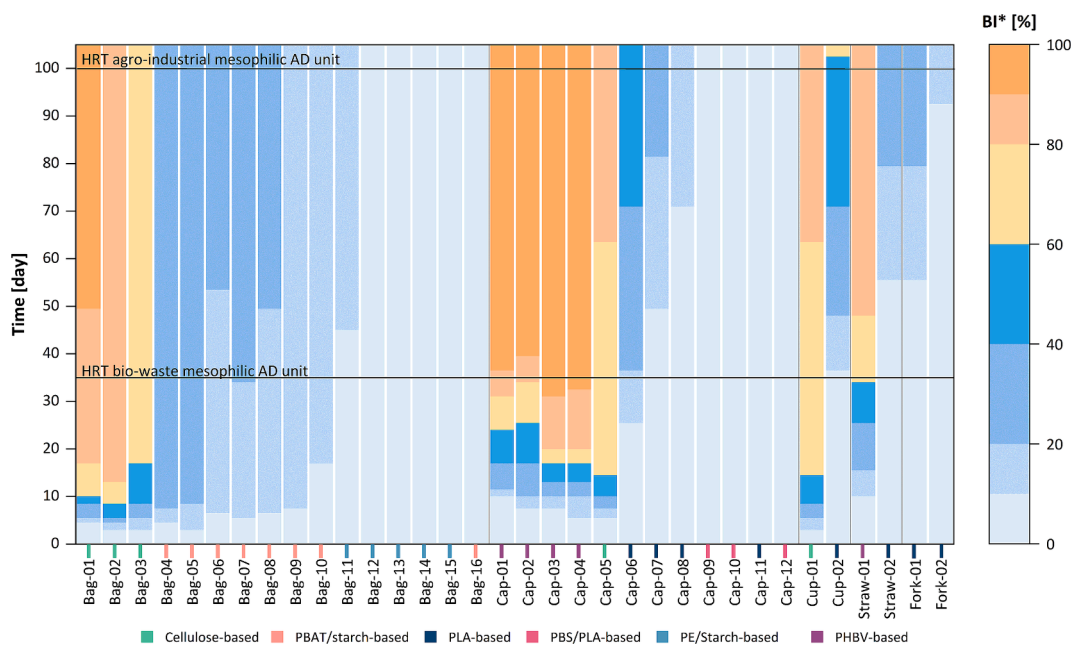


Fig. 3. Anaerobic biodegradability of compostable food packaging in function of time (BI* = biodegradability [normalized], PBAT = polybutylene adipate terephthalate, PE = polyethylene, PHBV = poly[3-hydroxybutyrate-co-3-hydroxyvalerate], PLA = polylactic acid, PBS = polybutylene succinate, HRT = hydraulic retention time, AD = anaerobic digestion).

acquisition, Conceptualization. **Valentin Puchelle**: Writing – review & editing, Methodology, Conceptualization. **Bruno Grassl**: Writing – review & editing, Supervision, Methodology, Conceptualization. **Sandra Domenek**: Writing – review & editing, Methodology, Conceptualization. **Florian Monlau**: Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biortech.2025.132273>.

Data availability

Data will be made available on request.

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