

Case Study on Kitchen Waste Collection Materials: Comparing the Effects of Biobased Bags on Anaerobic Digestion

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Separate collection of household bio-waste became mandatory across the European Union in 2024, increasing the use of biodegradable paper and plastic liners for kitchen waste. While these materials improve source-separation and hygiene, their behavior during Anaerobic Digestion (AD) remains insufficiently understood and may affect plant performance and digestate quality. This study evaluated five commercially available collection bags – three paper-based and two biodegradable plastic types – under mesophilic batch AD conditions. Paper bags increased methane and biogas yields by approximately 5–20 %, while biodegradable plastics resulted in similar or slightly reduced yields compared to controls. Neither material showed substantial structural degradation, but paper provided additional substrate and surface area, supporting modest efficiency gains. In contrast, persistent plastic fragments in the digestate may limit its agricultural use under strict EU fertilizer regulations, leading to higher post-treatment costs. These findings highlight that paper liners are more compatible with AD-based waste management systems, informing municipalities, policymakers, and operators in selecting collection tools that optimize resource recovery and regulatory compliance.

1. Introduction

Municipal solid waste management is a crucial environmental and policy challenge in the European Union (EU), particularly due to increasing waste volumes and the heterogeneous composition of waste streams. Bio-waste – including kitchen, food, and garden residues – accounts for around 34 % of municipal solid waste by weight (European Environment Agency, 2020). When landfilled, its anaerobic decomposition emits methane, thus significantly contributing to climate change (European Environment Agency, 2023). At the same time, biological treatment processes can recover valuable resources, including biogas and digestate.

Under the Waste Framework Directive, selective collection of bio-waste became mandatory by 31 December 2023, leading to the widespread introduction of collection liners and tools – typically biodegradable plastics, paper bags, or reusable containers – to support logistics and hygiene during household collection. At the same time, these materials enter downstream treatment processes and may influence their efficiency.

Anaerobic Digestion (AD) is widely recognized as a key method for bio-waste valorization (Cazaudehore et al., 2022), but process performance depends strongly on substrate composition, reactor design, and operational parameters (Sharma et al., 2023). Paper and biodegradable plastic liners differ in composition and biodegradability: paper contributes lignocellulosic material and shows partial degradation in AD, while most biodegradable plastics are designed for aerobic composting and often persist under strictly anaerobic conditions (Dolci et al., 2022), potentially requiring additional post-treatment (Pangallo et al., 2023).

Although research on compostability and life-cycle impacts has grown (Sipos et al., 2024), there is limited systematic evidence on how commercially available kitchen waste liners affect mesophilic AD performance, microbial accessibility, and digestate quality when co-digested with household food waste. This represents a practical knowledge gap for waste operators and regulators implementing EU-wide bio-waste collection.

Therefore, this study aims to evaluate the anaerobic biodegradability and process impacts of five widely used bio-waste collection bags – three paper-based and two biodegradable plastic types – under mesophilic batch conditions. The findings are interpreted in the context of operational performance, material persistence, and compliance with EU fertilizer regulations, providing actionable insights for AD plants and policymakers.

2. Materials and methods

Batch Anaerobic Digestion (AD) experiments were conducted in single-neck glass reactors with a total volume of 1 L to evaluate the biodegradability and biogas production potential of kitchen waste and biodegradable bags. Experiments were carried out in three independent series (C1-C3), each including three parallel replicates per treatment.

2.1 Inoculum and substrate

Mesophilic anaerobic sludge from an operating biogas plant was used as inoculum. The substrate consisted of kitchen waste in all three experiments, including vegetable (potato, carrot, onion, cucumber, tomato, parsley, celery, kohlrabi) and fruit (lemon, banana) trimmings. The composition of the waste was identical across all experiments, as it was prepared and homogenized in the laboratory from the same source materials.

A total of 80 g of homogenized kitchen waste was added to 700 mL of inoculum in each reactor, resulting in varying organic loading values across the three experimental series. These variations were accounted for by normalizing gas yields to the corresponding controls within each batch. The physico-chemical characteristics of both the inoculum and the substrate, including total solids (TS), volatile solids (VS), moisture content, and pH, are summarized in Table 1.

Table 1: Physico-chemical properties of inoculum and kitchen waste used in the three independent series of experiments

	TS (%)	VS (%)	Moisture content (%)	pH
Inoculum 1	2 %	68 %	98 %	7.12
Inoculum 2	6 %	69 %	94 %	7.90
Inoculum 3	2 %	74 %	98 %	7.46
Kitchen waste 1	20 %	95 %	80 %	5.13
Kitchen waste 2	13 %	92 %	87 %	4.63
Kitchen waste 3	14 %	92 %	86 %	4.96

2.2 Biobased bags

Five different commercially available bags, including two biodegradable plastic bags and three paper bags, were examined during the experiments. Plastic bags 1 (PIB1) and 2 (PIB2) were produced using starch, cellulose, and vegetable oils. Paper bags (PaB1-PaB3) are made of 100 % recycled, reinforced paper with water-soluble adhesives and inks. All five collecting bags were weighed and cut into small pieces (particle size approx. 1–2 cm). The amount of bag material corresponded to 2.5 % (w/w) of the total substrate.

2.3 Experimental setup and operation

The experimental setup was similar to that described by Kalauz et. al. (2025), with minor modifications. The 1 L reactors were sealed with caps equipped with inlet and outlet ports, and connected via HDPE pipes to a modified U-shaped tube used to measure the volume of the produced gas. Each reactor was linked to a PC via a data-acquisition system. After substrate addition, nitrogen gas was purged through the reactors for ten minutes to ensure anaerobic conditions. The fermenters were maintained at 37 °C, and the initial pH ranged from 7 to 8. The digestion period lasted 40 days, and reactors were stopped when daily gas production fell below 1 % of the cumulative volume. No mixing was applied during the experiments.

2.4 Analytical methods

Headspace gas analysis was conducted throughout the experimental period. The composition of the produced gas was determined two to three times per week using a gas chromatograph (HP 5890) equipped with a thermal conductivity detector (TCD) (oven temperature: 90 °C, detector temperature: 130 °C), with nitrogen acting as

the carrier gas. Gas samples were manually injected at 110 °C (Hamilton syringe). The measured biogas composition was assumed to reflect the average gas composition produced during each sampling interval. The total solids (TS) content of the inoculum and the kitchen waste substrate was measured gravimetrically after drying the samples at 105 °C for 24 h. The volatile solids (VS) content was determined from the weight loss following heating the samples at 550 °C for 2 h.

Thermogravimetric (TG) analyses were performed to evaluate changes in thermal behaviour and potential microbial colonization of paper materials. Thermal decomposition was studied using a MOM Derivatograph Q 1500D. Approximately 250 mg of each sample was placed in a parallel-walled corundum crucible and heated at a constant rate of 10 °C/min under static air conditions. Corundum served as the reference material.

2.5 Data normalization and control adjustment

AD experiments included control reactors (no bags). To ensure comparability, yields were normalized to the mean control of each series using Eq(1). Results are reported as a percentage of the control.

$$Y_{rel} = (Y_{treatment} / Y_{control}) \times 100 \quad (1)$$

where Y_{rel} is the normalized methane or biogas yield (%), $Y_{treatment}$ is the measured yield for each reactor, and $Y_{control}$ is the mean yield of the control reactors within the same batch (C1–C3).

2.6 Calculation of specific yields

Methane and biogas yields were expressed as normalized gas volumes per VS added ($\text{NmL CH}_4 \text{ g}^{-1} \text{ VS}$ and $\text{NmL biogas g}^{-1} \text{ VS}$, respectively). The results were subsequently expressed as percentages relative to the yields obtained in the corresponding control reactors. Organic load (OL) values were derived from the total solids (TS) and volatile solids (VS) contents of the substrate.

2.7 Statistical analysis

All statistical analyses were performed using Statistica 8 and Microsoft Excel software. The normalized methane and biogas yields (expressed as % of the corresponding control) were treated as dependent variables, while the type of collection bag (five experimental treatments: Paper 1-3, Plastic 1-2) served as the categorical independent variable. A one-way analysis of variance (ANOVA) was used to test whether the collection bag type had a significant effect on methane and biogas yields. The assumptions of normality and homogeneity of variances were verified using the Shapiro–Wilk and Levene's tests, respectively. When significant differences were detected ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) post-hoc test was applied to identify pairwise differences among the bag-type treatment means.

The relationship between methane and biogas yields (both expressed as % of control) was assessed using Pearson's correlation analysis. A correlation coefficient (r) close to 1 indicated that methane and total biogas production were strongly associated, suggesting that treatment effects primarily reflected changes in overall biodegradation rather than gas composition.

Statistical significance was considered at $p < 0.05$. Results are reported as mean \pm standard deviation unless stated otherwise.

3. Results and discussion

This section provides a comprehensive evaluation of the AD experiments performed with kitchen waste using biodegradable paper and plastic collection bags. The structural and thermal behavior of the bag materials was examined in parallel with methane production to clarify their contribution to process efficiency.

3.1 Visual observations and thermogravimetric analyses

For all collection bag types, visual inspection of the digestate at the end of the AD experiments revealed the presence of intact bag fragments (Figure 1), which appeared largely undecomposed. Since no mixing was applied, these materials were not subject to mechanical disintegration.



Figure 1: Digestate samples at the end of anaerobic digestion, containing fragments of paper and plastic collection bags. (a) Reaction mixture with Paper bag 1 (PaB1); (b) Reaction mixture with Plastic bag 2 (PiB2)

Microscopic observations (at 100x magnification) of PaB1 revealed no structural differences compared to an untreated reference sample (Figure 2). The water-soluble dye also remained visible after digestion.

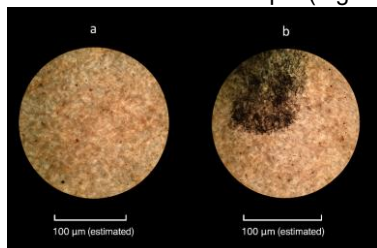


Figure 2: Light microscopic images of Paper bag 1 (PaB1) at 100x magnification. (a) Untreated sample; (b) Bag fragment recovered from the digestate at the end of the experiment

The TG analyses (Figure 3) showed three main decomposition stages. Before AD, the total mass loss of the paper sample was 39.83 %, with three characteristic regions: (I) 38–196 °C corresponding to moisture evaporation (2.72 %), (II) 196–381 °C attributed to cellulose and hemicellulose decomposition (25.27 %), and (III) 379–559 °C representing the oxidation of carbonaceous residue (11.84 %). These transitions are consistent with the well-known thermal behaviour of pure cellulose-based materials, which exhibit a dominant degradation step around 300–380 °C (Xu et al., 2021). After AD, the total mass loss increased by 82.42 %, particularly in the 180–374 °C region, indicating microbial biomass decomposition. Several studies confirm that microbial and algal biomass typically decomposes between 200 °C and 350 °C, producing characteristic DTG peaks distinct from those of pure lignocellulosic materials (Yang et al., 2023). The presence of this additional mass loss thus indicates the accumulation of microbial organic matter on the paper surface during fermentation. The third stage (374–550 °C) also showed a higher weight reduction (23.35 %), which may be attributed to the oxidation of carbonaceous char enriched with microbial residues (Díaz et al., 2024).

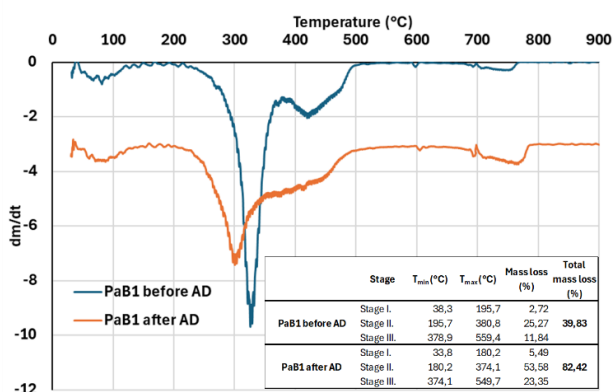


Figure 3: Derivative thermogravimetric (DTG) curves of Paper bag 1 (PaB1) before and after anaerobic digestion

In summary, although paper bag fragments remained visibly intact, thermogravimetric profiles confirmed biochemical degradation and microbial biomass accumulation on the material surface, which may contribute to additional methane generation.

3.2 Cumulative biogas and methane production

Based on the normalized results, paper bags consistently increased methane and biogas yields compared to the corresponding controls (approximately +5–20 %, Figure 4). In contrast, biodegradable plastic bags showed no significant improvement with slight decreases in both biogas and methane production. This performance aligns with the limited biodegradation observed visually.

One-way ANOVA indicated significant treatment effects ($p < 0.05$) on normalized methane and biogas yields, with pairwise differences mainly between PaB1 and PIB1, and between PaB1 and PaB2. Pearson correlation analysis confirmed a strong association between methane and biogas yields ($r \approx 0.99$), indicating that the differences primarily reflect overall biodegradation efficiency rather than gas composition.

Together with TG results, these data support that paper bags contribute extra biodegradable matter, while tested bioplastics do not.

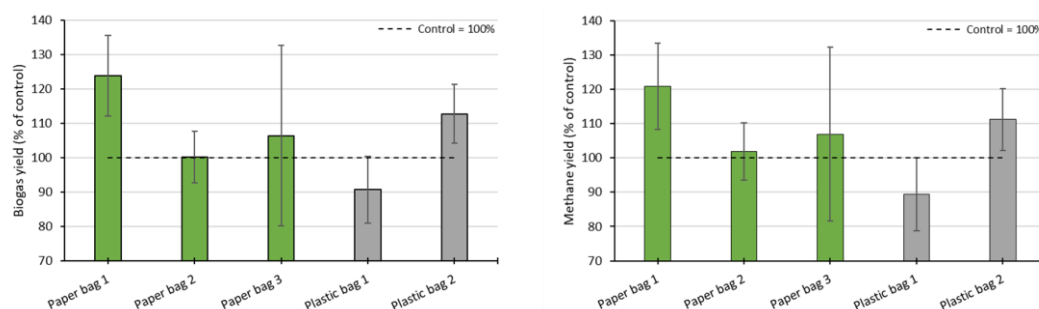


Figure 4: Normalized biogas and methane yields (% of control) obtained from kitchen waste during AD with different biodegradable paper and plastic collection bags. Bars represent mean values with standard deviation of parallel reactors as error bars. The dashed line (100 %) corresponds to the biogas yield of the control reactors

3.3 Broader implications for waste management

In addition to the process-level observations, the results have broader implications for the design of sustainable and regulation-compliant organic waste collection systems. Paper collection bags enhanced methane and biogas yields (+5–20 % compared to controls), while the biodegradable plastic bags showed neutral or slightly inhibitory effects. This indicates that the choice of collection material can influence both digestion efficiency and digestate quality. These findings are consistent with those of Dolci et al. (2021), who also observed improved biogas potential when paper liners were used, due to better moisture exchange and their relatively higher biodegradation during AD.

From an environmental perspective, paper-based materials are completely biodegradable and can be made from recycled fibers, promoting circular material flows. However, their production typically requires more energy and water – about 30–50 % higher primary energy use and 2–3 times more water compared to bioplastics (Life Cycle Initiative, 2020). Paper bags may have lower overall greenhouse gas emissions after treatment, provided they are effectively recovered through composting or AD. Energy recovery during AD can partially offset these production-related burdens.

In contrast, biodegradable plastics such as Mater-Bi degrade slowly under mesophilic anaerobic conditions, leaving visible fragments in the digestate (Bracciali et al., 2024). Such residuals can compromise digestate quality compliance under EU fertilising product regulations (Regulation (EU) 2019/1009), potentially requiring additional post-treatment or disposal. This may increase operational and compliance costs for AD plant operators.

Overall, these results show that although both materials are marketed as biodegradable, their performance under anaerobic conditions varies significantly, affecting both biogas production and downstream waste management. Integrating the process-level data presented here into local life cycle assessments and economic evaluations is crucial for developing sustainable, cost-effective, and regulation-aligned collection systems for biowaste in Hungary and across the EU.

4. Conclusions

The statistical results and process observations consistently demonstrate that biodegradable paper and plastic collection bags have distinct but modest influences on the anaerobic digestion of kitchen waste. Paper-based bags (PaB1–PaB3) generally yielded 5–20 % higher methane and biogas production compared to their respective controls. This enhancement, confirmed as statistically significant for PaB1, may result from partial cellulose hydrolysis or from an improved substrate structure that facilitates microbial access. Thermogravimetric data and visual observations suggest that paper materials provided not only additional biodegradable substrate but also extra surface area for microbial attachment, supporting modest improvements in overall biodegradation efficiency. In contrast, the biodegradable plastic bags (PIB1–PIB2) showed gas yields close to those of the controls, suggesting a neutral or slightly inhibitory influence on methane and biogas production. The strong correlation between methane and total biogas yields indicates that all variations primarily affected total gas formation rates rather than methane concentration, reinforcing that the bag materials did not alter gas quality. Overall, both types of collection bags can be integrated into anaerobic digestion without major process disturbances; however, paper-based bags offer a measurable advantage in gas yield and digestate quality. These findings provide practical insights for waste management systems in which AD is the primary treatment route under EU bio-waste collection policies.

This study was conducted under mesophilic batch conditions without mixing, which may underestimate the degradation achievable in industrial continuous reactors. Future research should assess bioplastic degradation under varied operational conditions and evaluate environmental and economic impacts through life-cycle approaches. In summary, paper-based liners appear more compatible with AD and regulatory digestate requirements, offering a small but relevant process benefit.

Acknowledgments

The authors acknowledge the financial support of the Establishment of a Waste Management Competence Center at the University of Pannonia project. Project no. 2022-1.1.1-KK-2022-00002 has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the 2022-1.1.1-KK funding scheme.

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