

Are compostable clamshells climate-better where composting does not exist? A streamlined comparative LCA of PET, PP, PLA and PHA food packaging under Lebanon's end-of-life conditions

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Abstract

Compostable bioplastics are promoted as low-carbon substitutes for fossil food packaging, but their benefit depends on end-of-life infrastructure that many countries lack. This study compares the cradle-to-grave climate impact of rigid clamshells made from PET, PP, PLA and PHA for cold food in Lebanon. There, 57% of municipal waste goes to sanitary landfills and 43% to open dumps, where much of it is burned. A streamlined LCA combines published eco-profiles, Lebanese electricity and waste data, and IPCC end-of-life methods across five scenarios, two biogenic carbon conventions and a 10,000-run Monte Carlo analysis.

Under current conditions, PP has the lowest impact (41.2 kg CO₂ eq per 1,000 containers), followed by PET (58.9) and PLA (60.4), while PHA is highest (105.6). PHA's result is driven by methane from landfills and dumps, which accounts for 45% of its total. Bio-based options outperform fossil ones only under open burning, or when landfilled biogenic carbon is credited as storage, which lowers PLA to 31.6. Ideal composting does not let either bio-based material beat PP.

The findings indicate that, in countries with weak waste systems, compostable packaging should follow, not precede, investment in organics collection, composting and landfill gas capture.

Keywords: life cycle assessment; bioplastics; PLA; PHA; food packaging; end-of-life; open dumping; landfill methane; Lebanon

1. Introduction

Single-use rigid containers for takeaway and ready-to-eat food are among the most visible plastic waste streams in urban areas. They are typically thermoformed from fossil-based polyethylene terephthalate (PET) or polypropylene (PP). Bio-based and compostable polymers, mainly polylactic acid (PLA) and polyhydroxyalkanoates (PHA), are increasingly promoted as substitutes, on the grounds that they reduce fossil carbon use and can return to the biosphere at end of life (Cruz et al., 2022; Yadav and Nikalje, 2024).

Whether these substitutes actually lower climate impacts depends heavily on what happens to them after use. Reviews of the life cycle assessment (LCA) literature show that end-of-life is one of the least standardised and most influential modelling choices for bioplastics (Fonseca et al., 2023; Pscherer and

Krommes, 2025). Many comparative studies assume access to industrial composting, anaerobic digestion or modern incineration. Yet the United Nations Environment Programme warns that the advantage of compostable packaging holds only where collection and organic treatment infrastructure exist (UNEP, 2022). Without that infrastructure, biodegradable items are landfilled, dumped or littered, and their impacts can equal or exceed those of conventional plastics.

This caveat matters most where most of the world's waste is managed: in low- and middle-income countries, where open dumping and open burning remain common. Open burning alone is estimated to handle 40–65% of municipal solid waste in such settings (Pathak et al., 2024). Landfilled biodegradable polymers can generate methane, a greenhouse gas with about 27 times the 100-year warming effect of CO₂. A recent global assessment suggests that landfilling biodegradable plastics could double the sector's climate impact (Piao and Yao, 2026). Despite this, few packaging LCAs model the waste systems that actually prevail in these countries, and none, to our knowledge, does so for Lebanon.

Lebanon offers a stark test case. Its waste sector has deteriorated through overlapping financial, energy and security crises. In 2023, eight sanitary landfills received about 57% of municipal waste, while the share sent to open dumps rose from 22% in 2018 to 43% (World Bank, 2025). The draft national strategy aims to phase out open dumping and burning within seven years, but it sets no target for bioplastics (CDR, 2024). The country has no industrial composting route for packaging, and electricity for manufacturing comes largely from private diesel generators. A recent LCA of municipal waste in Tripoli confirmed that open dumping is the most climate-intensive disposal route in the country (Jabali and Naghizade, 2026).

This study therefore asks a policy-relevant question: under Lebanon's real end-of-life conditions, do bio-based clamshells deliver lower climate impacts than fossil-based ones? We compare four materials, PET, PP, PLA and PHA, for a functional unit of 1,000 rigid 500 mL clamshells for cold or ambient food, from cradle to grave.

The study makes four contributions:

1. It models end-of-life using Lebanon's observed split between sanitary landfills, open dumps and open burning, with IPCC methods for each route.
2. It explicitly accounts for landfill methane from degradable polymers, which most packaging LCAs omit or treat as negligible.
3. It reports results under two biogenic carbon accounting conventions, showing how the choice changes the ranking.
4. It tests five end-of-life scenarios, from today's mix to ideal composting and recycling, and quantifies uncertainty with a 10,000-run Monte Carlo analysis.

The results are intended to inform Lebanese packaging policy, extended producer responsibility schemes and procurement decisions. They also offer a transferable template for other countries with similar waste systems.

2. Literature Review and Research Gap

Recent LCAs agree that bio-based packaging is not automatically climate-preferable, and that end-of-life assumptions often decide the ranking. This review covers 30 peer-reviewed studies and three institutional reports published between 2022 and 2026, grouped into five themes.

2.1 Comparative LCAs of single-use food packaging

Peantham and Varabuntoonvit (2024) compared PP, PLA and PLA-coated kraft paper containers in Thailand, where only 33% of plastic waste is properly managed. PP with mechanical recycling had the lowest global warming impact, at 61.8 kg CO₂ eq per 1,000 boxes. Landfilling PLA reversed its environmental benefit. Borda et al. (2026) compared PET, PLA and PHA bottles under properly managed and mismanaged end-of-life, and found that mismanagement sharply raised freshwater eutrophication for all three polymers.

Chen et al. (2024) estimated that 1,000 biodegradable products, including lunch boxes, emit 21–57 kg CO₂ eq, 14–62% less than conventional equivalents. Their advantage, however, assumed composting or anaerobic digestion. At the system level, Almadhi et al. (2023) found landfilling to be the worst plastic waste option in Saudi Arabia across most impact categories.

Other studies stress use-phase and behavioural factors. Aggarwal (2024) showed that reusable lunch boxes used 20 times cut climate impact by 59% compared with single-use boxes. Caspers et al. (2023) reviewed takeaway packaging LCAs and found that none modelled littering. UNEP (2022) concluded that compostable packaging helps only where collection and organic treatment infrastructure exist.

2.2 PLA: production burdens and real-world end-of-life

Fonseca et al. (2023) reviewed 81 PLA LCAs. They found that PLA has higher average freshwater and marine eutrophication than fossil plastics, driven by crop fertilisation. They also concluded that PLA's end-of-life management is not yet well established, with landfilling the worst option. Production footprints vary widely with feedstock: cane-sugar PLA can be near carbon-neutral cradle-to-gate, while microalgae-based PLA is far higher (Islam et al., 2025). Lignocellulosic PLA and chemical recycling are promising, but remain at early technology readiness (Rebolledo Leiva et al., 2023; Senila et al., 2024).

Evidence on PLA degradation outside ideal conditions is mixed. PLA resists mesophilic anaerobic digestion and generally needs hydrolysis above about 58 °C (Maragkaki et al., 2023a). Under mesophilic digestion at 37 °C, PLA films showed a lag of about 60 days before near-complete degradation after roughly 100 days (Montegiove et al., 2026). Pure PLA met EN 13432 in laboratory composting (Maragkaki et al., 2023b), but PLA-blend bags fell short of 90% decomposition after six weeks in a full-scale plant (Sikander et al., 2024).

2.3 PHA: variable production impacts and high degradability

PHA climate footprints span an order of magnitude. Sugarcane-based amorphous PHA has been reported at 0.86–1.59 kg CO₂ eq/kg (Lee et al., 2024). Biological extraction alone can contribute 4.59 kg CO₂ eq/kg (Abd Razak et al., 2024). Feedstock choice and energy recovery from waste streams are the main sources of this spread (Pelliconi and Righi, 2024).

PHA produced from organic waste with on-site cogeneration can outperform conventional items, but the benefit depends on the electricity it displaces (Saavedra del Oso et al., 2023). PHA's rapid anaerobic degradability is usually presented as an advantage. Sun et al. (2025) report complete mineralisation of PHB within days under simulated landfill and digestion conditions. Where biogas is not captured, however, the same property releases methane.

2.4 Biogenic carbon and methodological choices

Pscherer and Krommes (2025) reviewed 13 LCA standards and found that they treat biogenic carbon flows, storage duration and substitution differently. De Jong et al. (2026) showed that dynamic LCA often yields lower climate impacts for bio-based systems, depending on time horizon and assumed storage. In practice, whether landfilled biogenic carbon earns a storage credit can determine whether PLA beats fossil plastics.

Newer work extends the scope beyond climate. Piao et al. (2024) quantified impacts of biodegradable microplastics. Piao and Yao (2026) projected that landfilled biodegradable plastics could double the plastics industry's climate impact through methane.

2.5 Waste systems in low- and middle-income countries and Lebanon

Open burning handles an estimated 40–65% of municipal waste in many low- and middle-income countries and releases dioxins and particulate matter (Pathak et al., 2024). Wang et al. (2023) measured a PM_{2.5} emission factor of about 651 g/kg for burning plastic bottles in South Africa.

Compostable packaging needs functioning collection and clear labelling. Even in the United Kingdom, systems for compostable plastics are rare (Allison et al., 2024). In Malaysia, missing infrastructure was the main barrier identified for national compostable plastics guidelines (Mahadi et al., 2025).

In Lebanon, open dumping reached 43% of municipal waste in 2023 (World Bank, 2025), and the national strategy sets dump-closure targets but no bioplastics policy (CDR, 2024). In Tripoli, open dumping produced 485 kg CO₂ eq per tonne of waste, against 128 kg for incineration with residue landfilling (Jabali and Naghizade, 2026). No study has yet assessed packaging material choices against this waste system.

2.6 Summary of key comparative studies

Table 1 compares the scope of the most relevant recent studies with this study.

Table 1. Summary of key comparative LCA studies of plastic and bio-based packaging and their end-of-life coverage, compared with this study.

Study	Materials	Setting	End-of-life modelled	Open dumping/burning	Methane from landfilled biopolymer
Peantham and Varabuntoonvit (2024)	PP, PLA, PLA/paper	Thailand	Recycling, incineration, landfill,	Discussed, not modelled	Not reported

Study	Materials	Setting	End-of-life modelled	Open dumping/burning	Methane from landfilled biopolymer
			composting		
Borda et al. (2026)	PET, PLA, PHA	Generic	Recycling, incineration, mismanagement	Littering only	Not reported
Chen et al. (2024)	Conventional vs biodegradable	Generic (verify)	Recycling, composting, anaerobic digestion	No	Not reported
Almadhi et al. (2023)	Mixed plastic waste	Saudi Arabia	Landfill, incineration, recycling, pyrolysis	No	Not applicable
Saavedra del Oso et al. (2023)	PHA vs commercial items	Europe (prototypes)	Cradle-to-grave	No	Not reported
Jabali and Naghizade (2026)	Municipal waste	Tripoli, Lebanon	Open dumping vs controlled options	Yes	Not packaging-specific
This study	PET, PP, PLA, PHA	Lebanon	Landfill, dump, burning, composting, recycling	Yes	Yes (IPCC first-order decay)

2.7 Research gap

Three gaps emerge from this review:

1. Comparative packaging LCAs rarely model the waste systems of low- and middle-income countries, where open dumping and burning dominate.
2. Methane from landfilled or dumped degradable biopolymers, especially PHA, is seldom quantified in product-level comparisons.
3. Results are rarely reported under alternative biogenic carbon conventions, although the choice can reverse rankings.

No study has compared PET, PP, PLA and PHA food packaging for Lebanon or the wider Eastern Mediterranean. This study addresses all three gaps with a scenario-based, uncertainty-tested LCA grounded in Lebanon's observed waste data.

3. Life Cycle Assessment

The study is a streamlined, attributional LCA that follows the ISO 14040/14044 framework. It is built on published eco-profiles, literature data and IPCC default factors rather than a commercial database. The calculations were implemented in a spreadsheet model with live formulas, and the Monte Carlo and sensitivity analyses in a Python script.

3.1 Goal and scope

The goal is to compare the climate performance of four rigid clamshell materials, PET, PP, PLA and PHA, when used and discarded in Lebanon. The intended audience is Lebanese policymakers, packaging converters, food-service buyers and LCA practitioners. The study is comparative, but because it relies on secondary data and covers one impact category across the full life cycle, its results are not intended for comparative public assertions under ISO 14044 without critical review.

3.2 Functional unit

The functional unit is the containment and protection of 1,000 portions of cold or ambient food ($\leq 40\text{ }^{\circ}\text{C}$) in 500 mL rigid hinged clamshells, withstanding stacking during distribution and retail. Hot-fill applications are excluded, because amorphous PLA (glass transition about $55\text{--}60\text{ }^{\circ}\text{C}$) and amorphous PET cannot provide that function without heat-resistant grades. Container masses are those of the product specification used in this study (Table 2) and are treated as functionally equivalent for this use.

3.3 System boundary

The system is cradle-to-grave. It includes resin production, additives, import transport to Beirut and road distribution, thermoforming in Lebanon, post-consumer collection and end-of-life treatment. Filling, retail and consumer use are excluded because they are identical across alternatives. Capital goods and landfill operation are excluded as negligible.

3.4 Life cycle inventory

Foreground data per functional unit are taken from the inventory compiled for this study (Table 2).

Table 2. Foreground inventory per functional unit (1,000 clamshells of 500 mL).

Parameter	Unit	PET	PP	PLA	PHA
Resin	kg	18.50	13.50	18.60	17.20
Additives	kg	0.37	0.27	0.37	0.34
Thermoforming electricity	kWh	14.20	16.80	18.50	17.10
Cooling water	L	120	145	110	115
Carbon content	% mass	62.5	85.7	50.0	55.8
Sea freight to Beirut	km	3,000	3,000	11,000	12,000

Background data and their sources are summarised in Table 3.

Table 3. Background emission factors, uncertainty ranges and sources.

Input	Value used (range)	Source
PET resin, cradle-to-gate	2.19 (2.00–2.73) kg CO ₂ eq/kg	PlasticsEurope (2017), bottle grade
PP resin, cradle-to-gate	1.63 (1.45–2.00) kg CO ₂ eq/kg	PlasticsEurope (2014)
PLA resin, excluding biogenic uptake	2.33 (2.10–2.80) kg CO ₂ eq/kg	Morão and de Bie (2019), Thailand
PHA resin, excluding biogenic uptake	2.50 (1.00–6.00) kg CO ₂ eq/kg	Range from Righi et al. (2020), Lee et al. (2023)
Electricity for thermoforming	0.626 (0.364–0.80) kg CO ₂ eq/kWh	40% national generation (Ember, 2023) and 60% private diesel generators (UNFCCC CDM default)
Road freight	0.154 kg CO ₂ eq/t·km	DESNZ/DEFRA (2024)
Sea freight	0.016 kg CO ₂ eq/t·km	Container ship, typical value

PET and PP resins are represented by European average data, PLA by sugarcane-based production in Thailand, and PHA by a literature range. These choices reflect likely import origins, since Lebanon has no domestic polymer production.

3.5 End-of-life modelling

The base case reflects Lebanon's 2023 waste system: 57% of municipal waste goes to sanitary landfills and 43% to open dumps (World Bank, 2025). Half of the dumped waste is assumed to be openly burned (range 20–80%), as no national estimate exists. All routes are modelled with IPCC (2006, 2019) methods.

- **Sanitary landfill.** Methane from degradable polymer carbon follows the IPCC mass-balance approach, with methane correction factor 1.0, methane fraction 0.5, cover oxidation 0.1 and 20% gas capture (range 0–50%). The fraction of carbon that degrades is 0 for PLA (range 0–0.5) and 0.5 for PHA (range 0.3–0.8). PET and PP are treated as inert.
- **Open dump (unburned).** As above, with methane correction factor 0.6, no capture and no oxidation.
- **Open burning.** CO₂ from carbon oxidation (oxidation factor 0.71, range 0.58–0.85), plus 6.5 g CH₄ and 0.15 g N₂O per kg burned.
- **Composting (scenario only).** 4 g CH₄ per kg treated and 0.03 kg CO₂ eq/kg for operations.
- **Recycling (scenario only).** Cut-off approach: no burden and no credit to the first life.

3.6 Impact assessment and biogenic carbon

Climate change is assessed as GWP100 with IPCC AR6 factors: 29.8 for fossil methane, 27.0 for non-fossil methane and 273 for N₂O. Two biogenic carbon conventions are reported. In the base case (0/0), biogenic CO₂ uptake and release are both excluded, while biogenic methane is counted. In the alternative (–1/+1), uptake is credited as –1 and every biogenic release is counted, so biogenic carbon

remaining in landfills appears as a net credit. This credit is reported separately, because most guidance treats it as temporary storage.

3.7 Scenarios, sensitivity and uncertainty

Five end-of-life scenarios are assessed (Table 4).

Table 4. End-of-life scenarios.

Scenario	Description
S1 Lebanon current mix	57% sanitary landfill, 21.5% open dump, 21.5% open burning
S2 All sanitary landfill	Target state after closure of dumps
S3 All open burning	Rural worst case
S4 Ideal composting	90% of PLA and PHA composted; PET and PP as S1
S5 Fossil recycling	30% of PET and PP mechanically recycled; PLA and PHA as S1

One-at-a-time sensitivity analysis varies each parameter between its minimum and maximum. A Monte Carlo analysis draws 10,000 sets of parameters from triangular distributions, with container mass varied $\pm 10\%$. Shared parameters, such as electricity and waste shares, are drawn once per run for all materials, so pairwise comparisons reflect true differences rather than independent noise.

4. Results and Discussion

Under Lebanon's current waste system, PP has the lowest climate impact, PLA is on a par with PET, and PHA is the highest. Bio-based containers gain an advantage only where waste is openly burned, or when landfilled biogenic carbon is credited as storage.

4.1 Results by scenario

Deterministic results, in kg CO₂ eq per 1,000 containers (equal to g CO₂ eq per container), are given in Table 5. Figure 1 breaks down the S1 results by life cycle stage.

Table 5. Deterministic climate change results by scenario and biogenic carbon convention, kg CO₂ eq per 1,000 clamshells (lowest value in each row in bold).

Scenario	Accounting	PET	PP	PLA	PHA
S1 Lebanon current mix	0/0	58.9	41.2	60.4	105.6
S2 All sanitary landfill	0/0	51.5	34.1	59.6	120.4
S3 All open burning	0/0	86.0	67.4	63.6	61.9
S4 Ideal composting	0/0	58.9	41.2	62.0	65.1
S5 Fossil recycling 30%	0/0	56.7	39.1	60.4	105.6

Scenario	Accounting	PET	PP	PLA	PHA
S1 Lebanon current mix	-1/+1	58.9	41.2	31.6	88.2
S2 All sanitary landfill	-1/+1	51.5	34.1	25.5	102.9
S3 All open burning	-1/+1	86.0	67.4	54.0	52.0
S4 Ideal composting	-1/+1	58.9	41.2	58.7	62.9
S5 Fossil recycling 30%	-1/+1	56.7	39.1	31.6	88.2

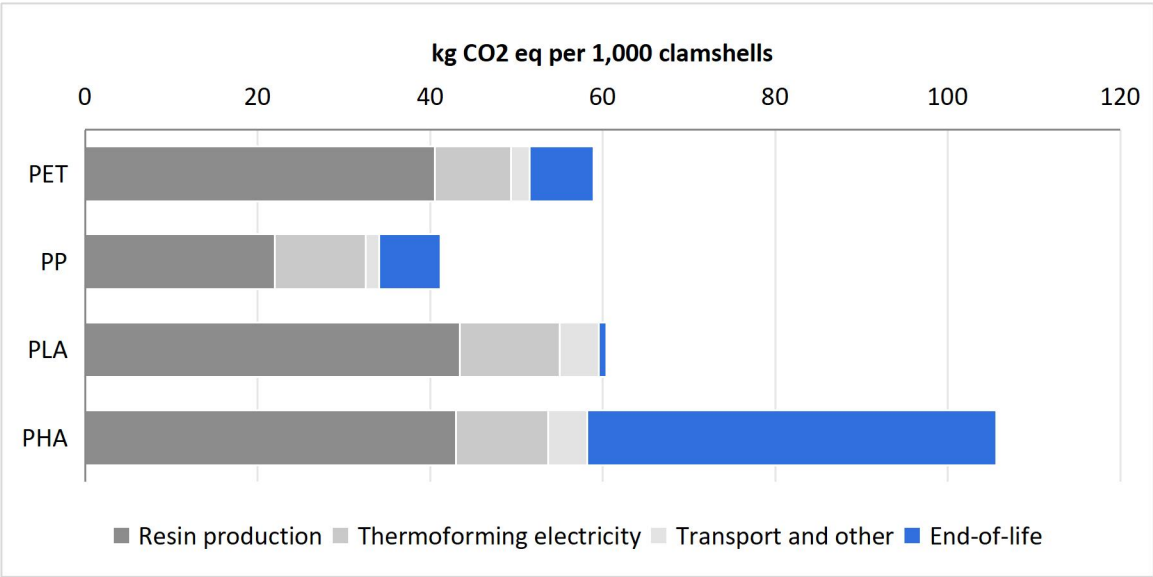


Figure 1. Contribution of life cycle stages to climate impact under Lebanon's current waste mix. Source: this study's calculations (scenario S1, 0/0 biogenic carbon accounting).

Resin production dominates every material, but end-of-life methane is what separates PHA from the rest.

The Monte Carlo analysis confirms the base-case ranking (Figure 2). In S1 with 0/0 accounting, the median results (5th–95th percentile) are 41.6 (36.3–47.4) for PP, 60.7 (53.4–69.0) for PET, 74.3 (59.9–97.3) for PLA and 116.2 (84.3–156.8) for PHA. PP was lower than both bio-based options in every run. PLA was lower than PET in only 9% of runs. Its median exceeds the deterministic value because landfill degradation of PLA is skewed upward in the uncertainty range. Across scenarios, the bio-based options overlap or beat the fossil ones only when all waste is burned (S3).

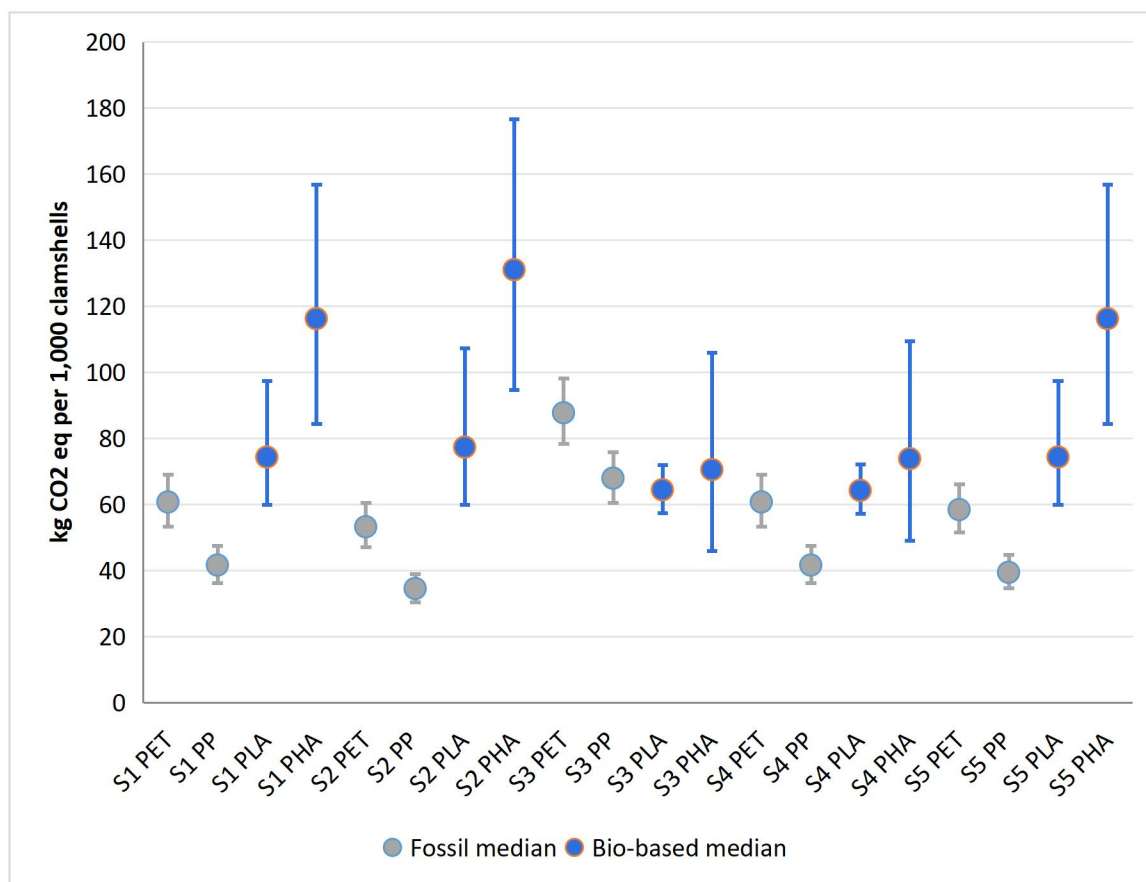


Figure 2. Uncertainty ranges by end-of-life scenario. Source: this study's calculations, 10,000 paired Monte Carlo runs per scenario.

PP stays lowest in four of five scenarios; PLA and PHA overlap or beat the fossil options only when all waste is burned, the least acceptable route for air quality.

Under $-1/+1$ accounting, PLA becomes the lowest option in S1 and S2. This rests on about 29 kg CO₂ eq per functional unit of biogenic carbon that stays in landfills and dumps. With that convention, PLA beat PET in 75% of runs and PP in 30%.

4.2 Drivers of impacts

Resin production dominates the fossil alternatives, at 69% of PET's total and 53% of PP's in S1 (Figure 1). PP's advantage comes mainly from its lower container mass (13.5 g versus 18.5 g) and lower resin footprint. Thermoforming electricity contributes 15–26% across all materials, because Lebanese converters rely heavily on diesel generators.

For PLA, resin production accounts for 72% of the total, and end-of-life only 1%, because PLA barely degrades in landfills. For PHA, end-of-life contributes 45% (47.4 kg CO₂ eq), almost entirely as methane from landfills and unburned dumps. For PET and PP, end-of-life impact (7.2–7.4 kg CO₂ eq in S1) comes almost entirely from open burning.

The sensitivity analysis identifies five influential parameters:

- **PHA resin footprint:** 79.8–165.8 kg CO₂ eq for PHA's total. With the industrial PHBH value of 12 kg CO₂ eq/kg, PHA reaches 270.
- **PLA landfill degradation:** raising the degradable fraction from 0 to 0.5 raises PLA's total from 60.4 to 105.6.
- **PHA landfill degradation and gas capture:** these move PHA between 87 and 134. Even with 100% gas capture, PHA (70.2) still exceeds PET (58.9).
- **Burned share of dumped waste:** PET and PP swing by about ± 4.5 . PHA moves the opposite way, because burning prevents methane.
- **Electricity factor:** a near-zero factor, such as on-site solar, lowers totals by 8–11 for every material without changing the ranking.

4.3 Comparison with the literature

Our base-case finding agrees with studies showing that the climate benefit of PLA disappears when it is landfilled (Peantham and Varabuntoonvit, 2024; Fonseca et al., 2023). It also supports UNEP's (2022) warning that compostable packaging helps only where organic treatment exists. Chen et al. (2024) reported 14–62% lower emissions for biodegradable products, but assumed composting or anaerobic digestion. Our S4 confirms that even ideal composting does not let PLA or PHA beat PP in Lebanon.

The PHA result is the most striking contrast. PHA is usually reported to have a low production footprint (Lee et al., 2024; Sun et al., 2025), and its rapid anaerobic degradability is presented as a benefit. Our results show that the same property makes PHA the worst option where landfill gas is not captured, consistent with Piao and Yao's (2026) global projection. The resin footprint range used here (1–6 kg CO₂ eq/kg) is consistent with the literature review by Righi et al. (2020).

The reversal under $-1/+1$ accounting reflects the methodological divergence documented by Pscherer and Krommes (2025) and de Jong et al. (2026). It shows that biogenic carbon conventions must be stated explicitly when comparing bio-based and fossil packaging.

4.4 Trade-offs

The results reveal three trade-offs:

1. **Climate versus persistence.** PET and PP are inert in landfills, which avoids methane but leaves persistent plastic. In open dumps they can fragment and leak to the environment, which this climate-only model does not capture.
2. **Climate versus agricultural impacts.** The literature consistently reports higher land use, water use and eutrophication for PLA than for fossil plastics. Peantham and Varabuntoonvit (2024) found 23.9 versus 0.68 m²a crop eq of land use and 5.9 versus 0.83 m³ of water for PLA versus PP containers.
3. **Climate versus local air quality.** Open burning gives the bio-based options their best climate scores, but it releases dioxins and particulate matter (Pathak et al., 2024; Wang et al., 2023). It cannot be considered an acceptable route.

4.5 Improvement opportunities

- **Lightweighting:** container mass scales impacts almost one-to-one; a 10% mass reduction lowers totals by 8–9%.

- **Low-carbon electricity:** solar power for thermoforming cuts 8–11 kg CO₂ eq per functional unit.
- **Landfill gas capture:** this is essential before degradable polymers, especially PHA, are introduced.
- **Separate organics collection:** without it, compostable claims cannot be realised.
- **Recycling of PET and PP:** this lowers fossil options further, although 30% recycling saves only about 2 kg CO₂ eq under cut-off.
- **Reuse:** reusable container systems can outperform all single-use options (Aggarwal, 2024).

4.6 Policy and industry implications

Lebanon should not promote compostable food containers as a climate measure until separate organics collection, industrial composting and landfill gas capture are in place. In the meantime, PP clamshells, lightweighting and recycling deliver larger and more certain savings.

The national strategy's targets to close open dumps and raise recycling to 20% within 10 years (CDR, 2024) are compatible with this priority. Closing dumps without gas capture, however, would worsen the case for PHA, as S2 shows. An extended producer responsibility scheme could fund the collection and treatment that compostable materials need. Labelling rules should prevent "biodegradable" claims for products that will be landfilled.

4.7 Limitations

- Only climate change is modelled across the full life cycle; other categories are discussed from the literature.
- Resin data are secondary and not specific to Lebanon's suppliers. The PHA value of 2.5 kg CO₂ eq/kg is an assumption within the published range.
- Electricity factors are combustion factors without upstream supply chains.
- Landfill methane is counted fully within the 100-year horizon, without time-dependent decay.
- The burned share of dumped waste (50%) and landfill gas capture (20%) are assumptions, tested in the sensitivity analysis.
- Leakage, littering and microplastic impacts are not quantified.

5. Conclusions

This study compared PET, PP, PLA and PHA clamshells for cold food in Lebanon, using the country's actual mix of sanitary landfills, open dumps and open burning. Four conclusions follow.

1. **PP is the lowest-carbon option today.** At 41.2 kg CO₂ eq per 1,000 containers, PP was lower than every alternative in four of five scenarios, and lower than both bio-based options in all Monte Carlo runs under base-case accounting.
2. **PLA offers no climate gain over PET in Lebanon.** PLA (60.4) is on a par with PET (58.9) in the base case and higher in most uncertainty runs; it beat PET in only 9% of them, because PLA's benefit depends on composting routes that do not exist.
3. **PHA is the highest emitter where landfill gas is not captured.** Methane from landfills and dumps accounts for 45% of PHA's 105.6 kg CO₂ eq, and PHA stays above PET even with full gas capture.

4. **Accounting choices can reverse the ranking.** Crediting biogenic carbon stored in landfills lowers PLA to 31.6 kg CO₂ eq, below every other option. Studies and policy claims should therefore state their biogenic carbon convention.

For Lebanon, the priority is not material substitution but waste-system reform: closing open dumps with gas capture, separating organics, and recycling PET and PP. Compostable containers should be promoted only after composting infrastructure exists. Until then, lightweight PP, low-carbon electricity for converters and reusable systems offer the most reliable savings.

Future work should extend the model to a full multi-impact LCA with primary supplier data, include leakage and microplastic impacts, and model heat-resistant grades for hot food.

Declarations

Data availability. The calculation model and the scripts used for the Monte Carlo and sensitivity analyses are available from the corresponding author on reasonable request. All input data are reported in the paper or taken from the cited sources.

References

1. Abd Razak, I.H., Phuang, Z.X., Woon, K.S., Sudesh, K. (2024). Life cycle assessment on global warming and fine particulate matter formation for biological extraction method in polyhydroxyalkanoates (PHA) production: a sustainable alternative. *Chemical Engineering Transactions*, 113, 397–402. <https://doi.org/10.3303/CET24113067>
2. Aggarwal, R. (2024). Comparative life cycle assessment of reusable and single use take-away lunch boxes used in student restaurants. *Cleaner Environmental Systems*, 14, 100223. <https://doi.org/10.1016/j.cesys.2024.100223>
3. Allison, A.L., Băitanu, A., Purkiss, D., Lorencatto, F., Michie, S., Miodownik, M. (2024). Enabling desired disposal of compostable plastic packaging: an evaluation of disposal instruction labels. *Frontiers in Sustainability*, 5, 1376519. <https://doi.org/10.3389/frsus.2024.1376519>
4. Almadhi, A., Abdelhadi, A., Alyamani, R. (2023). Moving from linear to circular economy in Saudi Arabia: life-cycle assessment on plastic waste management. *Sustainability*, 15(13), 10450. <https://doi.org/10.3390/su151310450>
5. Borda, F., Conte, R., Ambrogio, G., et al., Gagliardi, F. (2026). Environmental performance of PET and biopolymers: a comparative LCA of end-of-life scenarios. *International Journal of Advanced Manufacturing Technology*, 142(5), 2599–2613. <https://doi.org/10.1007/s00170-025-17057-7>
6. Caspers, J., Süßbauer, E., Coroama, V.C., Finkbeiner, M. (2023). Life cycle assessments of takeaway food and beverage packaging: the role of consumer behavior. *Sustainability*, 15(5), 4315. <https://doi.org/10.3390/su15054315>
7. CDR (2024). *Final Draft National Integrated Solid Waste Management Strategy of Lebanon*, Executive Summary, Rev. 01. Council for Development and Reconstruction / World Bank. cdr.gov.lb
8. Chen, G., Li, J., Sun, Y., Wang, Z., Leeke, G.A., Moretti, C., Cheng, Z., Wang, Y., Li, N., Mu, L., Li, J., Tao, J., Yan, B., Hou, L. (2024). Replacing traditional plastics with biodegradable plastics: impact on carbon emissions. *Engineering*, 32, 152–162. <https://doi.org/10.1016/j.eng.2023.10.002>

9. Cruz, R.M.S., Krauter, V., Krauter, S., et al., Varzakas, T. (2022). Bioplastics for food packaging: environmental impact, trends and regulatory aspects. *Foods*, 11(19), 3087. <https://doi.org/10.3390/foods11193087>
10. de Jong, M., Corona, B., Junginger, M., et al., Shen, L. (2026). From static to dynamic: reviewing the application and potential of dynamic LCA to bio-based systems. *International Journal of Life Cycle Assessment*, 31(4), 56. <https://doi.org/10.1007/s11367-026-02624-1> (complete the author list)
11. DESNZ/DEFRA (2024). *Greenhouse gas reporting: conversion factors 2024*. UK Government.
12. Ember (2024). *Yearly electricity data: Lebanon*. Ember, London.
13. Fonseca, A., Ramalho, E., Gouveia, A., Figueiredo, F., Nunes, J. (2023). Life cycle assessment of PLA products: a systematic literature review. *Sustainability*, 15(16), 12470. <https://doi.org/10.3390/su151612470>
14. IPCC (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 5: Waste*, Chapters 3 and 5.
15. IPCC (2019). *2019 Refinement to the 2006 IPCC Guidelines, Vol. 5: Waste*, Chapter 5.
16. IPCC (2021). *Climate Change 2021: The Physical Science Basis*, Working Group I, Chapter 7, Table 7.15.
17. Islam, M.M., Chaudry, S., Thornton, A.W., Haque, N., Lau, D., Bhuiyan, M., Pramanik, B.K. (2025). Environmental footprint of polylactic acid production utilizing cane-sugar and microalgal biomass: an LCA case study. *Journal of Cleaner Production*, 496, 145132. <https://doi.org/10.1016/j.jclepro.2025.145132>
18. ISO (2006). ISO 14040 and ISO 14044: Environmental management — Life cycle assessment.
19. Jabali, Y., Naghizade, A. (2026). Life cycle assessment of municipal solid waste management in Tripoli, Lebanon: from open dumping to integrated resource recovery. *Environments*, 13(10), 553. <https://doi.org/10.3390/environments13100553>
20. Kolstad, J.J., Vink, E.T.H., De Wilde, B., Debeer, L. (2012). Assessment of anaerobic degradation of Ingeo polylactides under accelerated landfill conditions. *Polymer Degradation and Stability*, 97, 1131–1141.
21. Lee, S., Lee, I., Seo, D., Kim, H., Joo, G., Lee, S., Park, K. (2024). Life cycle assessment of aPHA production. *ACS Sustainable Chemistry & Engineering*, 12(1), 72–84. <https://doi.org/10.1021/acssuschemeng.3c04788>
22. Mahadi, Z., Yahya, E.A., Yaacob, M., Mustafa Din, W., Arham, A.F., Hasim, N.A. (2025). Toward national guidelines for biodegradable and compostable bioplastics: a case study in the Federal Territory of Kuala Lumpur, Malaysia. *Polymers*, 17(16), 2165. <https://doi.org/10.3390/polym17162165>
23. Maragkaki, A., Tsompanidis, C., Velonia, K., Manios, T. (2023a). Pilot-scale anaerobic co-digestion of food waste and polylactic acid. *Sustainability*, 15(14), 10944. <https://doi.org/10.3390/su151410944>
24. Maragkaki, A., Malliaros, N.G., Sampathianakis, I., Lolos, T., Tsompanidis, C., Manios, T. (2023b). Evaluation of biodegradability of polylactic acid and compostable bags from food waste under industrial composting. *Sustainability*, 15(22), 15963. <https://doi.org/10.3390/su152215963>
25. Montegiove, N., Puglia, D., Pellegrino, R.M., Dominici, F., Calzoni, E., Pezzolla, D. (2026). Anaerobic co-digestion of polylactic acid (PLA) films with organic fraction of municipal solid

- waste: biodegradation, biogas yields, and metabolomic analysis. *Agronomy*, 16(14), 1303. <https://doi.org/10.3390/agronomy16141303>
26. Morão, A., de Bie, F. (2019). Life cycle impact assessment of polylactic acid (PLA) produced from sugarcane in Thailand. *Journal of Polymers and the Environment*, 27, 2523–2539. <https://doi.org/10.1007/s10924-019-01525-9>
27. Pathak, G., Nichter, M., Hardon, A., Moyer, E. (2024). The open burning of plastic wastes is an urgent global health issue. *Annals of Global Health*, 90(1), 3. <https://doi.org/10.5334/aogh.4232>
28. Peantham, K., Varabuntoonvit, V. (2024). Sustainable solutions in single-use food containers: a comprehensive life cycle assessment comparing plastic (PP) and its green alternative (PLA coated kraft paper, PLA). *Environmental Engineering Research*, 29(5), 230729. <https://doi.org/10.4491/eer.2023.729>
29. Pelliconi, M., Righi, S. (2024). Life cycle assessment applied to polyhydroxyalkanoates production phases: a mini review. *XVII Convegno della Rete Italiana LCA* (conference proceedings). <https://doi.org/10.5281/zenodo.11105211>
30. Piao, Z., Agyei Boakye, A.A., Yao, Y. (2024). Environmental impacts of biodegradable microplastics. *Nature Chemical Engineering*, 1, 661–669. <https://doi.org/10.1038/s44286-024-00127-0>
31. Piao, Z., Yao, Y. (2026). The role of biodegradable plastics in the global plastic future. *Nature Reviews Clean Technology*, 1–16. <https://doi.org/10.1038/s44359-025-00142-1>
32. PlasticsEurope (2014). *Eco-profiles and EPDs of the European Plastics Manufacturers: Polypropylene (PP)*.
33. PlasticsEurope (2017). *Eco-profile and EPD: Polyethylene Terephthalate (PET), Bottle Grade*.
34. Pscherer, T., Krommes, S. (2025). LCA standards for environmental product assessments in the bioeconomy with a focus on biogenic carbon: a systematic review. *International Journal of Life Cycle Assessment*, 30(2), 371–393. <https://doi.org/10.1007/s11367-024-02387-7>
35. Rebolledo Leiva, R., Ladakis, D., Ioannidou, S.-M., Koutinas, A., Moreira Vilar, M.T., González García, S. (2023). Attributional and consequential life cycle perspectives of second-generation polylactic acid: the benefits of integrating a recycling strategy. *Journal of Cleaner Production*, 420, 138354. <https://doi.org/10.1016/j.jclepro.2023.138354>
36. Righi, S., Guerra, R., Vogli, L., Baioli, F. (2020). Polyhydroxybutyrate from sewage sludge: life cycle assessment methodological choices and inventory. *Proceedings of the European Biomass Conference and Exhibition*, 831–836.
37. Saavedra del Oso, M., Nair, R., Mauricio Iglesias, M., Hospido Quintana, A. (2023). Comparative life cycle analysis of PHA-based consumer items for daily use. *Resources, Conservation and Recycling*, 199, 107242. <https://doi.org/10.1016/j.resconrec.2023.107242>
38. Senila, L., Kovacs, E., Resz, M.-A., Senila, M., Becze, A., Roman, C. (2024). Life cycle assessment (LCA) of bioplastics production from lignocellulosic waste (study case: PLA and PHB). *Polymers*, 16(23), 3330. <https://doi.org/10.3390/polym16233330>
39. Sikander, A., Deegener, S., Körner, I. (2024). Decomposition of biodegradable plastic bags for kitchen waste collection in industrial composting. *Frontiers in Sustainable Food Systems*, 8, 1433460. <https://doi.org/10.3389/fsufs.2024.1433460>
40. Sun, S., Yang, S., Qiu, Y., Ding, J., Wang, W., Wu, F., Chen, G.-Q. (2025). Life cycle design of polyhydroxyalkanoates (PHA). *National Science Review*, 12(12), nwaf517. <https://doi.org/10.1093/nsr/nwaf517>

41. UNEP (2022). *Single-use supermarket food packaging and its alternatives: recommendations from life cycle assessments*. United Nations Environment Programme, Nairobi.
lifecycleinitiative.org
42. UNFCCC CDM (2022). *Repository of default values: emission factors for diesel generator systems*.
43. Wang, S., Lydon, K.A., White, E.M., Grubbs, J.B., Lipp, E.K., Locklin, J., Jambeck, J.R. (2018). Biodegradation of poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) plastic under anaerobic sludge and aerobic seawater conditions: gas evolution and microbial diversity. *Environmental Science & Technology*, 52(10), 5700–5709. <https://doi.org/10.1021/acs.est.7b06688>
44. Wang, X., Firouzkouhi, H., Chow, J.C., Watson, J.G., Ho, S.S.H., Carter, W., De Vos, A.S.M. (2023). Chemically speciated air pollutant emissions from open burning of household solid waste from South Africa. *Atmospheric Chemistry and Physics*, 23, 15375–15393.
<https://doi.org/10.5194/acp-23-15375-2023>
45. World Bank (2025). *Lebanon Emergency Assistance Project (P509428): Environmental and Social Review Summary*, Report ESRSA04037. [worldbank.org](https://www.worldbank.org)
46. Yadav, K., Nikalje, G.C. (2024). Comprehensive analysis of bioplastics: life cycle assessment, waste management, biodiversity impact, and sustainable mitigation strategies. *PeerJ*, 12, e18013. <https://doi.org/10.7717/peerj.18013>