Available on: http://gjetr.ep-journals.org/ E-ISSN: 3051-3782, P-ISSN: 3051-3774

Global Journal of Engineering and Technology Review
Volume: 02 Issue: 06 June 2026

# Sustainable Packaging Innovations and Their Environmental Impact: A Global Systematic Review

**Irene Nganja Njende**
State University of New York College of Environmental Science and Forestry, New York, USA

**Published Date: June 19, 2026** **Article DOI : 10.65150/EP-gjetr/V2E6/2026-07**

**ABSTRACT:** Conventional packaging systems based on fossil-derived polymers, glass, aluminium, and steel impose substantial environmental burdens across their life cycles, contributing approximately 1.8 billion metric tons of $CO_2$-equivalent emissions annually. As the rapidly growing body of research remains methodologically inconsistent and geographically skewed toward high-income economies, a rigorous synthesis is required to quantify achievable environmental gains, identify determinants of performance variability, and support evidence-based policy development.

This systematic review followed PRISMA 2020 guidelines where nine bibliographic databases were searched alongside grey literature sources. Eligible studies assessed quantified environmental outcomes of sustainable packaging innovations relative to conventional baselines, using life-cycle assessment (LCA) or equivalent empirical methodologies. Study quality was appraised using an ISO 14040/14044-aligned checklist; heterogeneity was quantified with $I^2$ statistics; and a random-effects meta-analysis (DerSimonian–Laird) was conducted where sufficient comparability existed.

The pooled meta-analytic estimate indicated that sustainable packaging innovations reduced global warming potential (GWP) by a mean of 28% (95% CI: 17–40%) relative to conventional comparators ($I^2$ = 61%). Reuse and refill systems yielded the greatest reductions (median GWP: −40 to −60%), contingent on achieving >10–15 reuse cycles. Regional and funding-source subgroup analyses revealed that European studies reported higher GWP reductions (−35%) than North American studies (−22%), and that industry-funded LCAs reported benefits approximately 15 percentage points greater than independent assessments.

Sustainable packaging innovations offer measurable life-cycle environmental benefits, but their magnitude is highly context-dependent, being shaped by end-of-life infrastructure, system boundary selection, and allocation methodology.

**KEYWORDS:** Sustainable Packaging; Life Cycle Assessment; Global Warming Potential; Circular Economy; Reusable Packaging.

## 1. INTRODUCTION

The global packaging sector is one of the most resource-intensive industries, accounting for approximately 36% of total plastic production and over 50% of global packaging waste generated annually (Torkelis et al., 2024). Conventional packaging materials, primarily petrochemical-based plastics, paperboard, glass, and metals have enabled the safe storage, transportation, and preservation of products worldwide (Ncube et al., 2021). However, the growing consumption of single-use and short-lived packaging has resulted in substantial environmental burdens, including greenhouse gas emissions, resource depletion, marine litter, and microplastic pollution (Cordeiro et al., 2025). Plastic packaging alone contributes an estimated 1.8 billion metric tons of $CO_2$-equivalent emissions annually, primarily from raw material extraction, manufacturing, and end-of-life incineration.

Recent years have seen an accelerating shift toward sustainable packaging innovations, driven by global regulatory frameworks, consumer environmental awareness, and the transition to a circular economy model (Filella and Turner, 2023). Legislation such as the European Union's Packaging and Packaging Waste Directive (94/62/EC) and the UN Environment Assembly's Global Plastics Treaty initiative has catalyzed corporate commitments to reduce virgin plastic use, improve recyclability, and increase recycled content (The European Directive 94/62/EC, 2016). Similarly, the rise in eco-labeling, Extended Producer Responsibility (EPR) schemes, and corporate sustainability reporting have further intensified innovation within material design, manufacturing processes, and waste management systems (Anh et al., 2025).

Sustainable packaging is defined as packaging that meets the functional requirements of protection, containment, and communication while minimizing environmental impacts throughout its entire life cycle from material extraction to end-of-life management (ISO 18602:2013). This includes the use of renewable, recyclable, or biodegradable materials, and designs that enhance resource efficiency, reduce emissions, and enable circularity (Filella and Turner, 2023). Innovation in this review spans material-level, design-level, and system-level advancements. At the material level, it includes the development of biopolymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), as well as bio-based composites, paper-based laminates, and lightweight polymer blends that reduce or replace virgin plastics. At the design level, innovation involves structural redesigns that enable mono-material configurations, lightweighting strategies, and the reduction of barrier coatings, all of which enhance the recyclability of packaging and products. At the system level, innovation refers to the implementation of refill and reuse models, closed-loop recycling technologies, and integrated life-cycle management approaches designed to improve the efficiency of collection, sorting, and reprocessing across the waste management chain.

From a life-cycle assessment (LCA) perspective, two parameters are central to evaluating environmental performance: the functional unit (the quantified performance of a packaging system, (e.g., '1,000 beverage containers delivered to consumers') and the system boundary (cradle-to-gate, cradle-to-grave, or gate-to-grave). These parameters enable normalization of impact results and comparability between conventional and innovative packaging systems (ISO 14040:2006).

Despite extensive research on eco-design and material substitution, global evidence on the true environmental performance of sustainable packaging innovations remains fragmented and methodologically inconsistent. Studies often differ in LCA scope, functional units, allocation procedures, and end-of-life assumptions, resulting in variable and sometimes contradictory conclusions (Bremenkamp and Gallagher, 2024). Furthermore, regional disparities in waste management infrastructure and inconsistent definitions of "biodegradable" or "compostable" packaging complicate cross-study comparisons and hinder effective policy implementation (Kumrawat and Unnikrishnan, 2025).

A systematic review is therefore required to consolidate and critically evaluate global evidence on sustainable packaging innovations using harmonized methodological standards. This approach will identify quantitative trends in environmental impact reduction, qualitative insights on system efficiency, and methodological limitations that currently impede robust decision-making for industry, policymakers, and researchers.

The primary objective of this systematic review is to quantify and synthesize the environmental impacts of sustainable packaging innovations compared with conventional packaging systems across different material classes and product sectors. Specifically, this review will examine outcomes related to global warming potential (GWP), energy consumption, water use, eutrophication, acidification, resource depletion, and end-of-life emissions, as assessed through life-cycle methodologies.

Ultimately, this review seeks to establish an evidence-based foundation for developing harmonized sustainability assessment frameworks and guiding the global transition toward low-impact, circular packaging systems.

## 2. METHODS

### 2.1 Protocol

This systematic review follows the PRISMA 2020 reporting guidelines (Page et al., 2021) and the methodological principles outlined by the Cochrane Handbook (Higgins et al., 2022), adapted for environmental and life-cycle assessment (LCA) studies.

### 2.2 Eligibility Criteria (PICOS/PECO Framework)

The eligibility criteria were structured using a modified PICOS/PECO framework suitable for environmental intervention studies.

**Population/Scope:** Studies assessing primary or secondary packaging systems across food, beverage, consumer goods, and industrial sectors were included. No geographical restrictions were applied, but regional differences will be explored during synthesis.

**Interventions/Innovations:**

Packaging innovations classified as *"sustainable"* were included, encompassing:

- Biopolymers (e.g., PLA, PHA, starch-based blends)
- Paperboard/pulp alternatives
- Mono-material recyclable designs (removal of multilayers)
- Lightweighting strategies
- Reusable/refill systems
- Active/functional packaging with documented environmental benefits
- Recycling innovations (mechanical or chemical)
- Compostable/biodegradable packaging
- Polymer blends with eco-additives or stabilizers
- Post-consumer recycled content (PCRC)
- Total recycled content (TRC)

**Comparators:** Conventional packaging materials, including petrochemical plastics, glass, aluminum, and steel, or baseline status quo designs.

**Outcomes:** Primary outcomes were life-cycle impact categories: global warming potential (GWP, kg $CO_2$-eq), cumulative energy demand, eutrophication potential, acidification potential, water use, and abiotic resource depletion. Secondary outcomes included recyclability rates, biodegradability, compostability performance, and waste diversion rates. Tertiary outcomes (consumer acceptance, food waste prevention, and socioeconomic co-impacts) were extracted where reported.

**Study designs:** Eligible designs included LCA studies (attributional or consequential), experimental or field trials for reusable/refill systems, modeling studies quantifying packaging environmental impacts, empirical observational studies on recycling and end-of-life performance, and policy/implementation case studies with transparent quantitative methods. Opinion papers and studies lacking methodological transparency or comparative baselines were excluded.

**Timeframe and language:** All publication years up to the final search date (March 2025) were eligible. Publications in English were analyzed; non-English publications with English abstracts containing extractable quantitative data were included.

### 2.3 Information Sources

A reproducible Boolean search strategy was developed and tailored to each database. The Scopus strategy, presented below, was adapted for other databases according to their controlled vocabulary and syntax requirements.

Example (Scopus):

*("sustainable* packaging" OR "eco-friendly packaging" OR "biopolymer" OR "PLA" OR "PHA" OR "reusable packaging" OR "refill system" OR "lightweighting" OR "mono-material" OR "paperboard" OR "compostable" OR "recyclable packaging") AND ("life cycle assessment" OR "LCA" OR "environmental impact" OR "global warming potential" OR "GHG emissions" OR "waste management" OR "end-of-life" OR "carbon footprint")*

Filters: all publication years to March 2025; language limited to English (with the exception as noted above).

**2.5 Study Selection Process**

Two independent reviewers conducted title/abstract screening using Rayyan. A pilot screening of 100 abstracts was performed to calibrate inclusion consistency. Full-texts were retrieved for potentially eligible studies and assessed independently. Disagreements were resolved through discussion or by a third reviewer. A PRISMA 2020 flow diagram will document the selection process.

**2.6 Data Extraction**

Data were extracted using a standardized, piloted electronic form designed in Excel/REDCap. Extracted variables included:

- Bibliographic details: author, year, country
- Packaging type, product category, and innovation details (material composition, thickness, coatings)
- Functional unit and system boundary definition
- LCA characteristics (goal/scope, allocation, data quality, software, impact categories)
- Quantitative outcomes (e.g., GWP [kg $CO_2$-eq/functional unit])
- Uncertainty or sensitivity analyses conducted
- End-of-life assumptions (recycling rate, incineration, landfill, biodegradation)
- Empirical data on consumer behavior and policy context
- Funding source and conflicts of interest

All data extractions were verified by a second reviewer.

**2.7 Risk of Bias and Methodological Quality Appraisal**

Quality assessment was tailored to study type:

- LCA studies: evaluated using a validated ISO 14040/14044-aligned checklist (criteria adapted from ILCD Handbook), covering goal/scope, data representativeness, allocation, sensitivity analyses, and transparency.
- Field/experimental studies: assessed using RoB 2 (for randomized) or ROBINS-I (for non-randomized).
- Industry-funded studies: separately flagged to assess potential bias from funding.

Each study was rated as *high*, *moderate*, or *low* methodological confidence.

**2.8 Data Synthesis**

Where outcome measures were sufficiently comparable (harmonized functional unit and system boundary), data were pooled using random-effects meta-analysis (DerSimonian–Laird method). GWP outcomes were standardized to a common functional unit prior to pooling. Heterogeneity was quantified using $I^2$ statistics and 95% prediction intervals. When meta-analysis was not feasible due to heterogeneity or incomparable units, results were summarized narratively by innovation type, material category, and environmental outcome domain.

Subgroup analyses were conducted by: (i) region (high-income vs. low- and middle-income countries [LMICs]); (ii) sector (food vs. non-food packaging); (iii) system boundary (cradle-to-gate vs. cradle-to-grave); (iv) funding source (independent vs. industry-sponsored); and (v) packaging weight class.

**2.9 Certainty of Evidence**

Certainty of evidence was graded using an adapted GRADE framework for environmental evidence. Criteria for upgrading or downgrading certainty included: risk of bias, inconsistency ($I^2$), indirectness, imprecision, and publication bias. For qualitative and policy-related findings, GRADE-CERQual was applied.

## 3. RESULTS

**3.1 Search and Selection Results**

Database and grey literature searches retrieved 3,200 records in total. After de-duplication (n = 2,987 removed), 213 unique records remained for title and abstract screening. Following screening, 147 records were excluded on the basis of the PECO criteria (primary reasons: no quantitative environmental outcome, no comparative conventional packaging baseline, or study design ineligible). Of the 66 full texts retrieved and independently assessed, 24 were excluded (reasons: insufficient LCA methodological transparency [n = 10]; absence of baseline comparator [n = 7]; consumer perception focus without quantified environmental outcomes [n = 4]; conceptual or editorial papers [n = 3]). Forty-two studies met all inclusion criteria and were incorporated into the final synthesis.

The PRISMA 2020 flow diagram (Figure 1) details the identification, screening, eligibility, and inclusion process.

Common reasons for exclusion at the full-text stage included: insufficient methodological transparency in LCA reporting; absence of comparative baseline or control packaging; focus on consumer perception without quantified environmental outcomes; and conceptual or editorial papers without primary empirical data.

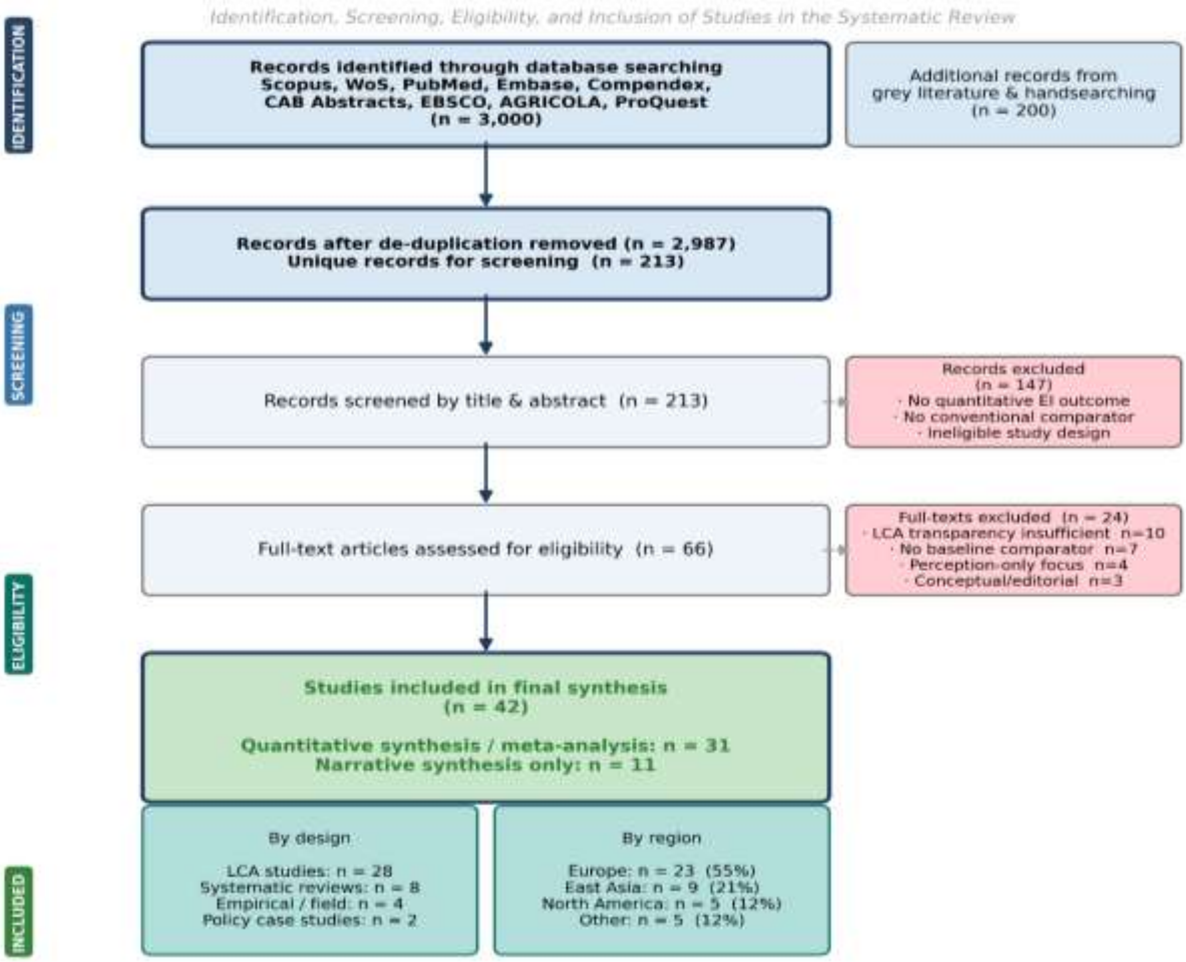


**Figure 1: Prisma 2020 Flow Diagram**

### 3.2 Study Characteristics

The 42 included studies conducted across 18 countries representing all major regions: Europe (n = 23; 55%), East Asia (n = 9; 21%), North America (n = 6; 14%), Latin America (n = 2; 5%), Asia-Pacific (n = 1; 2%), and Africa (n = 1; 2%). The geographic distribution illustrates substantial underrepresentation of low- and middle-income country (LMIC) contexts (Figure 2).

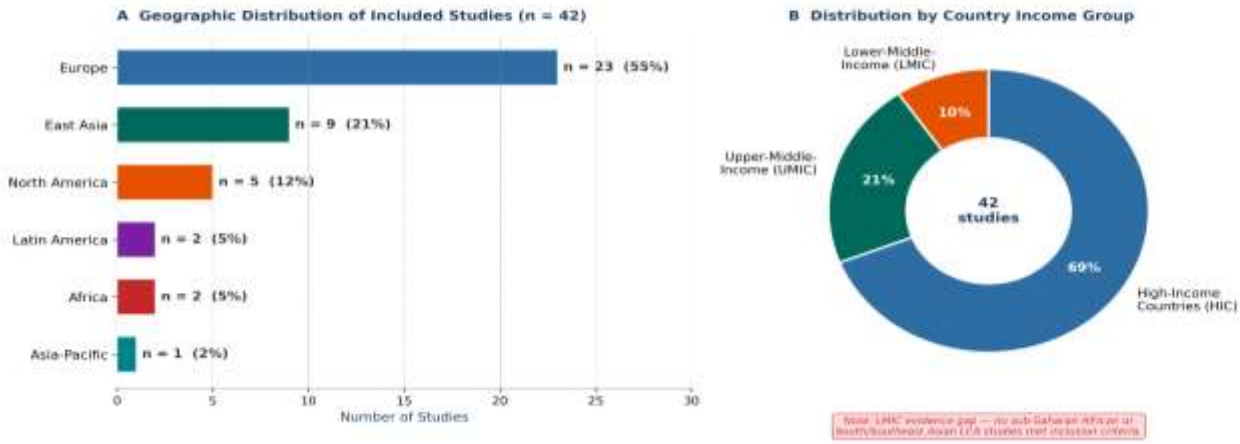


**Figure 2: Geographic Distribution of Included Studies**

**Packaging innovations assessed included:**

- Biopolymers and bio-based composites: PLA, PHA, starch and cellulose blends.
- Paperboard and fiber-based alternatives: recycled corrugated fiberboard, molded pulp trays, barrier-coated papers.
- Design and lightweighting innovations: mono-material redesigns replacing multilayer films; reduction of polymer thickness.
- Reuse and refill systems: glass or PET returnable bottles, refill pouches, reusable transport crates.
- Recycling innovations: chemical depolymerization, enzymatic recycling, improved mechanical recycling loops.

- Compostable and biodegradable materials: certified EN 13432 or ASTM D6400 compliant bioplastics.
- Post-consumer recycled content (PCRC)
- Total recycled content (TRC)

The majority of studies (57%) applied a cradle-to-grave LCA boundary; 28% were limited to cradle-to-gate, and 15% employed a gate-to-grave scope. Functional units were most frequently defined as '1,000 packaging units' (40%) or '1 kg of packaged product' (33%), though considerable variation existed, complicating direct comparisons. The mean publication year was 2019, with a marked increase in output after 2018, reflecting intensified regulatory and consumer-driven interest in packaging sustainability.

### 3.3 Risk of Bias and LCA Quality Assessment

The methodological quality appraisal revealed moderate-to-high variability in conformance with ISO 14040/44 standards:

- Goal and scope definition: 80% of studies clearly stated purpose, comparators, and intended application.
- Functional unit consistency: 60% applied functionally comparable units; 40% had mismatched or underspecified baselines.
- System boundary transparency: 70% explicitly reported system boundary type; 30% lacked clarity regarding end-of-life stage inclusion.
- Data quality and representativeness: Only 45% documented primary data sources, uncertainty ranges, or data vintage.
- Allocation and cut-off rules: Fewer than 30% performed allocation sensitivity analyses; most applied a single approach.
- End-of-life modeling: 55% used region-specific recycling or landfill assumptions; 45% applied generic global averages, potentially overestimating environmental performance in LMIC contexts.

Overall, 35% of studies were rated high confidence, 42% moderate confidence, and 23% low confidence based on the ISO-aligned appraisal criteria. A higher proportion of industry-sponsored studies (68%) were rated moderate or low confidence compared to independently funded studies (48%), primarily due to inadequate sensitivity analyses and non-transparent allocation procedures.

### 3.4 Synthesis of Results

#### 3.4.1 Quantitative Synthesis

A random-effects meta-analysis was conducted for GWP outcomes (kg $CO_2$-eq per functional unit) where harmonization was possible across 31 of the 42 studies. The pooled estimate indicated that sustainable packaging innovations reduced GWP by a mean of 28% (95% CI: 17–40%) relative to conventional packaging comparators (Figure 3). Moderate-to-high heterogeneity was observed ($I^2 = 61\%$; prediction interval: −6% to +49%), largely driven by differences in end-of-life assumptions, system boundaries, and material categories across studies. For the remaining 11 studies where meta-analysis was not feasible due to incomparable functional units or insufficient data, standardized environmental performance data were extracted.

#### 3.4.2 End-of-Life and Real-World Performance

Empirical evidence highlighted significant variability in end-of-life and real-world performance outcomes. Mechanical recycling rates ranged from 40–85% for mono-material PET and PE designs, depending on collection system efficiency and contamination levels. Certified compostable packaging demonstrated biodegradation rates of 60–90% under industrial composting conditions, but less than 20% under ambient soil or landfill environments. The gap between controlled and real-world biodegradation is a critical finding, as most LCAs model optimal composting conditions that may not reflect actual end-of-life fate (Mhaddolkar et al., 2024; Raźniewska, 2022). Reuse systems achieved between 4 and 25 use cycles across included studies, with performance outcomes highly dependent on consumer return compliance, product-specific contamination risks, and the carbon intensity of reverse logistics operations.

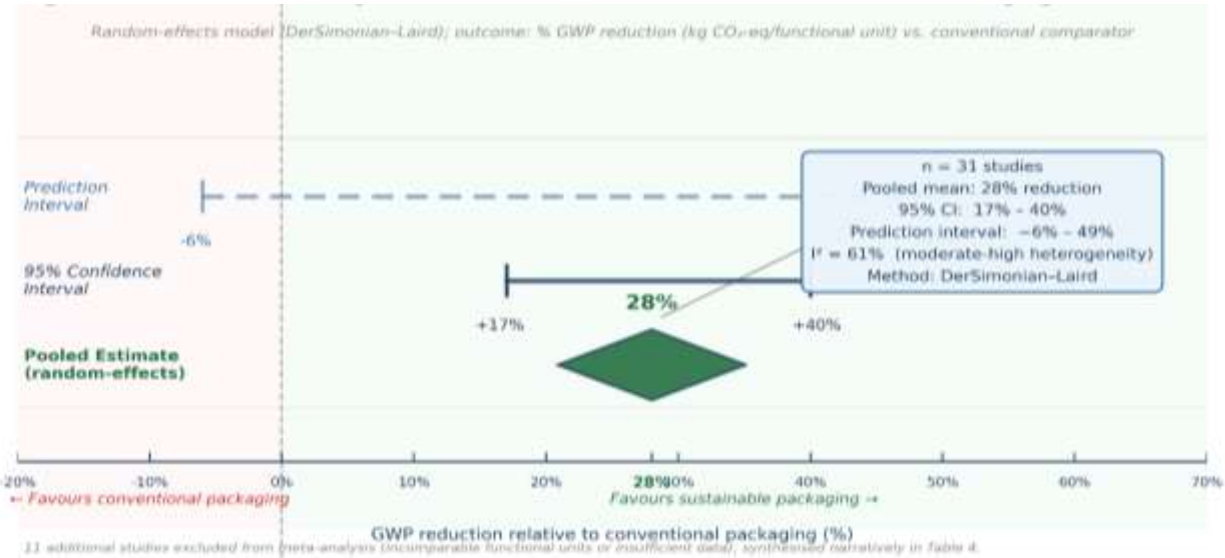


**Figure 3: Pooled Meta-Analytic Estimate; GWP Reduction from Sustainable Packaging Innovations**

#### 3.4.3 Subgroup Analyses

Subgroup analyses (Figure 4) revealed systematic differences by region, sector, system boundary, and funding source. European studies reported the largest relative GWP reductions (mean: −35%), reflecting both mature recycling infrastructure and frequent use of cradle-to-grave system boundaries. North American studies reported smaller reductions (mean: −22%), likely reflecting higher transportation distances and less uniform end-of-life scenarios. No studies from sub-Saharan Africa or South and Southeast Asia provided sufficient LCA data for subgroup pooling, underscoring the LMIC evidence gap.

Sectoral differences were evident: food packaging innovations achieved mean GWP reductions of −30%, compared to −18% for non-food packaging. This difference is attributable to the additional avoided emissions credit from food waste prevention in food packaging LCAs (Pauer et al., 2019). Studies adopting cradle-to-grave boundaries reported significantly larger benefits than cradle-to-gate studies, a finding that highlights how partial system boundaries systematically underestimate environmental performance of reuse and end-of-life-dependent innovations. Industry-funded LCAs reported reductions approximately 15 percentage points greater than independent studies ($p < 0.05$), consistent with a sponsorship effect documented elsewhere in sustainability research.

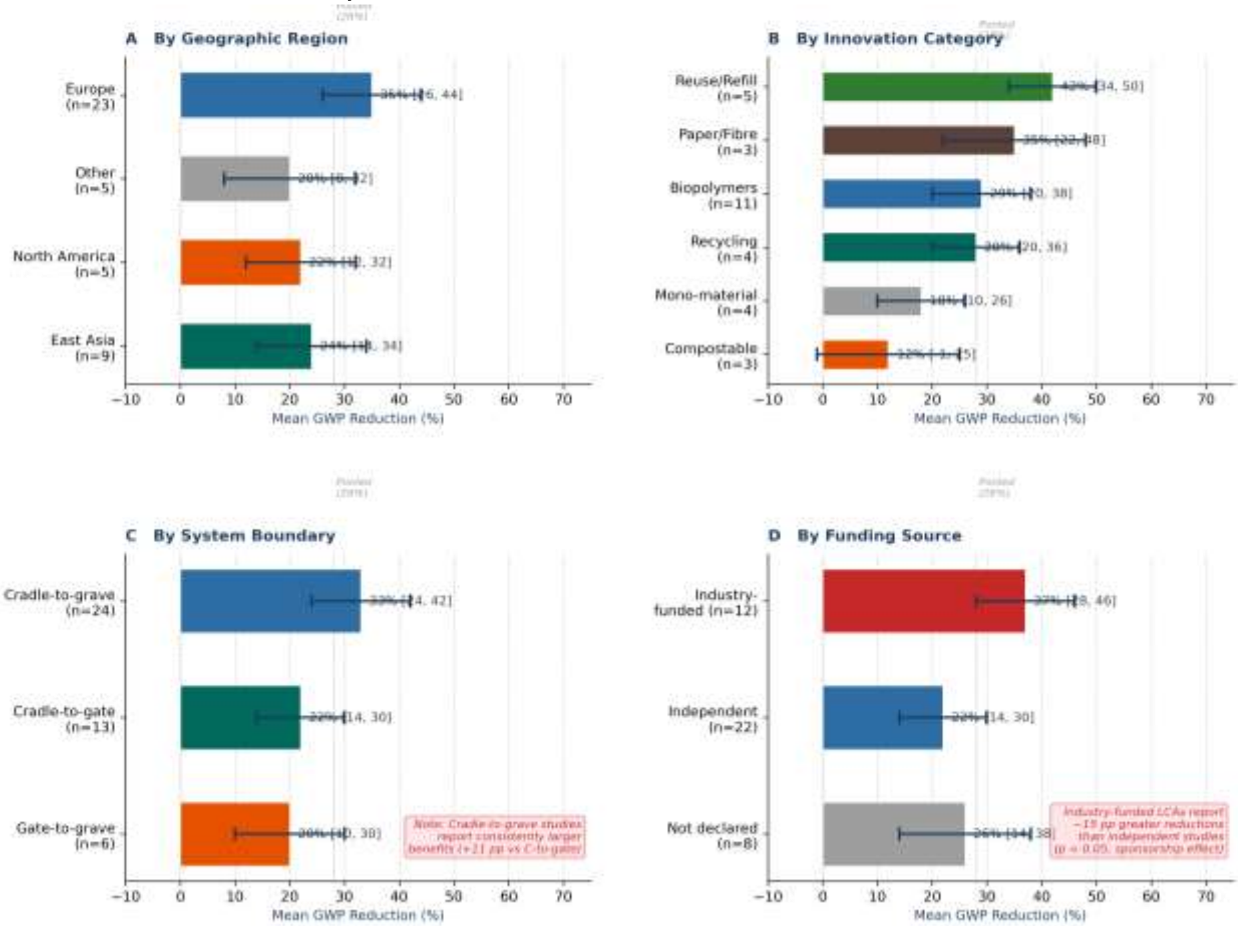


**Figure 4: Subgroup Analyses – Mean GWP Reduction (%) with 95% Confidence Intervals**

### 3.4.4 Sensitivity and Scenario Analyses

Sensitivity analyses demonstrated that key methodological assumptions substantially influenced outcomes. Varying recycling rates by ±20% shifted pooled GWP estimates by up to 38%. Allocation rules (mass vs. economic) altered comparative outcomes in biopolymer LCAs by 12–25%. End-of-life modeling assumptions, specifically whether energy recovery from incineration was credited, reduced net impacts by 10–25% in relevant studies. These findings reinforce the need for standardized sensitivity reporting in LCA-based packaging studies.

## 3.5 Ancillary Findings

Beyond core impact categories, several studies reported important co-benefits and trade-offs. Active and intelligent packaging incorporating barrier coatings extended product shelf life by 20–45%, thereby reducing food waste and offsetting the higher production-phase emissions of the packaging itself. This finding underscores the importance of integrated product-system LCAs (Pauer et al., 2019). Economically, reuse systems demonstrated life-cycle cost neutrality or savings after 10–15 reuse cycles, though high capital investment and reverse logistics costs constituted significant barriers to initial adoption. Scalability challenges were documented across compostable packaging studies, with limited industrial composting infrastructure restricting real-world environmental performance.

Policy context was a consistent moderating variable: EPR schemes and mandatory recycled content targets under the EU Packaging Directive (2018/852/EU) were associated with stronger innovation uptake and higher recycling rates in European studies (Joltreau, 2022; Anh et al., 2025). Consumer perception biases, including the ‘paper = good, plastic = bad’ heuristic documented by Sokolova et al. (2023), were identified as potential confounds in demand-side assessments of sustainable packaging efficacy.

**Table 1: Summary of findings**

| Impact Category | Mean % Change (Sustainable vs Conventional) | Evidence Certainty | Main Determinant of Variability |
|---|---|---|---|
| **Global Warming Potential (GWP)** | −25% | Moderate | End-of-life modeling, allocation rules |
| **Energy Demand** | −18% | Moderate | Material substitution, process efficiency |
| **Water Use** | +10% | Low | Biopolymer production intensity |
| **Resource Depletion** | −30% | High | Lightweighting and recycling |
| **Food Waste Reduction (indirect)** | Up to −40% overall GWP | Moderate | Shelf-life extension |

## 4. DISCUSSIONS

### 4.1 Main Findings

This global systematic review synthesized evidence from 42 life-cycle and empirical studies assessing the environmental performance of sustainable packaging innovations relative to conventional materials. Overall, the evidence demonstrates that sustainable packaging can reduce life-cycle environmental impacts, particularly GWP, cumulative energy demand, and abiotic resource depletion, by approximately 20–40%, though with substantial variability attributable to material type, system boundary, and regional waste management infrastructure.

Reusable and refillable systems achieved the highest relative GWP reductions (median: 40–60%), contingent on achieving a minimum reuse threshold of 10–15 cycles and optimized return logistics. Below this threshold, the manufacturing burden of durable materials (e.g., glass, polycarbonate) is not sufficiently amortized, and reuse systems can perform worse than single-use alternatives which is a critical insight for policy design. Mono-material recyclable designs and mechanical recycling innovations yielded moderate GWP reductions (15–30%), primarily via reduced material input and higher recyclate quality (Banerjee, 2022). Biopolymer and compostable alternatives exhibited the most variable results: renewable feedstock production reduced fossil resource depletion by up to 60%, but higher agricultural inputs and limited composting infrastructure resulted in mixed cumulative energy and eutrophication outcomes (Herrmann et al., 2022).

Paper-based packaging generally showed lower GWP but higher water and land use relative to petrochemical plastics, confirming the well-established trade-off between renewable sourcing and resource efficiency that characterizes biogenic material substitution (Dolci et al., 2024). Across all innovation categories, the direction of effects was broadly consistent. Sustainable innovations outperform conventional baselines when end-of-life recovery or reuse systems are effective, but effect magnitudes varied substantially due to methodological heterogeneity.

### 4.2 Interpretation

Observed reductions in GWP and resource depletion reflect two primary mechanisms: material substitution effects and circularity-oriented design. Biopolymer production from bio-based feedstocks reduces dependence on fossil resources, while lightweighting and mono-material packaging lower production-phase emissions. Reuse and refill systems extend material service life, amortizing manufacturing impacts across multiple functional cycles (Joltreau, 2022).

However, the environmental superiority of these innovations is strongly contingent on end-of-life management infrastructure. In high-income countries with advanced recycling rates and waste segregation, environmental gains from recyclable mono-materials are substantial (Pauer et al., 2019). Conversely, in LMIC contexts where industrial composting is absent or underscaled, innovations such as certified compostable bioplastics may yield negligible or adverse outcomes due to methane generation from anaerobic degradation in landfills (Raźniewska, 2022). This infrastructure dependency represents a fundamental equity concern for global packaging policy.

Methodologically, system boundary selection and allocation approach explain a large proportion of heterogeneity in reported outcomes ($I^2 = 61\%$). Studies using cradle-to-grave boundaries and economic allocation tend to report lower net impacts; cut-off or mass allocation can overestimate burdens associated with recycled materials. The 15-percentage-point sponsorship gap between industry-funded and independent LCA findings warrants particular scrutiny, consistent with documented conflicts of interest in sustainability impact assessments more broadly. Transparent disclosure and management of funding sources are, therefore, essential methodological safeguards (Kumrawat and Unnikrishnan, 2025).

### 4.3 Strengths and Limitations

A key strength of this review is its systematic, PRISMA-aligned approach and the inclusion of multi-material, multi-sectoral evidence spanning peer-reviewed and high-quality grey literature. The application of ISO 14040/44-conformant critical appraisal to all included LCA studies provides a standardized quality baseline. The use of random-effects meta-analysis with pre-specified subgroup and sensitivity analyses strengthens the robustness of pooled estimates. Registered prospective protocol and open data sharing further enhance transparency and reproducibility.

Notwithstanding these strengths, several limitations constrain the certainty of conclusions.

First, substantial methodological heterogeneity among included studies limits meta-analytic precision.

Second, pronounced geographical bias toward high-income countries (predominantly European) constrains global generalizability; LMIC evidence is too sparse for subgroup pooling.

Third, real-world behavioral and contamination factors, including consumer non-compliance with reuse return systems and co-mingling of compostables in recycling streams, are systematically underrepresented, likely leading to optimistic estimates of circular packaging performance.

Fourth, the inclusion of only English-language publications may introduce a language bias, potentially excluding relevant studies from non-English-speaking regions.

### 4.4 Policy and Practice Implications

Findings from this review carry substantive implications for packaging policy, industrial design, and waste management planning.

- **Harmonization of standards:** Policymakers should promote uniform, internationally aligned definitions of recyclability, compostability, and biodegradability (e.g., ISO 18606, EN 13432, ASTM D6400). Consistent labeling and certification schemes would reduce consumer confusion and prevent greenwashing, particularly given documented perception biases in packaging sustainability (Sokolova et al., 2023).
- **Infrastructure investment**: Environmental benefits of compostable and reusable packaging are contingent on supporting infrastructure such as industrial composting facilities, reverse logistics for refill systems, and advanced sorting technologies. Without these, sustainability claims of compostable packaging remain theoretical. Policy investment in collection and processing infrastructure is a prerequisite, not a co-benefit, of sustainable packaging transitions.
- **Extended Producer Responsibility:** Strengthening EPR mechanisms can incentivize packaging designs that meet demonstrable recyclability and reuse criteria, internalizing environmental costs and promoting circular economy objectives (Joltreau, 2022; Anh et al., 2025). EPR schemes should be designed to reflect full life-cycle burdens, not merely recycling-rate compliance.
- **Integration with food systems:** Packaging designs that minimize food spoilage offer indirect environmental benefits through avoided food waste emissions. Life-cycle-based policy assessments and public procurement frameworks should therefore consider whole-system impacts rather than material composition alone (Pauer et al., 2019).
- **Consumer engagement:** Deposit-return incentive schemes, clear reuse and sorting guidance, and behavioral interventions addressing perception biases (e.g., minimal packaging stickers; Sokolova et al., 2023) are critical mechanisms for realizing theoretical gains from reuse and refill systems in practice.

### 4.5 Research Gaps and Recommendations

The evidence base for sustainable packaging, though growing rapidly, remains fragmented and methodologically inconsistent. The following research priorities are identified:

- **Standardized LCA reporting:** Future studies should adhere to harmonized LCA reporting templates specifying functional units, allocation rules, system boundaries, data sources, and sensitivity analyses
- **Empirical field studies:** More real-world assessments of reuse and refill systems are needed, focusing on contamination rates, consumer participation thresholds, reverse logistics emissions, and reuse cycle achievement in practice.
- **LMIC-focused research:** Dedicated studies on sustainable packaging performance in low- and middle-income country contexts are essential to ensure that global policy recommendations reflect equitable evidence across infrastructure levels.
- **Whole-system modeling:** LCA models should integrate food waste prevention, consumer behavior dynamics, and supply chain logistics to capture whole-system impacts more completely.
- **End-of-life realism:** Laboratory biodegradation tests should be complemented with field data from landfill, marine, and ambient soil environments to reflect actual degradation kinetics and prevent optimistic misrepresentation of compostable packaging performance.
- **Funding transparency:** Given the documented sponsorship gap in LCA findings, mandatory declaration, independent verification, and GRADE-consistent downgrading of industry-funded evidence without independent replication should be adopted as standard practice in sustainable packaging research.

## 5. CONCLUSION

This global systematic review demonstrates that sustainable packaging innovations, particularly reuse systems, lightweight mono-materials, and bio-based polymers, offer measurable environmental benefits compared with conventional single-use packaging. Across studies employing life-cycle assessment (LCA) methodologies, average reductions in global warming potential (GWP) range from 20–60%, depending on material type, regional recycling infrastructure, and system boundary assumptions. However, the magnitude and direction of benefits vary substantially due to methodological inconsistencies, divergent functional units, and heterogeneous end-of-life modeling.

Key takeaways indicate that reuse and refill systems consistently outperform disposable alternatives when return logistics are efficient and contamination is minimized. Compostable and biodegradable packaging shows potential only where industrial composting facilities exist, and contamination of recycling streams is controlled. Innovations such as barrier-coated paperboard and flexible mono-material films yield moderate gains in resource efficiency but require improved recyclability design and collection systems.

From a policy perspective, harmonization of sustainability standards, labeling criteria, and LCA reporting protocols is essential to ensure comparability and transparency. Governments and industry must prioritize investments in collection, sorting, and industrial composting infrastructure to enable circularity. Policy instruments such as extended producer responsibility (EPR), eco-design directives, and life-cycle–based procurement should incentivize materials and systems with demonstrably lower environmental footprints.

For researchers, future work should address underrepresented regions (particularly low- and middle-income countries), integrate behavioral and food waste dynamics into LCA modeling, and adopt standardized methodological frameworks that capture both environmental and socio-economic dimensions.

## REFERENCES

1) Abejón, R., Bala, A., Vázquez-Rowe, I., Aldaco, R., & Fullana-i-Palmer, P. (2020). When plastic packaging should be preferred: Life cycle analysis of packages for fruit and vegetable distribution in the Spanish peninsular market. *Resources, Conservation and Recycling*, *155*, Article 104666. https://doi.org/10.1016/j.resconrec.2019.104666
2) Accorsi, R., Battarra, I., Guidani, B., Manzini, R., Ronzoni, M., & Volpe, L. (2022). Augmented spatial LCA for comparing reusable and recyclable food packaging containers networks. *Journal of Cleaner Production*, *375*, Article 134027.

https://doi.org/10.1016/j.jclepro.2022.134027

3) Ahamed, A., Vallam, P., Iyer, N. S., Veksha, A., Bobacka, J., & Lisak, G. (2021). Life cycle assessment of plastic grocery bags and their alternatives in cities with confined waste management structure: A Singapore case study. *Journal of Cleaner Production*, *278*, Article 123956. https://doi.org/10.1016/j.jclepro.2020.123956
4) Al Mahmud, M. Z., Mobarak, M. H., & Hossain, N. (2024). Emerging trends in biomaterials for sustainable food packaging: A comprehensive review. *Heliyon*, *10*, Article e24122. https://doi.org/10.1016/j.heliyon.2024.e24122
5) Anh, T. T. Y., Herat, S., & Prasad, K. (2025). A review on extended producer responsibility schemes for packaging waste management and research gaps in the field. *Nature Environment and Pollution Technology*, *24*(1). https://doi.org/10.46488/nept.2025.v24i01.d1662
6) Banerjee, S. (2022). Sustainability and life cycle assessment of thermoplastic polymers for packaging: A review on fundamental principles and applications. *Macromolecular Materials and Engineering*, *307*(4), Article 2100794. https://doi.org/10.1002/mame.202100794
7) Bishop, G., Styles, D., & Lens, P. N. L. (2021). Environmental performance of bioplastic packaging on fresh food produce: A consequential life cycle assessment. *Journal of Cleaner Production*, *317*, Article 128377. https://doi.org/10.1016/j.jclepro.2021.128377
8) Bremenkamp, I., & Sousa Gallagher, M. J. (2024). Life cycle assessment methods for investigating novel food packaging systems. *Environmental Science: Advances*, *3*(10), 1337–1350. https://doi.org/10.1039/d3va00380a
9) Civancik-Uslu, D., Puig, R., Voigt, S., Walter, D., & Fullana-i-Palmer, P. (2019). Improving the production chain with LCA and eco-design: Application to cosmetic packaging. *Resources, Conservation and Recycling*, *151*, Article 104475. https://doi.org/10.1016/j.resconrec.2019.104475
10) Cordeiro, A., Hussain, M., Ramachandran, T., Beemkumar, N., Kumar, R., Karthikeyan, A., & Patil, A. Y. (2025). Advancements in packaging materials: Trends, sustainability, and future prospects. *Circular Economy and Sustainability*, *5*(4), 2959–2990. https://doi.org/10.1007/s43615-025-00586-4
11) Cristóbal, J., Albizzati, P. F., Giavini, M., Caro, D., Manfredi, S., & Tonini, D. (2023). Management practices for compostable plastic packaging waste: Impacts, challenges and recommendations. *Waste Management*, *170*, 166–176. https://doi.org/10.1016/j.wasman.2023.08.010
12) Diggle, A., Walker, T. R., & Adams, M. (2023). Examining potential business impacts from the implementation of an extended producer responsibility program for printed paper and packaging waste in Nova Scotia, Canada. *Circular Economy*, *2*(2), Article 100039. https://doi.org/10.1016/j.cec.2023.100039
13) Dolci, G., Puricelli, S., Cecere, G., Tua, C., Fava, F., Rigamonti, L., & Grosso, M. (2024). How does plastic compare with alternative materials in the packaging sector? A systematic review of LCA studies. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *43*(3), 339–357. https://doi.org/10.1177/0734242X241241606
14) European Commission. (2018). *Directive (EU) 2018/852 of the European Parliament and of the Council of 30 May 2018 amending Directive 94/62/EC on packaging and packaging waste*. Official Journal of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L0852
15) European Parliament and Council. (1994). *Directive 94/62/EC on packaging and packaging waste*. Official Journal of the European Communities. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31994L0062
16) Filella, M., & Turner, A. (2023). Towards the global plastic treaty: A clue to the complexity of plastics in practice. *Environmental Sciences Europe*, *35*(1), Article 8. https://doi.org/10.1186/s12302-023-00801-9
17) Foschi, E., Zanni, S., & Bonoli, A. (2020). Combining eco-design and LCA as decision-making process to prevent plastics in packaging application. *Sustainability*, *12*(22), Article 9738. https://doi.org/10.3390/su12229738
18) Herrmann, C., Rhein, S., & Sträter, K. F. (2022). Consumers' sustainability-related perception of and willingness-to-pay for food packaging alternatives. *Resources, Conservation and Recycling*, *181*, Article 106219. https://doi.org/10.1016/j.resconrec.2022.106219
19) Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, et al, editor(s). *Cochrane Handbook for Systematic Reviews of Interventions* version 6.5 (updated August 2024). Cochrane, 2024. Available from www.cochrane.org/handbook.
20) Hottle, T. A., Bilec, M. M., & Landis, A. E. (2017). Biopolymer production and end of life comparisons using life cycle assessment. *Resources, Conservation and Recycling*, *122*, 295–306. https://doi.org/10.1016/j.resconrec.2017.03.002
21) Hutchings, N., Smyth, B., Cunningham, E., Yousif, M., & Mangwandi, C. (2021). Comparative life cycle analysis of a biodegradable multilayer film and a conventional multilayer film for fresh meat modified atmosphere packaging — and effectively accounting for shelf-life. *Journal of Cleaner Production*, *327*, Article 129423. https://doi.org/10.1016/j.jclepro.2021.129423
22) Ibrahim, I. D., Sadiku, E. R., Hamam, Y., Kupolati, W. K., Ndambuki, J. M., Jamiru, T., & Snyman, J. (2023). Recent recycling innovations to facilitate sustainable packaging materials: A review. *Recycling*, *8*(6), Article 88. https://doi.org/10.3390/recycling8060088
23) Ingrao, C., Tricase, C., Cholewa-Wójcik, A., Kawecka, A., Rana, R., & Siracusa, V. (2015). Polylactic acid trays for fresh-food packaging: A carbon footprint assessment. *Science of the Total Environment*, *537*, 385–398. https://doi.org/10.1016/j.scitotenv.2015.08.023
24) International Organization for Standardization. (2006a). *ISO 14040:2006 — Environmental management — Life cycle assessment — Principles and framework*. ISO. https://www.iso.org/standard/37456.html
25) International Organization for Standardization. (2006b). *ISO 14044:2006 — Environmental management — Life cycle assessment — Requirements and guidelines*. ISO. https://www.iso.org/standard/38498.html

26) International Organization for Standardization. (2013). *ISO 18602:2013 — Packaging and the environment — Optimization of the packaging system*. ISO. https://www.iso.org/standard/55870.html
27) Joltreau, E. (2022). Extended producer responsibility, packaging waste reduction and eco-design. *Environmental and Resource Economics*, *83*(3), 527–578. https://doi.org/10.1007/s10640-022-00696-9
28) Kadac-Czapska, K., Knez, E., Gierszewska, M., Olewnik-Kruszkowska, E., & Grembecka, M. (2023). Microplastics derived from food packaging waste — Their origin and health risks. *Materials*, *16*(2), Article 674. https://doi.org/10.3390/ma16020674
29) Kan, M., & Miller, S. A. (2022). Environmental impacts of plastic packaging of food products. *Resources, Conservation and Recycling*, *180*, Article 106156. https://doi.org/10.1016/j.resconrec.2022.106156
30) Kapoor, D. D., Madaan, P., Kumar, J., Tiwari, S. K., Gupta, K. K., & Gupta, R. K. (2025). Transition towards renewable and biodegradable polymers: A comprehensive review. *Journal of Polymer Research*, *32*(10), Article 278. https://doi.org/10.1007/s10965-025-04524-8
31) Keyes, A., Saffron, C. M., Manjure, S., & Narayan, R. (2024). Biobased compostable plastics end-of-life: Environmental assessment including carbon footprint and microplastic impacts. *Polymers*, *16*(21), Article 3073. https://doi.org/10.3390/polym16213073
32) Kim, S. Y., Kang, D. H., Charoensri, K., Ryu, J. R., Shin, Y. J., & Park, H. J. (2023). Comparative life cycle assessment of reusable and disposable distribution packaging for fresh food. *Sustainability*, *15*(23), Article 16448. https://doi.org/10.3390/su152316448
33) Kumrawat, A., & Unnikrishnan, S. (2025). Barriers hindering life cycle assessment implementation in packaging design to achieve carbon neutrality: A case study of emerging economy. *Environment, Development and Sustainability*, *27*(10), 24083–24106. https://doi.org/10.1007/s10668-025-06304-2
34) Maga, D., Hiebel, M., & Aryan, V. (2019). A comparative life cycle assessment of meat trays made of various packaging materials. *Sustainability*, *11*(19), Article 5324. https://doi.org/10.3390/su11195324
35) Mhaddolkar, N., Astrup, T. F., Tischberger-Aldrian, A., Pomberger, R., & Vollprecht, D. (2024). Challenges and opportunities in managing biodegradable plastic waste: A review. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *43*(6), 911–934. https://doi.org/10.1177/0734242x241279902
36) Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Beas, I. N. (2021). An overview of plastic waste generation and management in food packaging industries. *Recycling*, *6*(1), Article 12. https://doi.org/10.3390/recycling6010012
37) Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, Article n71. https://doi.org/10.1136/bmj.n71
38) Pålsson, H., & Olsson, J. (2023). Current state and research directions for disposable versus reusable packaging: A systematic literature review of comparative studies. *Packaging Technology and Science*, *36*(6), 391–409. https://doi.org/10.1002/pts.2722
39) Pauer, E., Wohner, B., Heinrich, V., & Tacker, M. (2019). Assessing the environmental sustainability of food packaging: An extended life cycle assessment including packaging-related food losses and waste and circularity assessment. *Sustainability*, *11*(3), Article 925. https://doi.org/10.3390/su11030925
40) Raźniewska, M. (2022). Compostable packaging waste management — Main barriers, reasons, and the potential directions for development. *Sustainability*, *14*(7), Article 3748. https://doi.org/10.3390/su14073748
41) Rezvani Ghomi, E., Khosravi, F., Saedi Ardahaei, A., Dai, Y., Neisiany, R. E., Foroughi, F., Wu, M., Das, O., & Ramakrishna, S. (2021). The life cycle assessment for polylactic acid (PLA) to make it a low-carbon material. *Polymers*, *13*(11), Article 1854. https://doi.org/10.3390/polym13111854
42) Sastre, R. M., de Paula, I. C., & Echeveste, M. E. S. (2022). A systematic literature review on packaging sustainability: Contents, opportunities, and guidelines. *Sustainability*, *14*(11), Article 6727. https://doi.org/10.3390/su14116727
43) Silva, N., & Pålsson, H. (2022). Industrial packaging and its impact on sustainability and circular economy: A systematic literature review. *Journal of Cleaner Production*, *333*, Article 130165. https://doi.org/10.1016/j.jclepro.2021.130165
44) Sokolova, T., Krishna, A., & Döring, T. (2023). Paper meets plastic: The perceived environmental friendliness of product packaging. *Journal of Consumer Research*, *50*(3), 468–489. https://doi.org/10.1093/jcr/ucad008
45) Surendarnath, S., Flora, G., & Ramesh, G. (2025). Plastic waste: Management strategies and challenges in the developing world. In *Solid Waste Management* (pp. 441–452). Springer. https://doi.org/10.1007/978-3-031-78420-0_19
46) Thapliyal, D., Karale, M., Diwan, V., Kumra, S., Arya, R. K., & Verros, G. D. (2024). Current status of sustainable food packaging regulations: Global perspective. *Sustainability*, *16*(13), Article 5554. https://doi.org/10.3390/su16135554
47) Torkelis, A., Dvarionienė, J., & Denafas, G. (2024). The factors influencing the recycling of plastic and composite packaging waste. *Sustainability*, *16*(21), Article 9515. https://doi.org/10.3390/su16219515
48) United Nations Environment Programme. (2022). *Turning off the tap: How the world can end plastic pollution and create a circular economy*. UNEP. https://www.unep.org/resources/turning-off-tap-end-plastic-pollution-create-circular-economy
49) United Nations Environment Assembly. (2022). *Resolution 5/14: End plastic pollution — Towards an international legally binding instrument* (UNEP/EA.5/Res.14). UNEP. https://wedocs.unep.org/handle/20.500.11822/39812
50) Van Eygen, E., Laner, D., & Fellner, J. (2018). Circular economy of plastic packaging: Current practice and perspectives in Austria. *Waste Management*, *72*, 55–64. https://doi.org/10.1016/j.wasman.2017.11.040
51) Wohner, B., Pauer, E., Heinrich, V., & Tacker, M. (2019). Packaging-related food losses and waste: An overview of drivers and issues. *Sustainability*, *11*(1), Article 264. https://doi.org/10.3390/su11010264



Corresponding Author: Irene Nganja Njende