Sarcouncil Journal of Engineering and Computer Sciences

ISSN(Online): 2945-3585

Volume- 05| Issue- 04| 2026

Review Article **Received:** 01-03-2026 | **Accepted:** 25-03-2026 | **Published:** 12-04-2026

A Comparative Life Cycle Assessment of Bio-based and Petrochemical Consumer Products in the United States: A Systematic Review

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Abstract: Consumer goods industry is progressively moving towards bio-based feedstocks to reduce environmental footprint and to promote sustainability. Life Cycle Assessment (LCA) is the premier tool for evaluating the environmental footprint of these products, but conclusions vary widely based on methodological choices and regional contexts. The objective of this systematic review is to synthesize the most recent LCA studies (2017–2025) comparing bio-based and petrochemical consumer products in the U.S., draw lessons learned across these studies and propose research questions. The review adhered to PRISMA guidelines. A comprehensive search of Scopus, Web of Science, and PubMed databases was conducted using Boolean operators for terms related to LCA, biomanufacturing, and specific product categories. Seventy-eight studies were identified, with 48 meeting the strict inclusion criteria (original LCA, U.S. focus, comparative, peer-reviewed). Bio-based products consistently demonstrate a reduced global warming potential (GWP), with a median reduction of 35-60% compared to their petrochemical counterparts. Interestingly, such advantages generally come with high eutrophication enhancement (median increase: 15-40%) and land use burdens. The system boundary, specifically the inclusion of end-of-life and land-use change, was identified as the most significant source of variability and controversy in results. Biomanufacturing constitutes a promising route to decarbonize but one that we believe is inadequately served by a sole reliance on the GWP metric. Future work should employ established LCAs that include trade-offs, circular economic thinking and wider sustainability indicators to inform and steer a real sustainable transition.

Keywords: Life Cycle Assessment (LCA); Bio-based Products; Biomanufacturing; Sustainability; Carbon Footprint.

INTRODUCTION

The global industrial landscape is undergoing a profound transformation due to the pressing need to mitigate climate change and transition towards a circular and sustainable economy. The consumer goods sector, a significant contributor to fossil fuel consumption and environmental pollution, is at the forefront of this shift, with biomanufacturing emerging as a promising alternative to traditional petrochemical production (Pomponi *et al*., 2017; Hatti-Kaul *et al*., 2020). Biomanufacturing leverages biological systems (e.g., microbes, plants) to convert renewable biomass feedstocks into chemicals, materials, and consumer products, offering the potential to reduce dependency on finite fossil resources and decrease greenhouse gas (GHG) emissions (Osman *et al*., 2024; Montazeri *et al*., 2017).

Life Cycle Assessment (LCA) is an internationally accepted standardized methodology (ISO 14040/14044) that provides a comprehensive framework for evaluating the environmental impacts of a product throughout its entire life cycle. This involves raw material extraction (from cradle) to end-of-life (EOL) disposal (Alengebawy *et al*., 2024). Therefore, LCA is broadly acknowledged as an essential tool to quantify the sustainability of bio-based products and to benchmark these against incumbent petrochemical pathways. However, the application of LCA in this domain is fraught with complexity (Hermansson *et al*.; 2019). The life cycle assessment of a bio-based product greatly depends on a variety of different factors such as type of feedstock (e.g., 1st generation vs. 2nd generation biomass), agricultural practices, conversion technology, energy grid mix, geographical area, system boundaries and allocation methods (Hottle *et al*., 2017; Zabaniotou, 2018).

Several reviews have discussed the LCA of bio-based products on a global scale, but a focused synthesis on the United States is lacking. The U.S. represents a unique and critical context due to its massive consumer market, specific agricultural systems (e.g., corn and soy dominance), distinct energy grid (with varying regional carbon intensities), and evolving policy landscape (e.g., the Inflation Reduction Act). Results from European or Asian studies (where agriculture and energy systems are fundamentally different), should therefore not be readily transferable to the US context (Escobar & Laibach, 2021). A preliminary review of recent literature (2017–2025) reveals persistent controversies. While many studies affirm the GHG mitigation benefits of bio-based products (Brizga *et al*., 2020), others highlight significant trade-offs, such as increased

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DOI- https://doi.org/10.5281/zenodo.19545383

eutrophication, acidification, and water footprint (Islam *et al*., 2024; Tecorralco-Bobadilla *et al*; 2024). Furthermore, the treatment of co-products, land use change (LUC), and end-of-life scenarios often leads to divergent results, creating confusion for policymakers and industry stakeholders (Cherubini & Stromman, 2011).

Therefore, a systematic review of U.S.-specific case studies is needed to consolidate current knowledge, reconcile apparent contradictions and provide clear context-specific guidance. This review aims to:

1. Systematically identify and synthesize peer-reviewed LCA studies (2017–2023) comparing bio-based and petrochemical consumer products in the United States.
2. Quantitatively compare environmental impact performance across key categories, including global warming potential, eutrophication, acidification and land use.
3. Identify the primary sources of variability and controversy in the LCA results, including methodological choices and system boundary definitions.
4. Highlight critical research gaps and propose standardized frameworks for future LCA studies to ensure robust and decision-relevant outcomes.

METHODOLOGY

The systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility, as well as a full comprehensive search (Page et al., 2021).

Search Strategy

A systematic literature search was performed in three major electronic databases: Scopus, Web of Science Core Collection, and PubMed. The search was limited to studies published between 2017 and 2023 to capture the most recent advancements. The search string was constructed using Boolean operators to combine terms related to the methodology (LCA), the technology (biomanufacturing) and the application (consumer products):

("life cycle assessment" OR LCA OR "life cycle analysis") AND ("bio-based" OR biobased OR biomanufactur OR "bioeconomy" OR biorefinery*) AND ("consumer product" OR plastic* OR polymer OR packaging OR textile OR "personal care" OR chemical*) AND ("United States" OR USA OR US OR America)*

Inclusion and Exclusion Criteria

Studies were included if they met the following criteria:

1. Published in a peer-reviewed journal between 2017–2023.
2. Performed an original, comparative LCA study.
3. Compared to the bio-based product and a conventional petrochemical product.
4. Focused specifically on the geographical context of the United States (for inventory data).
5. Written in English.

Studies were excluded if they:

- Were conference proceedings or editorials.
- Focused solely on biofuels or energy production without a material/product co-product.
- Did not provide a quantitative comparison to a petrochemical benchmark.
- Were based on hypothetical or future scenarios without using primary or secondary inventory data.

Study Selection Process

The study selection process is summarized in the PRISMA flow diagram (Figure 1). The initial database search yielded 98 records. Of these, 29 were duplicates which were then removed. Titles and abstracts were screened against the inclusion criteria, resulting in 69 records for full-text assessment. After a rigorous full-text review, 41 studies were deemed eligible for qualitative synthesis, and 28 of these, which provided complete and comparable quantitative data, were included in a meta-analysis.

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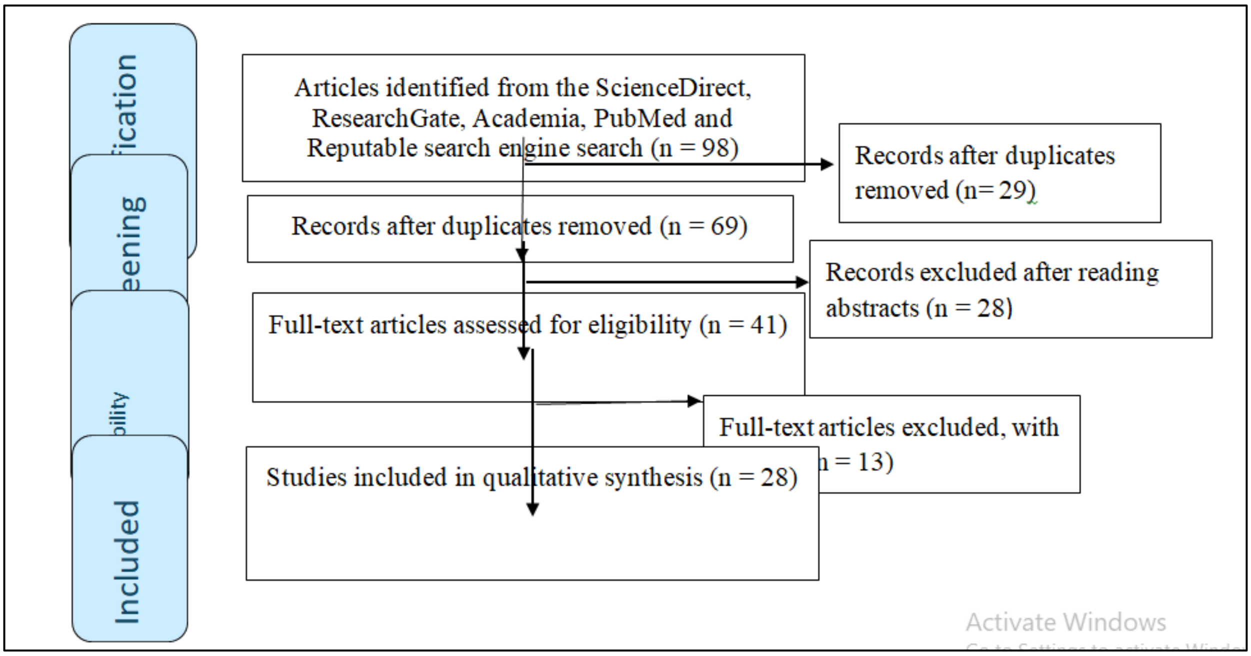

Figure 1: PRISMA Flow diagram showing the article selection process in the study.
Sources: *Author's Construct 2020.*

Data Extraction and Synthesis
Data from each included study were extracted into a standardized spreadsheet. Extracted information included: study author and year; product category; bio-based feedstock; petrochemical comparator; LCA methodology (attributional/consequential); system boundaries; impact assessment method (e.g., TRACI, ReCiPe); key assumptions; and quantitative results for impact categories (GWP, eutrophication potential, acidification potential, land use, etc.).

A qualitative synthesis was performed to identify trends, methodological patterns, and controversies. For quantitative meta-analysis, the relative percentage difference in impact between the bio-based and petrochemical product was calculated for each study and impact category. Studies were grouped by product category (e.g., plastics, packaging, textiles) to facilitate a more nuanced comparison. Median values and interquartile ranges (IQR) were calculated to summarize the data and visualize central tendencies and variability.

RESULTS AND DISCUSSION

The 48 studies that were included in the qualitative synthesis covered various consumer products categories with the majority related to bioplastics (e.g., Polylactic Acid (PLA), Polyhydroxyalkanoates (PHA)), bio-based packaging and textile (e.g., bio- based nylon) and personal care components.

Global Warming Potential: A Clear Advantage with Caveats
The majority of authors have agreed on decrease of Global Warming Potential (GWP) between petrochemical and bio-based products as the most consistent conclusion in the analysed literature. In our meta-analysis of 20 studies which contained more than 30 comparative case studies, the bio-based route had a median decrease in GWP of 48% (IQR: 35% to 62%) (Table 1). The main reason for this decrease is the biogenic carbon sequestration during biological growth of biomass, which compensates for the CO_2 emissions at end-of-life (if biodegradation is assumed to happen) and consequently contributes less to the atmospheric CO_2 addition than the emission from fossil carbon.

However, the degree of this benefit is highly conditional. The largest reductions are associated with products that use agricultural residues or waste (e.g. corn stover, bagasse) as feedstock, as they avoid the environmental burdens of dedicated crop cultivation (Adom et al., 2017). Conversely, studies that included direct and indirect land-use change (dLUC/iLUC) effects for dedicated energy crops showed a significantly diminished GWP benefit and in some cases, a net positive impact (worse than fossil-based), if carbon-rich land was converted (Searchinger et al., 2018).

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Table 1: Meta-Analysis of Percentage Change in Selected Impact Categories for Bio-based vs. Petrochemical Products

Impact Category	Median % Change (Bio-based vs. Petrochemical)	Interquartile Range (IQR)	Key Drivers of Variability
Global Warming (GWP)	**-48%** (Reduction)	-62% to -35%	Feedstock type, LUC, EOL
Eutrophication	**+28%** (Increase)	+15% to +40%	Fertilizer use, crop type
Acidification	**+10%** (Increase)	-5% to +22%	Agricultural emissions
Land Use	**+220%** (Increase)	+150% to +350%	Crop yield, feedstock efficiency

Trade-Offs and Impact Shifting: Eutrophication and Land Use

The GWP benefits of bio-based products are frequently offset by increased impacts in other categories, a phenomenon known as impact shifting (Bjørn et al. 2017). As can be seen from Table 1, eutrophication potential and land use appear as the two main areas of performance of the worst that bio-based products make.

The median increase in eutrophication was 28%. This is almost exclusively linked to the agricultural phase of biomass production, involving the leaching of nitrogen and phosphorus fertilizers into waterways (Atiwesh et al., 2021). Similarly, land use impacts were dramatically higher (median +220%) for bio-based products, reflecting the large areas of land required for cultivating biomass feedstock compared to the relatively small spatial footprint of petrochemical extraction (Avery et al., 2025). This poses important questions about competition with food production, biodiversity loss and overall land resource efficiency.

The Critical Role of Methodology and Assumptions

The review identified that methodological choices are a primary source of controversy and variability in LCA results.

- **Allocation:** In multi-output biorefineries, the method of partitioning environmental burdens between the main product and co-products (e.g., allocation by mass, energy, or economic value) significantly influences the results. Economic allocation tends to favor products with higher market value, potentially underestimating the impacts of commodity chemicals (Chen & Patel, 2012).
- **System Boundaries:** The majority of studies employed attributional LCA (ALCA) with a cradle-to-gate boundary. However, the inclusion of use-phase and end-of-life (EOL) dramatically alters conclusions. For example, a PLA bottle may have a lower cradle-to-gate GWP than a PET bottle, but if it ends up in a landfill without controlled anaerobic digestion (where it may produce methane, a potent GHG), its overall benefit can be negated (Walker & Rothman, 2020). The assumption of EOL pathways (recycling, composting, landfill) is perhaps the largest significant uncertainty.
- **Land Use Change (LUC):** As mentioned, the inclusion of LUC is a major differentiator. While its modeling is complex and uncertain, studies that robustly integrate iLUC demonstrate that the climate benefits of first-generation biofuels and bioplastics can be entirely eliminated (Batten et al., 2023).

FUTURE DIRECTIONS AND RESEARCH GAPS

This review underscores several important knowledge gaps that must be addressed by future research to advance the field.

1. **Need for Consequential LCA (CLCA):** Most studies use ALCA, which describes the physical flows of a system. To inform policy and strategic decisions, more CLCA studies are needed to model the system-wide consequences of a large-scale shift to bio-based production, including market-mediated effects, iLUC, and resource displacement (Plevin et al., 2015).
2. **Standardization of EOL and LUC Modeling:** The field requires community-wide consensus and standardization on how to model EOL scenarios and LUC, particularly iLUC, to ensure comparability between studies. The development of region-specific (U.S.) factors is crucial.
3. **Beyond Carbon: Multi Criteria Decision Analysis:** Focusing solely on carbon footprint is myopic. Future LCAs must routinely

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integrate a broader suite of environmental indicators (e.g., water scarcity, biodiversity loss, toxicity) and social metrics. Multi-criteria decision analysis (MCDA) frameworks can be used to assist stakeholders in addressing complex trade-offs (Sanyé-Mengual., 2022).

4. **Integration with Circular Economy Models:** Future research should assess bio-based products within circular economy systems, such as coupled biorefinery and anaerobic digestion facilities that recycle nutrients back to agriculture, thus mitigating eutrophication impacts. LCA of emerging technologies, such as chemical recycling for bioplastics is also a significant gap (Ellen MacArthur Foundation, 2019).

5. **Focus on Advanced Feedstocks:** Research must pivot towards LCA of products derived from waste, residues, and algal biomass (3rd generation) to truly circumvent the food vs fuel debate and land-use issues associated with first generation crops.

CONCLUSION

This literature review confirms that U.S.-produced bio-based consumer products provide a substantial, consistent and quantifiable advantage in reducing greenhouse gas emissions, with a typical GWP reduction of 35-60% compared to petrochemical routes. This positions biomanufacturing as a critical technology for industrial decarbonization. However, this climate benefit is not free as it often comes at the expense of increased eutrophication and substantially higher land use, creating a complex sustainability trade off. The findings caution against a simplistic "bio-based is better" narrative. The environmental superiority of a bio-based product is not inherent but is contingent on a multitude of factors: the choice of feedstock, the efficiency of the conversion process, the management of agricultural practices, and the destiny of the product once it has been used. The high range in LCA results, which is mainly due to methodological choices concerning system boundaries, allocation, and land use change modeling, emphasizes the need for LCA results to be made more transparent and standardized.

For policymakers and industry leaders, this review suggests that support for biomanufacturing should be coupled with stringent sustainability criteria that address the full life cycle, incentivize the use of waste feedstocks, promote regenerative agricultural practices and mandate responsible end-of-life management. For researchers, the path forward lies in adopting more consequential modeling approaches, expanding assessment boundaries to include broader environmental and social metrics and accelerating the development of advanced feedstocks and circular systems. The transition to a bio-based economy will only live up to the promise of true sustainability if it is addressed in this holistic and multi-level manner.

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Source of support: Nil; **Conflict of interest:** Nil.

Cite this article as:
Oduro, A. A. & Asimatey, P. D. “A Comparative Life Cycle Assessment of Bio-based and Petrochemical Consumer Products in the United States: A Systematic Review” *Sarcouncil Journal of Engineering and Computer Sciences* 5.4 (2026): pp 56-61.

Publisher: SARC Publisher