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(RESEARCH ARTICLE)

Landfilling vs. recycling in the U.S.: A policy and systems perspective on carbon footprint and end-of-life uncertainty

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Abstract

This study compares the environmental impacts of landfilling and recycling in the U.S., focusing on greenhouse gas emissions, predictability, and circular economy outcomes. Using qualitative thematic analysis of secondary data from EPA reports, peer-reviewed articles, and case studies, the research highlights that landfills provide predictable methane emissions under regulatory monitoring, while recycling outcomes vary due to contamination, downcycling, and global trade dependencies. Findings indicate that recycling offers significant potential for emissions reduction and economic benefits, but these gains require infrastructure investment and policy support. The paper concludes that integrating predictable landfill management with optimized recycling strategies is essential for achieving sustainability goals.

Keywords: Landfilling; Recycling; Greenhouse Gas Emissions; Circular Economy; Waste Management; Sustainability

1. Introduction

Municipal solid waste (MSW) generation in the United States reached 292.4 million tons in 2018, equal to 4.9 pounds per person per day, yet only 32.1% was diverted through recycling and composting [1]. Despite decades of investment, recycling rates have stagnated, while 146.1 million tons of MSW were landfilled, largely food waste (24%), plastics (18%), and paper (12%) [1]. Global market disruptions, notably China's National Sword policy, further destabilized export-dependent recycling systems by restricting imports of mixed paper and plastics, increasing contamination challenges and pushing recyclable materials back into landfills [2,3].

At the same time, declining landfill capacity, longer haul distances, and rising regulatory requirements have increased tipping fees to over $50 per ton nationally [4]. Landfills also remain a major climate concern, generating 110.7 million metric tons of CO_2-equivalent of methane in 2018, making them the third-largest source of anthropogenic methane emissions in the U.S. [5]. While engineered landfills offer predictable emissions trajectories through methane capture and post-closure monitoring [11,13], they contribute minimally to circular economy goals. Conversely, recycling is promoted for resource conservation and emissions reduction, yet its actual performance varies widely due to contamination, downcycling, processing energy intensity, and export to regions with weaker environmental oversight [2,15].

This study compares landfilling and recycling from a policy and systems perspective, emphasizing predictability versus uncertainty in end-of-life pathways. By analyzing emissions patterns, operational challenges, and policy frameworks, the research aims to inform strategies that improve carbon accounting accuracy and support sustainable waste management in the U.S. This analysis is critical given global projections that waste generation will rise from 2.1 billion tons in 2023 to 3.8 billion tons by 2050, with economic costs increasing from USD 361 billion to USD 640.3 billion [8]. The U.S. context, with over 2,500 MSW landfills, half still operational, and more than 532 landfill-gas-to-energy systems

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[10, 11, 12], highlights the importance of evaluating end-of-life options that balance environmental impact, system reliability, and policy feasibility.

1.1. Objectives and Research Questions

This study addresses the gap in understanding how predictability versus uncertainty in end-of-life waste pathways influences carbon accounting and sustainability reporting. While recycling is widely assumed to be environmentally superior, real-world performance is highly variable due to contamination, downcycling, and export dependence. Conversely, landfills, though criticized, offer predictable emissions trajectories under U.S. regulatory standards.

Objectives

- Assess the predictability of emissions and environmental impacts from U.S. landfill operations, including post-closure standards and methane capture.
- Investigate uncertainties in recycling pathways, contamination, export trends, and downcycling, and their effects on carbon footprint reporting.
- Examine policy and system implications of these differences, especially regarding circular economy goals and greenhouse gas inventories.
- Recommend strategies to improve transparency and accountability in waste management reporting.

Research Questions

- How do U.S. landfill practices ensure stable emissions and long-term environmental control?
- What uncertainties exist in recycling pathways, and how do they affect carbon footprint reporting?
- What policy and system implications arise from differences in predictability and uncertainty between landfilling and recycling?

2. Literature Review

Municipal solid waste (MSW) management has been widely studied, with research comparing landfilling and recycling primarily through life-cycle assessments (LCAs). Global waste generation is projected to reach 3.8 billion tons by 2050, increasing pressure on governments to adopt sustainable disposal systems [8,9]. In the U.S., engineered landfills remain the dominant end-of-life option despite decades of recycling advocacy [1,2, 3].

2.1. Landfilling Systems and Predictability

Modern U.S. landfills are highly regulated under the Resource Conservation and Recovery Act (RCRA) and 40 CFR Part 258, incorporating liner systems, leachate collection, and methane capture technologies [6,13,14]. Studies highlight that landfills provide relatively predictable emissions trajectories, enabling stable carbon accounting compared to more variable waste pathways [11,13]. Methane emissions remain a major concern, as landfills are the third-largest source of anthropogenic methane in the U.S. [5,7]. However, landfill gas-to-energy (LFGTE) projects, over 532 currently operating, convert captured methane into renewable energy, partially offsetting emissions [12]. While economically viable, rising tipping fees and limited capacity challenge long-term sustainability [4].

2.2. Recycling Systems and Uncertainty

Recycling is promoted as a cornerstone of the circular economy, reducing resource extraction and emissions. Yet its performance is highly variable due to contamination, downcycling, and reliance on global trade [2,3,15]. The 2018 China National Sword policy disrupted international recyclables markets, forcing many U.S. municipalities to landfill materials previously exported [2]. Contamination rates in U.S. curbside programs average 17–25%, and Material Recovery Facility (MRF) rejection rates can reach 30%, reducing actual recovery [16]. Export dependence further complicates carbon accounting, as materials may be improperly processed abroad [19]. While LCAs generally favor recycling under ideal conditions, real-world inefficiencies often diminish these benefits [15].

2.3. Carbon Accounting Challenges

LCAs assume optimal recycling conditions, uniform contamination rates, and stable markets, assumptions rarely met in practice. Conversely, landfill emissions are easier to model due to controlled conditions and regulatory oversight [11,13]. This contrast underscores the need to examine predictability versus uncertainty in waste pathways, particularly for greenhouse gas inventories and sustainability reporting.

2.4. Policy and Systems Perspective

Federal climate initiatives, including the Inflation Reduction Act and EPA's Methane Emissions Reduction Program, prioritize landfill methane mitigation [6,7]. Recycling policies remain fragmented across states, creating inconsistent outcomes. Literature suggests that aligning waste policy with carbon accounting accuracy requires acknowledging landfill stability and addressing recycling system uncertainties through infrastructure investment and extended producer responsibility (EPR) programs [2,3].

2.5. Summary of Gaps Identified in Literature

Overall, the literature reveals a clear gap: while extensive research compares the environmental impacts of recycling and landfilling through life-cycle assessments, few studies examine these systems through a policy and systems perspective focused on predictability versus uncertainty. Existing research often assumes stable recycling markets and high material recovery rates, overlooking real-world systemic constraints that influence carbon footprint outcomes. This gap underscores the need for research that evaluates not only environmental impacts but also the reliability of each end-of-life pathway for carbon reporting and sustainability decision-making.

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3. Materials and Methodology

This study adopts a qualitative comparative analysis rather than a full life-cycle assessment (LCA), justified by three factors:

- Variability in recycling outcomes (contamination, export, downcycling) makes quantitative modeling unreliable without primary data.
- The research aims to explore policy and system implications, requiring thematic interpretation.
- Existing secondary data from authoritative sources (EPA, OECD, peer-reviewed studies) provide sufficient evidence for comparing predictability versus uncertainty in end-of-life pathways.

3.1. Data Sources and Rationale

Data was drawn exclusively from secondary sources selected for credibility and relevance

Table 1 Summary of Secondary Data Sources Used in the Study

Source	Purpose	Key Metrics Extracted
EPA WARM Model	Estimate GHG emissions	CO_2-equivalent emissions per ton
EPA GHG Inventory	Assess landfill methane emissions	Annual methane emissions (MMT CO_2e)
EPA Recycling Infrastructure Assessment	Identify recycling contamination and operational challenges	Contamination %, MRF rejection rates
Academic Reviews & Case Studies	Examine recycling uncertainties and global trade	Downcycling trends, export dependency
OECD & UNEP Reports	Global waste management context	Projected waste generation and trade flows

3.2. Analysis Steps

- Data Extraction: Gathered key metrics from EPA reports, WARM model, and literature.
- Thematic Coding: Classified findings into three categories, landfill predictability, recycling uncertainty, and policy implications.
- Comparative Assessment: Evaluated the impact of predictability versus uncertainty on carbon accounting and circular economy outcomes.
- Policy Mapping: Linked findings to U.S. regulatory frameworks (RCRA, MERP) and global sustainability targets (SDG 12.3).

3.3. Rationale for Conceptual Comparison

A conceptual approach integrates technical, economic, and policy dimensions without relying on assumptions that can distort LCAs (e.g., ideal contamination rates or stable global markets). This method provides actionable insights for policymakers and practitioners aiming to improve transparency and accountability in waste management reporting.

4. Results and Discussion

4.1. Landfilling

Modern U.S. landfills operate under strict standards, including liners, leachate collection, and methane capture systems [13,14]. In 2022, methane emissions from municipal solid waste and industrial landfills were 100.9 MMT CO_2e and 18.9 MMT CO_2e, respectively [10]. Regulatory post-closure monitoring and methane capture systems (50–75% efficiency) provide predictable emissions trajectories, supporting reliable carbon accounting and compliance with federal programs such as the Methane Emissions Reduction Program (MERP) [10].

Limitations: Landfills occupy large areas, require decades of monitoring, and contribute minimally to circular economy objectives. Long-term environmental risks include groundwater contamination and biodiversity disruption.

Policy Implication: Landfills provide a stable baseline for greenhouse gas inventories but cannot achieve material recovery goals. Integration with organics diversion and recycling remains essential.

4.2. Recycling

Recycling has the potential to reduce up to 96 MMT CO_2e annually and could create 370,000 full-time equivalent jobs if optimized [7]. However, performance is highly variable due to contamination (17–25%) and MRF rejection rates (15–30%) [16]. Global trade adds uncertainty, as exported recyclables may be landfilled or incinerated abroad. Downcycling reduces the material substitution potential, limiting climate benefits [20].

Policy Insight: Extended Producer Responsibility (EPR), deposit-return systems, and investments in domestic infrastructure and advanced sorting technologies are critical to improving recycling outcomes and reducing systemic uncertainty.

4.3. Comparative Insights

Landfills provide predictable emissions, supporting stable carbon accounting but limited circular economy benefits. Recycling offers higher potential for emissions reduction and job creation but suffers from systemic uncertainties due to contamination, downcycling, and global trade.

Integrated Approach: Combining predictable landfill management with optimized recycling strategies maximizes environmental benefits. National recycling policies must consider global market dynamics to avoid unintended consequences and fully achieve sustainability and circular economy goals.

Limitations

This study relies exclusively on secondary data from EPA reports, academic literature, and global waste management assessments. While these sources are authoritative, they may not capture regional variations in landfill or recycling operations. Quantitative modeling was not performed, limiting the ability to provide precise emission estimates. Findings reflect national averages and conceptual comparisons rather than site-specific data. Additionally, the absence of primary field research restricts insights into operational practices and emerging technologies. Future studies should include city-level audits, real-time GHG measurements, and longitudinal tracking of recycling performance to strengthen empirical validity.

5. Conclusion

Landfilling and recycling represent two contrasting approaches to waste management in the U.S. Landfills offer predictable emissions trajectories, supporting reliable carbon accounting, but contribute minimally to circular economy objectives. Recycling, while less predictable, has the potential to significantly reduce greenhouse gas emissions and conserve resources, provided contamination, downcycling, and export uncertainties are addressed.

Achieving sustainability goals requires an integrated strategy:

- Maintain predictable landfill management with methane capture systems.
- Optimize recycling through domestic infrastructure, policy harmonization, and public engagement.
- Incorporate Extended Producer Responsibility (EPR) and deposit-return systems to strengthen material recovery.

By combining predictability with systemic improvements, the U.S. can advance toward accurate carbon accounting, circular economy objectives, and climate mitigation targets.

Compliance with ethical standards

Disclosure of conflict of interest

The author declares no conflict of interest.

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