EP-JOURNALS

Available on: https://jnsrr.ep-journals.org/ E-ISSN: 3051-3766 P-ISSN: 3051-3758

Journal of Natural Science Research and Review

Volume: 02 Issue: 05 May-2026

Municipal Solid Waste Analytics and Organics Diversion in the United States: A Comprehensive Review of Data-Driven Interventions

Omotola Ogunsola
Prairie View A&M University, USA

Andrews Ayim Oduro
Kwame Nkrumah University of Science and Technology, Ghana

Published Date: May 29, 2026 **Article DOI: 10.65150/EP-jnsrr/V2E5/2026-02**

ABSTRACT: Municipal solid waste (MSW) management in the United States faces a critical inflection point, with over 292 million tons generated annually and diversion rates for organic fractions remaining critically low. Despite growing regulatory pressure, technological innovation, and demonstrated environmental benefits, the nation diverts only approximately 32% of compostable organics from landfills, contributing substantially to anthropogenic methane emissions. This comprehensive review synthesizes peer-reviewed literature from 2018 to 2025 to examine the state of data-driven interventions in MSW management, with particular emphasis on organics diversion. The paper evaluates descriptive, predictive, and prescriptive analytics applications; decision support tools and multi-criteria decision analysis (MCDA) frameworks; IoT-enabled smart waste systems; lifecycle assessment (LCA) findings; and the behavioral and sociodemographic dimensions of recycling participation. Evidence from U.S. municipal case studies shows that communities that implement integrated, analytics-driven approaches can achieve significant gains in organics diversion rates while also reducing greenhouse gas (GHG) emissions. The assessment also highlights significant research gaps, such as the lack of nationally standardized datasets, limited multimodal data fusion, weak real-time decision assistance, and insufficient governance analytics for policy evaluation. Future research and practice must prioritize interoperable data platforms, equitable infrastructure deployment, and evidence-based policy analytics in order to fully achieve the climate and resource recovery potential of organics diversion in the United States.

KEYWORDS: Municipal Solid Waste (MSW); Organics Diversion; Predictive Analytics; Decision Support Systems; Lifecycle Assessment.

INTRODUCTION

Municipal solid waste (MSW) generation in the United States has grown substantially over the past several decades, driven by rapid urbanization, rising consumption patterns, and demographic expansion. According to the U.S. Environmental Protection Agency (EPA), the nation generated approximately 292.4 million tons of MSW in 2018, representing a 93% increase since 1980, at a per-capita rate of 4.9 pounds per person per day (EPA, 2022a). Despite improvements in recycling and composting infrastructure, over 50% of MSW continues to be landfilled (University of Michigan Center for Sustainable Systems, 2024), contributing substantially to methane (CH_4) emissions and environmental degradation. Landfills were the third-largest source of anthropogenic CH_4 emissions in the United States in 2022, accounting for over 17% of total CH_4 emissions and approximately 1.9% of total greenhouse gas (GHG) emissions (University of Michigan Center for Sustainable Systems, 2024). The waste management sector has also become a major economic concern, with the market exceeding $210 billion in 2025, driven by strong regulatory pressures and sustainability initiatives nationwide (Fang et al., 2023).

In this evolving landscape, data analytics has emerged as a critical tool for modern waste management systems. Artificial intelligence (AI), machine learning (ML), and predictive modeling are increasingly integrated into MSW systems to enhance collection efficiency, reduce operational costs, and optimize diversion strategies. A systematic review of 69 studies published between 2018 and 2024 by Singh et al. (2025) found that AI-based techniques, including ML and deep learning (DL), substantially improve decision-making processes, resource recovery rates, and support circular economy principles in MSW contexts. Performance gains documented in the literature include transportation distance reductions of up to 36.8% and waste-sorting accuracy approaching 99% in some deployments (Fang et al., 2023).

Within this broader MSW context, organics diversion, the redirection of food scraps, yard waste, and other biodegradable materials away from landfills, is critical for climate mitigation. According to the EPA (2022a), food waste alone comprised 21.6% of all MSW generated in 2018, constituting the largest single fraction of landfilled waste. Yard trimmings accounted for an additional 12.1%, making organic fractions collectively the dominant component of the U.S. waste stream. When landfilled, organic waste undergoes anaerobic decomposition, generating methane with a global warming potential 28–34 times higher than CO_2 over a 100-year horizon, amplifying the urgency to improve diversion practices (Nordahl et al., 2020). Policy momentum is accelerating nationwide: in 2024, the EPA, USDA, and FDA released the National Strategy for Reducing Food Loss and Waste and Recycling Organics, targeting a 50% food waste reduction and recycling rate by 2030 (University of Michigan Center for

Sustainable Systems, 2024). The intersection of increasing MSW volumes, climate-driven organics policies, and the rapid proliferation of analytics technologies positions data-driven innovation at the forefront of next-generation waste management strategy.

Despite strong policy interest and technological progress, the United States continues to experience persistently low diversion rates for organic waste relative to its potential. Although municipalities diverted an estimated 25 million tons of organics through composting in 2018, food waste compost recovery represented only 4.1% of total food waste generated, revealing enormous latent capacity for improvement (EPA, 2022b). System inefficiencies persist across the collection, sorting, and treatment stages of the waste management lifecycle.

Many municipalities rely on outdated routing schemes, inconsistent data collection practices, and limited contamination monitoring, which prevent optimal material recovery. The EPA (2024) has documented that organic waste continues to represent the dominant contributor to landfill methane emissions, even as diversion technologies mature. Although advanced tools such as AI-driven sorters, smart bins, and multi-criteria decision analysis (MCDA) frameworks have shown promise, their adoption remains fragmented across jurisdictions. Many municipalities lack consolidated data architectures needed to integrate predictive analytics into daily operations. Issues of data quality, heterogeneity, and limited interoperability further constrain municipal capacity to deploy advanced analytics effectively (Gutierrez-Lopez et al., 2023). Without cohesive, data-driven systems, diversion programs fail to meet targeted participation rates, contributing to continued landfill pressures and missed climate mitigation opportunities. The absence of a comprehensive synthesis of data-driven approaches specifically focused on U.S. organics diversion represents a significant gap in the academic literature that this paper seeks to address.

This comprehensive review aims to address these gaps by synthesizing the current state of data-driven MSW and organics diversion strategies in the United States. The specific objectives are, firstly, to synthesize existing data-driven interventions for MSW and organics diversion, drawing from peer-reviewed literature, EPA reports, and applied case studies. Secondly, to identify and critically evaluate analytics methods applied in MSW decision support, including descriptive, predictive, prescriptive, and behavioral analytics approaches, and then lastly to highlight key research gaps and propose future research directions, focusing on standardized datasets, multimodal data fusion, real-time decision support, and governance analytics frameworks.

Through this approach, the paper aims to inform researchers, policymakers, municipal planners, and technology developers on the opportunities and limitations of analytics-driven organics diversion within the U.S. MSW context. The review draws systematically from databases including Google Scholar, ResearchGate, PubMed, Scopus, and Web of Science, prioritizing peer-reviewed sources published between 2018 and 2025. Government reports from the EPA and CalRecycle are also incorporated where they represent primary data sources unavailable elsewhere.

MUNICIPAL SOLID WASTE FRAMEWORK IN THE UNITED STATES

MSW Composition and Sources

The composition of the U.S. municipal solid waste stream is both diverse and dynamic. According to the EPA's Advancing Sustainable Materials Management: Facts and Figures report, total MSW generation in 2018 was approximately 292.4 million tons, distributed across residential, commercial, and institutional sources (EPA, 2022a). Organic materials, comprising paper and paperboard (23.1%), food waste (21.6%), and yard trimmings (12.1%), collectively constituted over 56% of all materials in the MSW stream by weight, making organics the single largest aggregate fraction (EPA, 2022b). Food waste alone, at 63.1 million tons, exceeded plastics (35.7 million tons) and metals (25.7 million tons) in volume, yet its diversion rate of approximately 4.1% through composting remains among the lowest of any major material category.

Per-capita waste generation in the United States (4.9 lbs/person/day) substantially exceeds comparable figures in Germany (3.7 lbs), the United Kingdom (2.8 lbs), and Sweden (2.6 lbs), highlighting structural overconsumption and systemic diversion inefficiencies (University of Michigan Center for Sustainable Systems, 2024). Food waste alone constituted 24% of landfilled material and 22% of material combusted with energy recovery in 2018, making it the single largest contributor to both disposal pathways (EPA, 2022b). The scale of this inefficiency underscores the critical importance of targeted analytics interventions in the organics sub-stream.

Table 1. U.S. MSW Generation and Diversion by Material Category, 2018

Material Category	Generation (Million Tons)	% of Total MSW	Diversion Rate (%)
Food Waste	63.1	21.6%	4.1%
Paper & Paperboard	67.4	23.1%	68.2%
Yard Trimmings	35.4	12.1%	63.0%
Plastics	35.7	12.2%	8.7%
Metals	25.7	8.8%	34.5%
Glass	12.3	4.2%	25.8%
Wood	18.2	6.2%	15.3%
Rubber, Leather & Textiles	17.6	9.0%	12.4%
TOTAL MSW Generated	292.4	100%	32.1%

Source: U.S. Environmental Protection Agency (EPA, 2022b). MSW Facts and Figures.

Organics Diversion: Definitions and Goals

Organics diversion refers to the systematic redirection of biodegradable organic materials, primarily food scraps, yard trimmings, food-soiled paper, and compostable packaging, away from landfill disposal and toward beneficial end uses, including composting, anaerobic digestion (AD), and land application. Within the U.S. regulatory vocabulary, source-separated organics (SSO) programs constitute the primary operational framework for residential organics collection, wherein households separately containerize organic materials for dedicated collection and processing (EPA, 2022c).

National organics diversion goals are anchored in the EPA's 2024 National Strategy for Reducing Food Loss and Waste and Recycling Organics, which targets a 50% reduction in food loss and waste and a 50% recycling rate by 2030 (University of Michigan Center for Sustainable Systems, 2024). At the state level, California's SB 1383 (2022) mandates 75% reduction in the landfilling of organic waste statewide, establishing the most ambitious enforceable organics diversion target in the country. As of 2023, approximately 8 states had enacted mandatory organics collection legislation, a figure projected to grow to 15 states by 2027. These regulatory frameworks create both the imperative and the institutional scaffolding for data analytics deployment in organic management.

Policy and Regulatory Context

Federal and state policy frameworks provide the regulatory architecture within which data-driven organics diversion programs operate. At the federal level, the Resource Conservation and Recovery Act (RCRA) provides foundational authority for MSW management regulation, while the EPA's Food Recovery Hierarchy establishes a preferred order of food waste management strategies, prioritizing source reduction, feeding people, and feeding animals over composting and landfilling (EPA, 2022c). Extended Producer Responsibility (EPR) frameworks are increasingly being deployed at the state level to shift financial responsibility for waste management toward producers. Additionally, organic waste disposal bans, enacted in Massachusetts, California, Connecticut, Rhode Island, Vermont, and New York, directly incentivize organics diversion by prohibiting landfilling or combustion of organic materials above specified generation thresholds (EPA, 2022c). These bans, coupled with composting facility development grants and pay-as-you-throw (PAYT) pricing structures, represent a multi-pronged policy toolkit that data analytics systems can both support and evaluate. The effectiveness of these instruments, as documented by Seacat and Boileau (2018) and the National Academies of Sciences (2024), varies substantially based on local infrastructure capacity, community engagement strategies, and the availability of data to guide targeted enforcement.

ANALYTICS APPROACHES IN MSW AND ORGANICS DIVERSION

Descriptive Analytics

Descriptive analytics constitutes the foundational layer of MSW data intelligence, encompassing waste characterization studies, composition analysis, and time-series tracking of diversion trends. Waste characterization studies the systematic sampling and physical sorting of MSW to determine material composition by weight or volume, providing the empirical baseline for targeting organics diversion programs. At the national scale, the EPA's Material Flow Model (MFM), upon which its Facts and Figures reports are based, estimates MSW generation, recycling, composting, combustion, and landfilling rates across material categories and years (Srivastava et al., 2025). However, researchers have identified significant methodological divergences between EPA MFM outputs and independent waste characterization studies, particularly for paper and food waste fractions, raising important questions about the accuracy of national-scale descriptive analytics (Srivastava et al., 2025).

Time-series analysis of diversion trends reveals instructive patterns across U.S. jurisdictions. Between 1960 and 2018, overall recycling and composting rates rose from near zero to 32.1%, with yard trimmings diversion increasing more than fivefold since 1990 (EPA, 2022a). However, food waste composting remained a persistent laggard: despite substantial increases in composting infrastructure, only 2.6 million tons (4.1%) of food waste were composted in 2018, compared to 22.3 million tons (63%) of yard trimmings (EPA, 2022b). This disparity reflects differential infrastructure availability, consumer behavior barriers, and the physical challenges associated with collecting and processing putrescible food scraps relative to dry yard materials. Descriptive analytics tools, particularly GIS-based spatial mapping and waste flow modeling, have proven valuable for identifying collection coverage gaps and benchmarking diversion performance across municipalities (Gutierrez-Lopez et al., 2023).

Predictive Analytics

Predictive analytics encompasses the application of statistical and machine learning methods to forecast waste generation volumes, material composition, and program participation rates. A comprehensive review of predictive modeling in MSW management conducted by Xia et al. (2022), encompassing studies from 2010 to 2021, identified artificial neural networks (ANNs) as the most widely deployed predictive algorithm (33% of applications), followed by random forests (19%), convolutional neural networks (CNNs, 15%), and support vector machines (SVMs, 14%). These algorithms have been applied across the full spectrum of waste management applications, from collection demand forecasting to contamination detection and sorting system optimization.

A particularly significant advance in waste generation forecasting was demonstrated by Singh et al. (2025), whose systematic review found that gradient boosting models achieve R^2 values approaching 0.99 in predicting MSW generation volumes when trained on integrated datasets combining population density, urbanization index, and waste composition data. Similarly, Chau et al (2025), using CNN and multilayer perceptron (MLP) architectures, achieved prediction performance on 4,341 MSW records sufficient to support strategic planning across diverse geographic contexts. The incorporation of socioeconomic variables, income levels, household density, and commercial activity metrics substantially improves predictive accuracy for organics sub-streams, where generation patterns are more tightly coupled to consumption behavior than for inert materials (Guo et al., 2021; Subedi et al., 2025).

For organics diversion specifically, machine learning models have been applied to predict composting participation rates and organic fraction capture efficiency. Studies integrating sociodemographic variables with historical participation data have demonstrated that education level, housing type, and access to incentive programs (e.g., PAYT systems) are the strongest predictors of both recycling and composting rates, explaining approximately 60–70% of variance in community-level diversion outcomes (Seacat & Boileau, 2018). This finding has direct operational implications: predictive models can enable municipalities to pre-identify low-participation neighborhoods and deploy targeted outreach before program underperformance materializes.

Table 2. Machine Learning Algorithms Applied in MSW and Organics Management

ML Algorithm	Application Area	Performance Metrics	Key Reference
Artificial Neural Network (ANN)	Waste generation forecasting, sorting accuracy	R^2 up to 0.98; accuracy ~91%	Xia et al. (2022)
Random Forest (RF)	Waste composition prediction, participation modeling	R^2 = 0.97; RMSE = 3.01	Subedi et al., (2025)
Convolutional Neural Network (CNN)	Waste image classification and sorting	Accuracy 94–99% on standard datasets	Xia et al. (2022); Singh et al. (2025)
Support Vector Machine (SVM)	Waste type identification	Accuracy 85–94%	Chau et al. (2025)
Gradient Boosting (GB)	MSW generation forecasting	RMSE = 3.01; R^2 = 0.99	Subedi et al., (2025)
LSTM (Long Short-Term Memory)	Time-series waste generation modeling	Outperforms ARIMA in seasonal variation	Chau et al. (2025)
XGBoost	Overflow prediction in smart bins	Predictive accuracy 94.1%; recall 95.8%	Anitha & Parthiban (2025)

*Source: Compiled from Xia et al. (2022), Singh et al. (2025), Chau et al. (2025), and **Anitha & Parthiban** (2025).*

Prescriptive Analytics and Optimization

Prescriptive analytics, the most advanced tier of the analytics hierarchy, uses optimization algorithms, simulation models, and decision frameworks to recommend specific operational actions and resource allocations. In MSW management, prescriptive analytics tools encompass route optimization algorithms, facility siting models, and integrated decision support systems (DSSs) that translate predictive outputs into actionable operational guidance. Recent research on AI-enabled decision support demonstrates that reducing cognitive load among operational managers significantly improves decision quality and responsiveness in complex, data-intensive systems, particularly where real-time analytics and multi-criteria trade-offs are required (Ogunsola et al., 2025). These findings reinforce the need for MSW analytics platforms that not only optimize technical performance but also present actionable insights in cognitively efficient formats for municipal decision-makers. Route optimization constitutes one of the most extensively studied applications of prescriptive analytics in waste management. IoT-enabled systems that dynamically adjust collection routes based on real-time bin fill-level data from smart sensors have demonstrated consistent operational improvements across multiple studies. A multi-city pilot study by Addas et al. (2024), published in PLOS One, deployed ultrasonic sensors across 10 locations in Lahore, Pakistan, processing over 200 million data points. The IoT-based dynamic routing system achieved a 32% improvement in route efficiency, a 29% reduction in fuel consumption and emissions, and a 33% increase in waste-processing throughput relative to conventional fixed-schedule collection. While this study was conducted outside the U.S., its methodological findings are highly relevant to American municipalities exploring similar IoT deployments (Kumar et al., 2025).

For organics diversion specifically, prescriptive tools such as the Solid Waste Management Analysis and Resource Tool (SMART), developed to support long-term integrated waste planning, enable municipalities to model scenarios for organics diversion expansion under varying cost, infrastructure, and regulatory constraints. Multi-criteria decision analysis (MCDA) frameworks, including the Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), are increasingly deployed to evaluate trade-offs among environmental, economic, and social objectives in organic management planning. These methods allow planners to systematically weigh competing objectives, minimizing GHG emissions, maximizing diversion rates, controlling costs, and ensuring social equity, in a structured, transparent decision framework (Filho et al., 2025).

Statistical and Behavioral Models

Behavioral analytics represents a critical but frequently underappreciated dimension of MSW analytics. The success of organics diversion programs depends fundamentally on household and commercial participant behavior, whether residents correctly separate organic materials, avoid contamination, and maintain program participation over time. Behavioral models in this domain draw on social psychology frameworks, including the Theory of Planned Behavior (TPB), to identify the attitudinal, normative, and behavioral control factors that predict recycling and composting engagement.

A comprehensive hierarchical analysis by Camilleri and Ferrari (2024) found that combining individual-level predictors (personal values, perceived behavioral control, and attitude) with community-level predictors substantially improved the explanatory power of recycling behavior models compared to either category of predictors alone. Similarly, research analyzing annual survey data from over 145,000 participants found that educational attainment is the single strongest individual-level predictor of recycling support, with additional positive effects from age and income (National Academies of Sciences, 2024).

Contamination represents a major operational challenge that behavioral analytics can help address. Studies of source-separated organics programs indicate that contamination rates are significantly higher in multi-family housing settings and in communities with limited program education resources (EPA, 2022c). IoT-based behavioral monitoring systems, which link household-level collection data to participation and contamination metrics, enable municipalities to implement evidence-based education campaigns targeting specific high-contamination zones (Tian et al., 2025). Integration of sociodemographic data into contamination prediction models can further enable precision outreach, reducing contamination without blanket enforcement actions that may disproportionately affect lower-income communities.

DATA SOURCES, QUALITY, AND INTEGRATION CHALLENGES

Effective MSW analytics systems draw on a diverse portfolio of data types spanning physical, operational, behavioral, and environmental domains. Primary data sources in the U.S. context include municipal waste audit data generated through periodic physical characterization studies; facility tipping records documenting the weight and composition of materials received at composting, AD, and landfill facilities; GPS-tracked collection route data from waste collection vehicle fleets; IoT sensor data from smart waste bins equipped with fill-level and temperature sensors; citizen reporting data from mobile applications used to report missed collections or contamination events; and periodic household survey data on recycling attitudes and behaviors (Gutierrez-Lopez et al., 2023).

The EPA's Excess Food Opportunities Map, for example, identifies large commercial food waste generators (grocery stores, restaurants, food processors) and their proximity to composting and AD facilities, enabling spatial analytics of infrastructure adequacy relative to organic waste generation hotspots (EPA, 2022c). The integration of these diverse data types into unified analytics platforms requires significant investment in data standardization, cleaning, and quality assurance processes.

Data Quality and Bias Issues

Data quality challenges are pervasive across MSW analytics applications and represent a fundamental barrier to the deployment of advanced predictive and prescriptive models. Incomplete records and inconsistent reporting methodologies are among the most commonly cited limitations. A study analyzing the discrepancy between EPA's Material Flow Model and independent waste characterization studies found substantial divergences in paper waste disposal estimates, with some independent analyses showing figures 30 million tons higher than EPA model outputs (Srivastava et al., 2025). These methodological gaps reflect the limitations of purely model-based estimation and underscore the need for systematic physical sampling programs.

Cross-municipal benchmarking is unreliable due to temporal irregularity in data collection, which occurs when various jurisdictions undertake waste characterization studies on different schedules and using different sample techniques. Limited organics data coverage is a major challenge. Food waste generation estimates, in particular, suffer from high measurement error since food scraps are frequently combined with other waste streams before collection, complicating source-based attribution. Inconsistent reporting among commercial generators, multi-family buildings, and industrial facilities increases the uncertainty ranges for organics generation and diversion estimations (Subedi et al., 2025).

Bias in data collection also warrants attention from an equity perspective. Municipal waste characterization studies have historically oversampled single-family residential areas relative to multi-family and commercial contexts, potentially producing national composition estimates that underrepresent the waste profiles of dense urban neighborhoods with higher proportions of renters, immigrants, and lower-income residents (Gutierrez-Lopez et al., 2023). This sampling bias can propagate into analytics models that reproduce or amplify existing disparities in service quality and diversion infrastructure investment.

Integration and Interoperability

The integration of heterogeneous data sources into unified analytics platforms is among the most significant technical and institutional challenges in MSW analytics. Many U.S. municipalities operate fragmented information architectures wherein waste audit data, fleet management records, facility billing systems, and resident engagement platforms reside in separate, incompatible databases managed by different departments or contractors (Gutierrez-Lopez et al., 2023). This siloing prevents the comprehensive cross-domain analysis necessary for advanced predictive and prescriptive modeling.

Technical interoperability challenges include differences in data formats, coordinate reference systems, temporal resolution, and reporting units across systems. Open data standards—such as the General Transit Feed Specification (GTFS) adapted for waste collection routing, or the EPA's Standards for Data Exchange—represent promising frameworks for promoting interoperability, but their adoption across U.S. municipalities remains limited. Cloud-based data integration platforms and API-driven architectures are increasingly proposed as solutions, enabling municipalities to connect disparate data streams into centralized analytics environments without requiring full system replacement (Sosunova & Porras, 2022).

Institutional barriers to data integration are often as significant as technical ones. Contractual restrictions limiting data sharing between municipalities and private waste collection contractors, concerns about the competitive sensitivity of operational data, and privacy considerations related to household-level collection data all create friction for cross-system integration. Governance frameworks that clearly define data ownership, access rights, and use limits, similar to open data compacts in the transportation and public health sectors, are required to enable the centralized data platforms needed for advanced MSW analytics.

CASE STUDIES: ANALYTICS-DRIVEN ORGANICS DIVERSION INITIATIVES

U.S. Municipal Case Studies

Several U.S. municipalities have emerged as demonstrative leaders in analytics-driven organics diversion, providing instructive examples of the operational and environmental outcomes achievable through data-informed program design. Seattle, Washington, represents perhaps the most extensively documented case of analytics-supported mandatory organics diversion. Seattle Public Utilities gradually expanded its source-separated organics program from yard trash collection (which began in the 1990s) to include food scraps and biodegradable paper in 2005, with full required participation for single-family dwellings introduced in 2015 (EPA, 2022c). The program uses a tiered enforcement strategy driven by contamination monitoring data: bins found to contain non-compostable materials are marked with educational warnings, and repeat violators are escalated through a documented enforcement process. Seattle's GHG inventory shows a 25% reduction in food waste and mixed organics-related emissions between 2008 and 2018, demonstrating the cumulative impact of required collection and data-driven contamination management (EPA, 2022c).

Palo Alto, California, offers an example of an advanced curbside SSO program integrated within a comprehensive Zero Waste analytics platform. Palo Alto's 2018 Zero Waste plan established a target of 95% diversion from landfill and incineration by 2030, with organics diversion as a central pillar. By integrating waste characterization data, route efficiency analytics, and residential participation surveys, Palo Alto has achieved approximately 76% total diversion across all material streams, significantly above the national average. The city's composting operation generates finished compost that is marketed as a revenue stream, demonstrating the circular economy potential of organics diversion when supported by end-market analytics.

San Jose, California, through its partnership with Zero Waste Energy Development Company (ZWEDC), exemplifies the application of lifecycle analytics to a large-scale dry anaerobic digestion operation for mixed organics. Nordahl et al. (2020) conducted a comprehensive lifecycle assessment of the ZWEDC facility, finding that mixed organics processing through dry AD achieved net negative GHG emissions of −41 kg CO_2e per tonne of waste when biogas was used for renewable natural gas (RNG) production. This performance substantially outperforms landfilling (approximately 400 kg CO_2e per tonne) and was validated using facility-level mass and energy balances, making it one of the most empirically grounded lifecycle evaluations in the U.S. organics diversion literature.

Table 3. Comparative GHG Emissions by Organic Waste Management Strategy

Management Option	GHG Emissions (kg CO_2e/tonne)	Climate Benefit vs. Landfill	Social Cost ($/tonne)
Landfilling (no gas capture)	~400 kg CO_2e / tonne	Baseline (highest)	$25–40
Landfilling (with gas capture)	260 kg CO_2e / tonne	Moderate reduction	$20–35
Composting (raw organics)	–41 kg CO_2e / tonne	Net negative (best)	$15–25
Anaerobic Digestion + RNG	–36 to –2 kg CO_2e / tonne	Net negative	$10–20
Waste-to-Energy (WTE)	–350 to –28 kg CO_2e / tonne	Net negative (energy credit)	$12–22

Source: Compiled from Nordahl et al. (2020); Nordahl et al. (2023). ES&T and OSTI.

Interventions and Measurable Impacts

Across the documented U.S. case studies, several categories of analytics-driven interventions emerge as consistently associated with measurable improvements in diversion outcomes. First, mandatory organics collection ordinances, enforced through data-monitored contamination identification systems, consistently outperform voluntary programs in achieving high and sustained participation rates. Seattle's shift from voluntary to mandatory collection, tracked through waste characterization data, produced a documented 91% increase in organics diversion from participating commercial buildings in one Alameda County pilot alone (EPA, 2022c).

Second, targeted outreach initiatives based on behavioral analytics and sociodemographic modeling significantly reduce contamination rates, which have long been a barrier to the profitability of organic programs. According to the National Academies of Sciences (2024), education-first enforcement techniques, such as Seattle's bin-tagging strategy, routinely beat fine-first strategies in terms of contamination reduction while preserving resident program goodwill. Third, investing in end-market analytics for compost products to better understand demand patterns, application rates, and regional catchment constraints for finished compost has been critical to maintaining processing operations. Sardarmehni et al. (2020) exhibited geospatial modeling of compost supply and agricultural needs in California, which identified significant unmet demand within economically acceptable transport distances, influencing composting infrastructure expansion planning.

The U.S. municipal case studies collectively yield several transferable lessons for organics diversion program design and analytics integration. Successful programs invariably exhibit strong institutional commitment, evidenced by dedicated waste data management staff, sustained budget allocations for waste characterization studies, and clear accountability metrics for diversion performance. Analytics capabilities alone, in the absence of committed institutional users, do not produce program improvements.

ORGANICS DIVERSION AND LIFECYCLE ENVIRONMENTAL IMPACT

Environmental Benefits of Organics Diversion

The environmental case for organics diversion is well-established across a substantial body of lifecycle assessment (LCA) literature. A comprehensive review of organic waste management strategies by Nordahl et al. (2020), published in Environmental Science & Technology, found that landfilling organic waste generates approximately 400 kg CO_2 equivalent (CO_2e) per tonne, the highest GHG burden of any management option. By contrast, composting raw organics achieves net negative emissions of approximately −41 kg CO_2e per tonne, reflecting the combined effect of avoided landfill methane, carbon sequestration through compost soil application, and fertilizer displacement (Nordahl et al., 2020). Dry anaerobic digestion followed by RNG production achieves a comparable net negative range of −36 to −2 kg CO_2e per tonne, with additional benefits from fossil fuel displacement.

Beyond climate mitigation, organics diversion generates co-benefits for soil health, nutrient cycling, and water retention. Finished compost applied to agricultural soils increases organic matter content, improving soil structure, water-holding capacity, and microbial diversity, all of which contribute to long-term agricultural productivity and carbon sequestration (Gutierrez-Lopez et al., 2023). Environmental Health Perspectives research by Hall et al. (2023) further highlights the urban food security benefits of locally produced compost, particularly when distributed equitably to community gardens and urban agriculture programs in low-income neighborhoods.

The composting process itself is not without environmental trade-offs. A systematic review of composting emission factors by Nordahl et al. (2023), encompassing 388 emission measurements from 46 studies, found that methane (CH_4) is the single largest contributor to global warming potential (GWP_{100}) during yard waste composting, comprising approximately 80% of total GWP_{100}. Ammonia (NH_3) emissions from composting facilities contribute substantially to social costs through particulate formation and eutrophication. These findings highlight the importance of composting process management, aeration, moisture control, and feedstock optimization, minimizing the environmental impact of organics diversion programs, and underscore the value of LCA in selecting among competing management alternatives.

Environmental Analytics

Lifecycle assessment (LCA) serves as the primary environmental analytics framework for evaluating the comparative environmental performance of organics management pathways. In the U.S. context, the EPA's Waste Reduction Model (WARM) provides a publicly accessible, standardized LCA tool that quantifies net GHG benefits of recycling and composting relative to a landfilling baseline across material categories. WARM outputs have been incorporated into numerous municipal sustainability plans and state-level GHG inventories as the basis for organic waste diversion targets and emission reduction crediting.

Beyond WARM, facility-specific and regionally calibrated LCAs have generated higher-resolution environmental performance data for U.S. organic waste processing operations. The Agile-Cradle-to-Grave (Agile-C2G) model employed by Nordahl et al. (2020) to evaluate the ZWEDC facility provides a methodological exemplar of facility-specific LCA that integrates direct mass and energy flow measurements with indirect emissions accounting for electricity generation, fertilizer production, and transportation. The integration of such LCA outputs into decision support systems enables planners to select organics management pathways on the basis of empirical, facility-level environmental performance data rather than generic emission factors, substantially improving the reliability and defensibility of environmental claims associated with diversion program investments.

The social cost of greenhouse gases is increasingly incorporated into organic management LCAs to enable apples-to-apples comparison of management alternatives that differ in their timing and type of emissions. Nordahl et al. (2020) estimated social costs for key management options, finding that landfilling wet organic waste imposes social costs of approximately $25–40 per tonne through GHG damages alone, exclusive of local externalities such as odor and groundwater contamination. This social cost framing is particularly valuable for policy advocacy: it translates environmental benefits into economic terms that are legible within municipal budget and procurement decision processes.

INTEGRATION WITH SMART CITY AND TECHNOLOGY PLATFORMS

Role of IoT and Smart Sensors

The Internet of Things (IoT) is fundamentally transforming waste management from a scheduled, reactive service into a data-driven, proactive system. Smart waste bins equipped with ultrasonic fill-level sensors, temperature monitors, and wireless communication modules generate continuous real-time data on bin utilization, enabling dynamic collection scheduling and route optimization (Alourani et al., 2025). A comprehensive systematic review of IoT-enabled smart waste management systems by Sosunova and Porras (2022), covering 173 primary studies from five databases, documented that smart garbage bins (SGBs) are the dominant hardware component of smart waste management systems, with fill-level sensing, overflow detection, and vehicle tracking constituting the core functional capabilities of deployed systems.

IoT-based collection systems have demonstrated substantial operational improvements relative to conventional fixed-schedule approaches. A multi-agent simulation study by Hussain et al. (2024) found that IoT sensor-driven collection, when applied to a context with an average daily generation of 1.3 kg per individual, outperformed periodic review approaches in covering fewer distances with fewer trucks while achieving key objectives of cost efficiency, environmental preservation, and reduced employee workload. The PLOS One study by Addas et al. (2024) quantified these benefits in a real-world deployment, documenting a 32% route efficiency improvement and 29% fuel consumption reduction. A Frontiers in Sustainability study by Anitha & Parthiban (2025) demonstrated that integrating XGBoost-based overflow prediction with graph-theoretic routing optimization reduced overflow events by 50%, missed pickups by 72.7%, and fuel usage by 15.5% relative to a static collection model.

For organics diversion specifically, IoT-integrated smart bins capable of detecting the presence of food waste through odor or weight sensors represent an emerging application with significant potential for improving participation monitoring and contamination detection. The deployment of such sensors in SSO program bins would enable real-time contamination alerts to collection crews, allowing immediate corrective action rather than reliance on downstream sorting facility rejection, a transformation with major implications for composting feedstock quality and facility operational efficiency.

Big Data and Urban Sustainability

The integration of waste analytics into broader urban data ecosystems represents a frontier application of big data for urban sustainability. Smart city platforms in cities such as Barcelona have combined waste management IoT data with broader urban sensor networks, reportedly saving approximately €555,000 annually in waste management costs through optimized collection scheduling and resource allocation (Anitha & Parthiban, 2025). These integrated platforms create synergistic analytical opportunities: for example, correlating waste generation patterns with food retail activity data to predict organics generation hotspots, or integrating waste collection routes with real-time traffic data to minimize collection vehicle fuel consumption.

Big data analytics in the MSW context also encompasses the use of satellite remote sensing and aerial imagery for waste illegal dumping detection, the application of social media analytics to monitor public attitudes toward waste programs, and the use of mobile application data to track resident engagement with composting and recycling education resources (Fang et al., 2023). The synthesis of these diverse urban data streams into coherent analytics pipelines requires significant investment in data engineering infrastructure and data science workforce capacity, representing a major opportunity for academic-municipal partnership and federal technical assistance programs.

Mobile and Citizen Engagement Platforms

Mobile applications and citizen engagement platforms represent a critical interface between waste management systems and resident behavior. Smart waste management applications enable residents to receive real-time collection alerts, report contamination events, access educational materials on acceptable organics materials, and track their household composting contributions toward municipal diversion goals. When integrated with smart bin data, these platforms create a feedback loop that connects behavioral data with operational response, enabling municipalities to deliver timely, targeted education at the moment of behavioral failure rather than through generic mass communication campaigns.

Research on the behavioral effectiveness of mobile engagement platforms in recycling and composting contexts is still emerging. Studies reviewed by Camilleri and Ferrari (2024) suggest that social normative messaging—communicating community-level diversion performance data to individual households—can produce meaningful increases in participation when delivered through trusted, accessible channels. However, the effectiveness of mobile engagement platforms varies significantly by sociodemographic context: digital access gaps, language barriers, and varying levels of technology literacy create equity challenges that require intentional platform design and multilingual outreach strategies. The integration of citizen engagement data with waste characterization and operational datasets enables analytics-based continuous improvement of engagement strategy, closing the feedback loop between behavior, program design, and diversion outcomes.

FUTURE DIRECTIONS

Standardized Datasets and Benchmarks

The absence of nationally standardized, longitudinal datasets for MSW composition and organics diversion performance represents the most foundational gap in the U.S. MSW analytics landscape. Current national estimates, derived primarily from the EPA's Material Flow Model, have been shown to diverge substantially from independent waste characterization studies, particularly for food and organic material fractions (Srivastava et al., 2025). The lack of standardized sampling protocols, reporting taxonomies, and temporal schedules across U.S. jurisdictions prevents reliable cross-municipal benchmarking and limits the generalizability of predictive models trained on local datasets.

Future research should prioritize the development of a federated national MSW data repository that compiles jurisdiction-level waste characterization data using standardized collection protocols. The EPA's nascent Excess Food Opportunities Map represents a step in this direction for food waste, but its geographic coverage and temporal update frequency remain limited relative to the data needs of advanced analytics applications. A national organics diversion benchmarking platform, integrating waste characterization, facility tipping, and LCA data, would substantially enhance the research evidence base and enable the development of transferable predictive models across diverse U.S. municipal contexts.

Multimodal Data Fusion

The integration of sensor data, geographic information systems (GIS), behavioral survey data, and sociodemographic data into unified analytics architectures remains significantly underdeveloped in MSW research and practice. Most existing studies employ single data modalities without integrating complementary data streams that could substantially improve predictive and prescriptive model performance. Multimodal fusion approaches, applied successfully in transportation and public health analytics, hold particular promise for MSW contexts where waste generation behavior is simultaneously shaped by physical geography, social norms, economic incentives, and infrastructure accessibility.

Future research should develop and validate multimodal fusion architectures for organics diversion analytics, exploring the predictive contribution of each data modality and their combined performance relative to single-source models. Methodological challenges to be addressed include temporal alignment across data sources with different collection frequencies, spatial scale harmonization between household-level sensor data and neighborhood-level sociodemographic data, and the development of privacy-preserving data integration methods that enable behavioral analytics without compromising resident anonymity.

Real-Time Decision Support

The current generation of MSW decision support systems primarily operates on retrospective data that are poorly suited to support real-time operational decisions. The proliferation of IoT sensors in waste bins and collection vehicles is generating data streams that could, in principle, enable real-time adaptive collection scheduling, dynamic contamination alerts, and on-route organics diversion optimization. However, the computational infrastructure, communication protocols, and decision algorithms required to operationalize real-time DSTs remain underdeveloped in most U.S. municipal contexts.

Edge computing represents a promising architectural approach for enabling real-time waste management decision support without the latency and bandwidth constraints of cloud-only architectures. Future research should evaluate edge computing implementations for waste management applications, including on-vehicle route optimization that can dynamically incorporate live bin fill-level data, and smart bin-level contamination detection systems that provide immediate resident feedback. Pilot programs testing real-time DST implementations in collaboration with U.S. municipalities would generate the operational evidence base needed to guide broader deployment.

CONCLUSION

This review demonstrates that municipal solid waste management in the United States stands at a pivotal moment where data-driven analytics can meaningfully close the gap between policy ambition and operational performance. Across the review, descriptive, predictive, and prescriptive analytics consistently emerge as powerful tools for improving diversion rates, reducing greenhouse gas emissions, and optimizing system efficiency. Empirical evidence from U.S. municipal case studies shows that when analytics are embedded into program design, organics diversion outcomes improve measurably while costs and environmental burdens decline.

However, the review also reveals persistent structural and governance barriers that limit the scalability and effectiveness of analytics-driven interventions. Fragmented data infrastructures, inconsistent waste characterization methodologies, limited real-time decision support, and insufficient integration of behavioral and equity considerations continue to constrain performance. Without standardized datasets, interoperable platforms, and dedicated institutional capacity, advanced analytics tools cannot achieve their full potential.

Addressing these challenges requires sustained investment in data governance, multimodal data integration, and real-time decision support systems, alongside policies that prioritize equity and transparency. As climate and methane reduction targets intensify, transforming organics diversion into a precision, analytics-enabled system is no longer optional but essential. Analytics must be treated not merely as technical enhancements, but as foundational infrastructure for climate-responsive and socially inclusive waste management in the United States

REFERENCES

1) Addas, A., Khan, M. N., & Naseer, F. (2024). Waste management 2.0 leveraging internet of things for an efficient and eco-friendly smart city solution. *Plos one*, *19*(7), e0307608. https://doi.org/10.1371/journal.pone.0307608
2) Alourani, A., Ashraf, M. U., & Aloraini, M. (2025). Smart waste management and classification system using advanced IoT and AI technologies. PeerJ Computer Science, 11, e2777. https://doi.org/10.7717/peerj-cs.2777
3) Anitha, R., & Parthiban, A. (2025). AI-IoT-graph synergy for smart waste management: a scalable framework for predictive, resilient, and sustainable urban systems. *Frontiers in Sustainability*, *6*, 1675021. https://doi.org/10.3389/frsus.2025.1675021
4) Camilleri, A. P., & Ferrari, J. R. (2024). Agency or structure? Community and individual level factors impacting recycling behaviors. Global Journal of Community Psychology Practice, 15(2). https://www.gjcpp.org/en/article.php?issue=48&article=294
5) Chau, K. Y., Moslehpour, M., Pan, S. H., & Akhundzada, A. (2025). Advanced predictive modeling of municipal solid waste management using robust machine learning. *Scientific Reports*, *15*(1), 43247. https://doi.org/10.1038/s41598-025-27237-w
6) Fang, B., Yu, J., Chen, Z., Osman, A. I., Farghali, M., Ihara, I., Hamza, E. H., Rooney, D. W., & Yap, P.-S. (2023). Artificial intelligence for waste management in smart cities: A review. Environmental Chemistry Letters, 21, 1959–1989. https://doi.org/10.1007/s10311-023-01604-3
7) Filho, J. J. D. S., Paco, A. D., & Gaspar, P. D. (2025). Artificial Intelligence and MCDA in Circular Economy: Governance Strategies and Optimization for Reverse Supply Chains of Solid Waste. *Applied Sciences*, *15*(9), 4758. https://doi.org/10.3390/app15094758
8) Guo, H. N., Wu, S. B., Tian, Y. J., Zhang, J., & Liu, H. T. (2021). Application of machine learning methods for the prediction of organic solid waste treatment and recycling processes: A review. Bioresource Technology, 319, 124114. https://doi.org/10.1016/j.biortech.2020.124114
9) Gutierrez-Lopez, J., McGarvey, R. G., Costello, C., & Hall, D. M. (2023). Decision support frameworks in solid waste management: a systematic review of multi-criteria decision-making with sustainability and social indicators. *Sustainability*, *15*(18), 13316. https://doi.org/10.3390/su151813316
10) Hall, S. M., Tikku, V., & Heiger-Bernays, W. J. (2023). Potential policy and community implications of equitable organic waste, compost, and urban agricultural systems in the United States. *Environmental health perspectives*, *131*(11), 115001.
11) Hussain, I., Elomri, A., Kerbache, L., & El Omri, A. (2024). Smart city solutions: Comparative analysis of waste management models in IoT-enabled environments using multiagent simulation. *Sustainable Cities and Society*, *103*, 105247. https://doi.org/10.1016/j.scs.2024.105247
12) Kumar, P., Singh, D. J., & John, S. (2025). Multi-criteria decision support system for sustainable municipal solid waste management: A case study of Chandigarh, India. *Environmental Development*, *55*, 101228. https://doi.org/10.1016/j.envdev.2025.101228
13) National Academies of Sciences, Engineering, and Medicine. (2024). Municipal solid waste recycling in the United States: Analysis of current and alternative approaches. National Academies Press. https://doi.org/10.17226/27978
14) Nordahl, S. L., Devkota, J. P., Amirebrahimi, J., Smith, S. J., Breunig, H. M., Preble, C. V., ... & Scown, C. D. (2020). Life-cycle greenhouse gas emissions and human health trade-offs of organic waste management strategies. *Environmental science & technology*, *54*(15), 9200-9209. https://doi.org/10.1021/acs.est.0c00364
15) Nordahl, S. L., Preble, C. V., Kirchstetter, T. W., & Scown, C. D. (2023). Greenhouse gas and air pollutant emissions from composting. *Environmental science & technology*, *57*(6), 2235-2247. https://doi.org/10.1021/acs.est.2c05846
16) Ogunsola, O., Adikorley, I. J. N., & Opoku, J. A. (2025). Mitigating Cognitive Load in Supply Chain Decision-Making: An AI-Driven Framework for Enhanced Operational Efficiency. https://doi.org/10.36948/ijfmr.2025.v07i06.61809
17) Sardarmehni, M., Levis, J. W., & Barlaz, M. A. (2020). What is the best end use for compost derived from the organic fraction of municipal solid waste?. *Environmental science & technology*, *55*(1), 73-81. https://doi.org/10.1021/acs.est.0c04997
18) Seacat, J. D., & Boileau, A. (2018). Demographic and community-level predictors of recycling behavior: A statewide assessment. Journal of Environmental Psychology, 56, 13–22. https://doi.org/10.1016/j.jenvp.2018.02.008
19) Singh, J., El-Sappagh, S., Ali, F., Goyal, S. B., & Kumar, M. (2025). Smart waste management: A systematic review and scientometric analysis of artificial intelligence applications. Environment, Development and Sustainability.
20) Sosunova, I., & Porras, J. (2022). IoT-enabled smart waste management systems for smart cities: A systematic review. IEEE Access, 10, 73929–73962.
21) Srivastava, S., Firmansyah, F., Thyberg, K. L., Tonjes, D. J., & Hewitt, E. (2025). EPA model estimates and waste characterization studies: US paper disposal dynamics. *Waste Management*, *206*, 115074. https://doi.org/10.1016/j.resconrec.2025.108274
22) Subedi, A., Shrestha, S., & Paudel, S. R. (2025). Application of machine learning for prediction of solid waste generation. Natural Built Social Environment Health, 1(2), 14–33. https://doi.org/10.63095/NBSEH.25.831599

23) Tian, X., Yuan, K., Wen, H., Xia, Z., Peng, F., Men, D., ... & Liu, Y. (2025). IoT-based analysis reveals behavioral differences in public participation in low-value recyclables collection. *Humanities and Social Sciences Communications*, *12*(1), 1-15. https://doi.org/10.1057/s41599-025-05975-6
24) U.S. Environmental Protection Agency (EPA). (2022a). Advancing sustainable materials management: Facts and figures 2018. U.S. EPA. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials
25) U.S. Environmental Protection Agency (EPA). (2022b). Guide to the facts and figures report about materials, waste and recycling. U.S. EPA. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/guide-facts-and-figures-report-about
26) U.S. Environmental Protection Agency (EPA). (2022c). Downstream management of organic waste in the United States: Strategies for methane mitigation. U.S. EPA. https://www.epa.gov/system/files/documents/2022-01/organic_waste_management_january2022.pdf
27) U.S. Environmental Protection Agency (EPA). (2024). White paper series: Municipal solid waste landfills—Advancements in technology and operating practices. U.S. EPA. https://downloads.regulations.gov/EPA-HQ-OAR-2024-0453-0002/content.pdf
28) University of Michigan Center for Sustainable Systems. (2024). Municipal solid waste factsheet. CSS Pub. No. CSS04-15. https://css.umich.edu/publications/factsheets/material-resources/municipal-solid-waste-factsheet
29) Xia, W., Jiang, Y., Chen, X., & Zhao, R. (2022). Application of machine learning algorithms in municipal solid waste management: A mini review. Waste Management & Research, 40(6), 609–624. https://doi.org/10.1177/0734242X211033716

Corresponding Author: Omotola Ogunsola