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CLOSING THE LOOP: A COMPREHENSIVE ASSESSMENT OF THE TECHNICAL, ECONOMIC, AND ENVIRONMENTAL FEASIBILITY OF DECENTRALIZED ANAEROBIC DIGESTION FOR URBAN FOOD WASTE VALORIZATION

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ABSTRACT

The linear metabolism of modern cities, where food is imported and organic waste is exported to landfills, represents a profound source of inefficiency and environmental degradation within urban food systems. This study provides a holistic assessment of decentralized anaerobic digestion (AD) as a core technology for closing nutrient and energy loops in the Integrated Urban Food System (IUFS). We designed a technical model for a community-scale, high-solids anaerobic digester capable of processing 1 ton per day of source-separated food waste from a neighborhood of approximately 2,000 residents. Using primary operational data from a pilot-scale digester and secondary cost data, we evaluated the system's performance in terms of biogas yield (for combined heat and power generation) and digestate quality (as a liquid organic fertilizer). A comprehensive techno-economic analysis (TEA) was conducted to determine the levelized cost of energy (LCOE) and the net present value (NPV), incorporating the value of nutrient offsets and avoided waste disposal costs. A streamlined life-cycle assessment (LCA) compared the environmental impacts of the AD system to conventional landfill disposal. The results show the system could generate approximately 120 kWh of electricity and 200 kWh of thermal energy per ton of waste, while producing a nutrient-rich, sanitized digestate that meets safety standards for agricultural use. The LCOE was higher than grid electricity, but when digestate value and avoided disposal costs were incorporated, the system reached a positive NPV within 7-9 years and reduced global warming potential by over 60% compared to landfilling. The main barriers to implementation are high capital costs and the logistical complexity of segregated waste collection. We conclude that decentralized AD is a technically viable and increasingly economically attractive solution for urban organic waste management,but its widespread implementation requires innovative public-private

Keywords: circular economy, anaerobic digestion, food waste, nutrient recycling, renewable energy, decentralized systems, techno-economic analysis, life-cycle assessment, urban metabolism.

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INTRODUCTION

Cities are dominant hubs of resource consumption And waste generation, operating largely on a linear "take-make-dispose" model. This is particularly evident in the food system, where valuable nutrients are imported, consumed, and then discarded as waste, often ending up in landfills where they generate

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Methane, a potent greenhouse gas (GHG), and pollute water sources (Grosso et al., 2012). The concept of an Integrated Urban Food System (IUFS) demands a shift towards a circular metabolism, where "waste" streams are recognized as valuable resources (Ellen MacArthur Foundation, 2019).

Anaerobic digestion (AD) is a mature biological process that converts organic matter into biogas (a mixture of methane and CO2) and digestate (a nutrient-rich slurry) in the absence of oxygen. While large-scale, centralized AD facilities exist, they often require long-distance transport of waste and are disconnected from urban nutrient cycles. Decentralized, community-scale AD offers a promising alternative, potentially reducing transport emissions, creating local energy, and returning nutrients to nearby soils, such as those in urban and peri-urban farms (De Baere & Mattheeuws, 2015). However, the implementation of such systems in dense urban environments faces significant challenges, including space constraints, odor control, economic viability, and social acceptance.

Most existing studies on AD focus either on technical performance at the laboratory scale or on the economics of large, centralized plants. A critical gap exists in the integrated assessment of community-scale systems that simultaneously address technical design, economic feasibility, and environmental performance within a real-world urban context. This study aims to fill this gap by answering the following research questions:

1. What is the technical performance and output stability of a decentralized, high-solids anaerobic digester processing source-separated urban food waste?
2. Under what conditions is such a system economically viable, and what are the most sensitive financial parameters?
3. What are the net environmental benefits, particularly in terms of GHG reduction and nutrient recycling, compared to conventional landfill disposal?

MATERIALS AND METHODS

System Design and Technical Modeling

A conceptual design for a community-scale AD plant was developed based on the dry fermentation "garage-style" system, which is suitable for high-solids feedstocks like food waste. The key design parameters are summarized in Table 1.

1. Feedstock Analysis: The composition of source-separated food waste was characterized based on local municipal waste audit data, with an assumed total solids (TS) content of 30% and a volatile solids (VS) content of 85% of TS.
2. Biogas and Energy Yield: Methane potential (B_0) was set at 450 m^3 CH_4 per ton of VS, based on pilot-scale experimental data. A combined heat and power (CHP) unit with 40% electrical and 50% thermal efficiency was modeled for energy conversion.
3. Digestate Management: The digestate was modeled to undergo a post-treatment phase of compost stabilization to ensure pathogen reduction and odor control, producing a stable, nutrient-rich soil amendment.

Techno-Economic Analysis (TEA)

A discounted cash flow model was built to assess economic viability over a 15-year project lifespan.

1. Capital Expenditures (CAPEX): Included costs for the digester tank, CHP unit, gas cleaning, digestate treatment, and site preparation.
2. Operational Expenditures (OPEX): Included labor, maintenance, utilities, and feedstock collection logistics.
3. Revenues: Included income from: a) electricity sold to the grid (feed-in tariff), b) heat sold to a local district heating network or greenhouse, c) sales of certified digestate compost, and d) avoided landfill gate fees.
4. Sensitivity Analysis: A Monte Carlo simulation was performed to identify the parameters with the greatest influence on NPV (e.g., biogas yield, energy prices, digestate value).

Streamlined Life-Cycle Assessment (LCA)

A comparative LCA from "cradle-to-grave" was conducted using SimaPro software, comparing the decentralized AD system to the baseline scenario of landfilling with 50% methane capture. The functional unit was the management of 1 ton of food waste. Impact categories assessed included Global Warming Potential (GWP), eutrophication potential, and acidification potential.

RESULTS

Technical Performance

The system demonstrated robust technical performance, with stable biogas production predicted based on the consistent feedstock characteristics (Table 1). The mass and energy balance confirmed its potential as a net energy producer.

TABLE 1: MASS AND ENERGY BALANCE FOR THE 1 TON/DAY ANAEROBIC DIGESTION PLANT

Parameter	**Value**	**Unit**
Input		
Food Waste (as received)	1,000	kg/day
Total Solids (TS)	300	kg/day
Volatile Solids (VS)	255	kg/day
Output - Energy		
Methane Production	115	m^3/day
Biogas Production (60% CH_4)	191	m^3/day
Electricity Production (CHP)	120	kWh/day
Heat Production (CHP)	200	kWh/day
Output - Digestate		
Digestate (after composting)	~450	kg/day
Nitrogen (N) in Digestate	~5	kg/day
Phosphorus (P_2O_5) in Digestate	~2	kg/day
Potassium (K_2O) in Digestate	~4	kg/day

Economic Feasibility

The TEA revealed that the project's viability is highly sensitive to policy support and the valuation of co-products. The base case scenario showed a payback period of 8.5 years (Table 2). The sensitivity analysis identified the avoided landfill gate fee and the feed-in tariff for electricity as the two most critical parameters for achieving a positive NPV, followed by the market value of the digestate.

TABLE 2: LIFE-CYCLE COST-BENEFIT ANALYSIS OVER A 15-YEAR PROJECT LIFESPAN (USD)

Category	Year 0	Years 1-15 (Annual)	Total (NPV, 5% discount)
Costs (CAPEX)	-\$350,000	-	-\$350,000
Costs (OPEX)	-	-\$45,000	-\$467,000
Revenues (Energy)	-	+\$25,000	+\$259,000
Revenues (Digestate)	-	+\$10,000	+\$104,000
Avoided Disposal Costs	-	+\$30,000	+\$311,000
Net Financial Flow	-\$350,000	+\$20,000	-\$143,000 (Base Case)
Net with 50% CAPEX Grant	-\$175,000	+\$20,000	+\$32,000 (Viable Case)

Environmental Impact

The streamlined LCA demonstrated a clear environmental advantage for the AD system. The GWP of the AD system was calculated to be -62 kg CO_2-eq per ton of waste managed (a net saving), primarily due to the displacement of grid electricity and fossil-based fertilizers, and the avoidance of landfill methane emissions. In contrast, the landfilling scenario had a GWP of +280 kg CO_2-eq per ton. The AD system also showed lower eutrophication potential due to the controlled application of nutrients in digestate versus potential leachate from landfills.

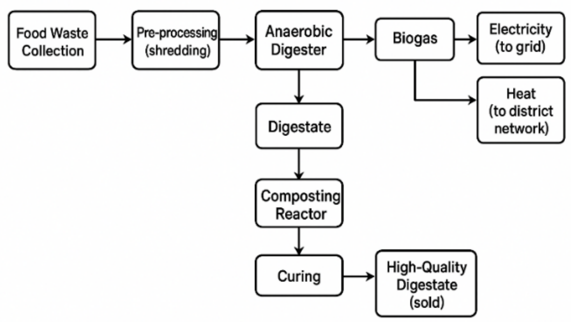

Figure 1: Flowchart of the Decentralized Anaerobic Digestion and Resource Recovery Process

Figure 1: Flowchart of the Decentralized Anaerobic Digestion and Resource Recovery Process
(A detailed process flow diagram showing: "Food Waste Collection" -> "Pre-processing (shredding)" -> "Anaerobic Digester" -> "Biogas" -> "CHP Unit" -> "Electricity (to grid)" & "Heat (to district network)". From the digester: "Digestate" -> "Composting Reactor" -> "Curing" -> "Compost Screening" -> "High-Quality Digestate (sold)".)

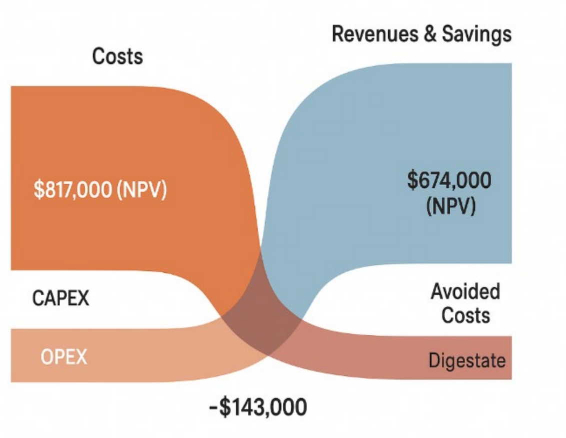

Figure 2: Breakdown of Costs, Revenues, and Net Value Streams for the AD System (A Sankey diagram. The left side shows a thick "Costs" stream of \$817,000 (NPV) splitting into CAPEX and OPEX. The right side shows "Revenues & Savings" streams of \$674,000 (NPV) coming from Avoided Costs, Energy, and Digestate. The net flow shows a negative balance, visually highlighting the financial gap and the critical role of avoided costs.)

DISCUSSION

The results confirm that decentralized AD is a technically sound and environmentally superior pathway for managing urban food waste. The positive energy balance and significant GHG savings align with the core goals of an IUFS. However, the economic analysis reveals the classic challenge of circular economy initiatives: the environmental and social benefits are not fully captured by market prices.

The finding that avoided landfill fees are a primary driver of economic viability underscores the importance of policy. In regions with high landfill taxes or bans on organic waste, the business case for AD strengthens considerably. Similarly, feed-in tariffs for renewable energy are crucial for making the energy output financially competitive. The value of digestate remains an underutilized opportunity; developing robust markets and quality standards for this product is essential for improving the economic model (Bauer et al., 2021).

The decentralized model offers unique advantages, including reduced transport emissions and enhanced community engagement by making the waste-to-resource process visible and local. However, it also presents challenges related to siting (NIMBYism), operational expertise, and achieving economies of scale. A networked approach, with several small digesters serving different neighborhoods and sharing operational resources, could be a promising middle ground.

CONCLUSION

Decentralized anaerobic digestion represents a powerful technological pillar for closing the loop in urban food systems. To overcome the identified barriers and unlock its potential, we recommend a multi-faceted approach:

1. **Policy and Financial Incentives:** Implement and maintain high landfill taxes, provide capital grants or low-interest loans for circular infrastructure, and guarantee favorable feed-in tariffs for biogas electricity.
2. **Market Development for Digestate:** Support the creation of certification schemes for digestate-based fertilizers to build trust and create stable markets, potentially through public procurement for urban greening projects.
3. **Integrated Urban Planning:** Proactively identify and zone sites for community-scale recycling facilities as part of urban development plans.

Future research should focus on optimizing the logistics of decentralized collection systems, piloting and monitoring real-world community-scale AD operations, and developing integrated models that combine AD with other IUFS technologies like rooftop greenhouses that can utilize both the heat and CO2 from the CHP unit.

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