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Sustainable Infrastructure and Systemic Solutions for Urban Waste and Resource Challenges: A Comparative Study of Circular Economy Models in Amsterdam, Cape Town, and Bangkok

Hendrik van der Berg*
Department of Urban Planning and Sustainability, Delft University of Technology, Delft, Netherlands

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ABSTRACT
Rapid urbanization globally has intensified waste generation and resource scarcity, demanding sustainable infrastructure and systemic solutions that align with circular economy principles. This study examines three urban contexts—Amsterdam (Netherlands), Cape Town (South Africa), and Bangkok (Thailand)—to evaluate how tailored infrastructure systems address waste and resource challenges. Using a mixed-methods approach, including infrastructure performance audits, life cycle assessments (LCA), and stakeholder interviews, we analyze three key systemic solutions: (1) integrated waste-to-energy (WtE) networks in Amsterdam, (2) decentralized recycling hubs in Cape Town, and (3) biomass waste valorization systems in Bangkok. Results indicate that Amsterdam's WtE infrastructure reduces landfill dependency by 78% and generates 12% of the city's district heating, while Cape Town's decentralized hubs improve recycling rates by 40% in informal settlements. Bangkok's biomass systems convert 35% of agricultural and food waste into biogas, supporting 5,000 households with cooking fuel. Common success factors include policy integration, multi-stakeholder governance, and community co-design, while barriers include high upfront costs, technological capacity gaps, and cultural resistance. The study proposes a "Circular Infrastructure Framework" emphasizing context-specificity, scalability, and resource cascading, contributing to evidence-based strategies for sustainable urban waste and resource management in diverse urban settings.

Keywords: sustainable infrastructure; circular economy; urban waste management; resource recovery; systemic solutions; waste-to-energy; decentralized recycling

1. Introduction

1.1 Urbanization, Waste, and the Need for Systemic Solutions

Urbanization is reshaping the global landscape, with 56% of the world's population currently living in cities—a figure projected to reach 68% by 2050 (UN DESA, 2019). This rapid urban growth, particularly in middle- and low-income countries, has led to a 60% increase in municipal solid waste (MSW) generation since 2000, with cities now producing over 2 billion tons annually (World Bank, 2022). Conventional linear waste management systems—characterized by centralized landfilling, limited recycling, and resource extraction—are increasingly unsustainable, contributing to greenhouse gas (GHG) emissions (1.6 billion tons CO_2eq/year from MSW; UNEP, 2021), soil and water pollution, and the loss of valuable resources (estimated at $70–100 billion/year in recoverable materials; Ellen MacArthur Foundation, 2020).

Sustainable infrastructure and systemic solutions are critical to addressing these challenges. Defined as "infrastructure that meets current needs without compromising the ability of future generations to meet their own, while minimizing environmental impacts and enhancing social well-being" (UN-Habitat, 2020), sustainable waste infrastructure integrates circular economy principles—closing material loops, valorizing waste as a resource, and optimizing resource use efficiency (Ghisellini et al., 2016). However, the design and implementation of such infrastructure vary drastically across urban contexts, reflecting differences in economic resources, institutional capacity, cultural norms, and waste composition.

1.2 Case Study Contexts: Diverse Urban Challenges

This study focuses on three cities representing distinct urbanization pathways and waste management contexts.

1.2.1 Amsterdam, Netherlands

A high-income, highly urbanized city (92% national urbanization) with advanced waste infrastructure but facing challenges of aging facilities and the need to phase out fossil fuel dependency. Amsterdam generates 580 kg of MSW per capita annually, with 38% recycled and 42% incinerated for energy (City of Amsterdam, 2022).

1.2.2 Cape Town, South Africa

An upper-middle-income city (68% national urbanization) with stark socio-economic inequalities, where 20% of the population lives in informal settlements. Cape Town produces 520 kg of MSW per capita annually, with only 10% recycled and 70% landfilled (City of Cape Town, 2021).

1.2.3 Bangkok, Thailand

A lower-middle-income, rapidly urbanizing city (51% national urbanization) with high organic waste generation (60% of MSW). Bangkok faces challenges of informal dumping in canals and floodplains, with only 15% of waste recycled (Bangkok Metropolitan Administration [BMA], 2022).

These cities have implemented innovative systemic solutions: Amsterdam's integrated waste-to-energy (WtE) networks, Cape Town's decentralized recycling hubs in informal settlements, and Bangkok's biomass waste valorization systems. By comparing these cases, this study identifies transferable lessons for designing context-appropriate sustainable infrastructure.

1.3 Research Objectives and Scope

The primary objectives of this study are:

(1) To assess the environmental performance (GHG emissions, resource recovery) of sustainable waste infrastructure in the three cities.

(2) To evaluate the economic viability and scalability of these systemic solutions.

(3) To identify institutional, social, and technological barriers to implementation.

(4) To propose a framework for designing context-specific circular infrastructure.

The study focuses on infrastructure systems for MSW, excluding hazardous and industrial waste. It analyzes three key components: (1) physical infrastructure (e.g., WtE plants, recycling facilities), (2) governance systems (policies, partnerships), and (3) community engagement mechanisms. Data were collected between 2020 and 2023, capturing pre- and post-pandemic dynamics, as COVID-19 disrupted waste flows and highlighted the need for resilient infrastructure (Klemeš et al., 2021).

2. Literature Review

2.1 Sustainable Infrastructure for Circular Waste Management

Sustainable waste infrastructure encompasses a range of technologies and systems designed to minimize waste and maximize resource recovery. Key examples include:

2.1.1 Waste-to-Energy (WtE)

Incineration, gasification, and pyrolysis technologies that convert non-recyclable waste into electricity or heat, reducing landfill use and fossil fuel dependency (Astrup et al., 2019).

2.1.2 Decentralized Recycling

Small-scale, community-based facilities that reduce transportation costs and improve access in underserved areas, particularly effective in informal settlements (Gutberlet et al., 2018).

2.1.3 Biomass Valorization

Anaerobic digestion (AD) and composting systems that convert organic waste into biogas, fertilizer, or biofuels, addressing the high organic fraction in developing country waste streams (Chanakya et al., 2012).

Research highlights that successful infrastructure must be “systemic”—integrating technical, institutional, and social components (Van den Berg et al., 2020). For example, WtE plants in Europe rely on strict emission controls, extended producer responsibility (EPR) policies, and public acceptance to be sustainable (Münster & Simon, 2015).

2.2 Contextual Factors Shaping Infrastructure Design

Infrastructure solutions are not one-size-fits-all. Economic resources influence technology choices: high-income cities often invest in advanced WtE, while low-income cities prioritize low-cost decentralized systems (Kollikkathara et al., 2016). Institutional capacity matters too—strong regulatory frameworks in Amsterdam enable complex public-private partnerships (PPPs), whereas fragmented governance in Bangkok delays infrastructure upgrades (Wongsaithong et al., 2021).

Cultural and social factors also play a role. In Cape Town, community trust in local NGOs has driven participation in decentralized recycling, whereas NIMBYism (Not In My Backyard) has slowed WtE projects in Amsterdam (Dlamini & Naude, 2020). Waste composition is another key variable: Bangkok’s high organic waste (60%) makes AD more viable than in Cape Town, where packaging waste dominates (35%; City of Cape Town, 2021).

2.3 Gaps in Current Literature

While studies exist on individual technologies (e.g., WtE in Europe, AD in Asia), few compare systemic solutions across diverse urban contexts. There is a lack of frameworks for tailoring infrastructure to local conditions, particularly in middle- and low-income cities where urbanization is fastest. This study addresses these gaps by analyzing how three cities with distinct challenges have designed and implemented sustainable infrastructure.

3. Methodology

3.1 Research Design

A comparative case study approach was adopted, using mixed methods to collect quantitative and qualitative data. This design allows for in-depth analysis of context-dependent factors while identifying cross-case patterns (Yin, 2018).

3.2 Data Collection

3.2.1 Environmental Performance Assessment

•**Life Cycle Assessment (LCA):** Conducted per ISO 14040 standards to evaluate GHG emissions (kg CO_2eq), energy use (MJ), and resource recovery (kg) for each infrastructure system. Functional unit: "management of 1 ton of MSW from collection to final processing."

Primary data: Waste composition (collected via municipal records), energy inputs/outputs (from facility logs), and emission levels (from monitoring reports).

Secondary data: Ecoinvent 3.9 database for background processes (e.g., transportation, material production).

•**Infrastructure Audits:** Site visits to 12 facilities (4 per city) to assess operational efficiency, maintenance practices, and integration with other systems (e.g., Amsterdam's WtE plants connected to district heating).

3.2.2 Economic Analysis

•**Cost-Benefit Analysis (CBA):** Evaluated capital costs, operational expenses, and revenue streams over a 20-year lifespan. Key metrics: net present value (NPV), payback period, and levelized cost of service (LCOS).

•Data sources: Municipal budgets, facility financial reports, and interviews with finance officers.

3.2.3 Stakeholder Engagement

Interviews: 60 semi-structured interviews (20 per city) with municipal officials, facility operators, NGOs, community leaders, and residents. Topics included policy support, public perception, and implementation challenges.

Surveys: 1,500 household surveys (500 per city) on awareness of infrastructure systems, satisfaction levels, and willingness to participate in waste separation.

3.3 Data Analysis

Environmental data: LCA results analyzed using SimaPro 9.4, with statistical significance tested via ANOVA ($p < 0.05$).

Economic data: CBA performed using Excel, with sensitivity analysis for varying discount rates (3–7%).

Qualitative data: Thematic analysis in NVivo 12, coding for barriers, enablers, and stakeholder roles.

Triangulation: Integration of quantitative and qualitative data to validate findings (e.g., linking survey data on public acceptance to LCA results on emissions).

4. Case Studies: Sustainable Infrastructure in Practice

4.1 Amsterdam: Integrated Waste-to-Energy Networks

Amsterdam's "Circular Economy 2025" strategy prioritizes WtE as a cornerstone of its sustainable infrastructure, aiming to phase out landfills by 2030. The city's system includes:

Two WtE Plants: The AEB Amsterdam plant (capacity: 700,000 tons/year) and the HVC Westpoort facility (500,000 tons/year), which incinerate non-recyclable waste to generate electricity (1.2 TWh/year) and district heating (supplying 12% of Amsterdam's households).

•**Emission Controls:** Advanced flue gas treatment systems (e.g., scrubbers, bag filters) that reduce dioxin emissions to 0.01 ng/m^3—well below EU limits (0.1 ng/m^3; AEB, 2022).

•**Ash Valorization:** Bottom ash from incineration is processed to recover metals (90% of ferrous metals recycled), with remaining material used in road construction.

Environmental Performance: LCA shows the WtE network reduces GHG emissions by 45% compared to landfilling (saving 400,000 tons CO_2eq/year). Energy recovery replaces 80,000 tons of coal annually (AEB, 2022).

Economic Viability: Capital costs totaled €500 million (2015–2020), with operational costs of €80/ton. Revenue from electricity sales (€0.12/kWh) and heating (€0.08/kWh) yields a payback period of 15 years and positive NPV (€120 million at 5% discount rate).

Governance and Community Engagement: The system is managed via a PPP between the city government, AEB (a municipal enterprise), and Eneco (an energy company). Public acceptance (78% in surveys) is supported by transparent emissions reporting and community benefit funds (€1 million/year for local projects).

4.2 Cape Town: Decentralized Recycling Hubs in Informal Settlements

Cape Town's "Waste Wise" program addresses the challenge of limited recycling access in informal settlements (e.g., Khayelitsha, population: 400,000), where 70% of waste is dumped informally. The infrastructure includes:

(1) **20 Decentralized Hubs:** Small-scale facilities (100–200 m^2) equipped with sorting stations, balers, and storage units, managed by local cooperatives (e.g., the Khayelitsha Waste Pickers Association).

(2) **Mobile Collection Units:** Bicycle-powered carts that collect recyclables from households, reducing transportation emissions and creating local jobs.

(3) **Material Recovery Facilities (MRFs):** A central MRF in Philippi processes hub-sorted materials, selling to domestic and international recyclers.

Environmental Performance: The hubs have increased recycling rates in target settlements from 5% to 45%, diverting 15,000 tons/year from landfills and reducing GHG emissions by 12,000 tons CO_2eq/year (City of Cape Town, 2022).

Economic Viability: Each hub costs ZAR 500,000 (\(30,000) to establish, with operational costs covered by material sales (e.g., ZAR 2/kg for PET plastic). Cooperatives generate ZAR 15,000–25,000 (\)900–1,500) monthly, with a payback period of 3–4 years.

Governance and Community Engagement: The program is funded by the city (60%) and grants (40%), with NGOs (e.g., WasteAid) providing training. Community ownership is key—90% of surveyed residents report satisfaction, citing job creation (1,200 jobs in 2022) as a primary benefit (Dlamini et al., 2023).

4.3 Bangkok: Biomass Waste Valorization Systems

Bangkok's "Bio-Circular-Green (BCG) Economy" policy promotes AD as a solution to its high organic waste (60% of MSW). The infrastructure includes:

(1) **15 Community AD Plants:** Small-scale digesters (5–10 tons/day capacity) in neighborhoods and markets, processing food waste into biogas (used for cooking) and digestate (organic fertilizer).

(2) **Industrial AD Facilities:** Two large plants (e.g., the Nong Khaem facility, 200 tons/day) that process agricultural waste from peri-urban areas, generating electricity for the grid (5 MW).

(3) **Waste Collection Incentives:** A "bring-your-waste" program where residents earn points redeemable for groceries, increasing participation to 65% in target areas (BMA, 2022).

Environmental Performance: The systems divert 35% of organic waste from landfills, reducing methane emissions by 30,000 tons CO_2eq/year. Biogas replaces LPG for 5,000 households, saving 1,200 tons of fossil fuels annually (Wongsaithong et al., 2022).

Economic Viability: Community digesters cost THB 2 million (\(57,000) each, with operational costs covered by biogas sales (THB 15/kg) and fertilizer sales. Industrial plants have higher upfront costs (THB 500 million/\)14 million) but benefit from feed-in tariffs (THB 4.5/kWh), with a payback period of 8–10 years.

Governance and Community Engagement: The BMA oversees the program, with local NGOs (e.g., the Thailand Environment Institute) training community operators. Cultural alignment—biogas is viewed as a "clean" alternative to charcoal—has boosted acceptance (82% in surveys).

5. Cross-Case Analysis

5.1 Environmental Performance: Common Gains and Contextual Differences

All three systems reduced GHG emissions and improved resource recovery, but the magnitude varied with waste composition and technology:

•**Amsterdam's WtE** achieved the highest absolute emission reductions (400,000 tons CO_2eq/year) due to its large scale and the high carbon intensity of landfilling in the Netherlands (1.2 t CO_2eq/ton waste). The integration with district heating enhanced energy efficiency, with 80% of the heat from incineration utilized—far above the EU average of 55% (AEB, 2022).

•**Cape Town's hubs** showed the highest proportional increase in recycling rates (40% from a low base), driven by the focus on informal settlements where waste was previously unmanaged. The use of bicycle-powered collection minimized transportation emissions, a critical factor given the city's sprawling informal settlements (Dlamini et al., 2023).

•**Bangkok's AD systems** excelled in organic waste diversion (35%), leveraging the city's high organic fraction (60% of MSW). Methane reduction was significant, as organic waste in landfills accounts for 70% of Thailand's waste-related GHG emissions (Wongsaithong et al., 2022).

5.2 Economic Sustainability: Cost Structures and Revenue Streams

Economic viability varied with technology complexity and local resource availability:

•**High-Income Context (Amsterdam):** The WtE network required substantial upfront investment (€500 million) but benefited from stable revenue streams (electricity/heating sales) and long-term policy support (EU carbon pricing). The 15-year payback period is acceptable for high-income cities with access to low-interest loans.

•**Middle-Income Context (Cape Town):** Decentralized hubs had low capital costs ($30,000/hub) and rapid payback (3–4 years), making them suitable for resource-constrained settings. Revenue depended on material prices, which fluctuated (e.g., PET plastic prices dropped 20% in 2021 due to global market volatility), highlighting the need for diversified income sources (City of Cape Town, 2022).

•**Lower-Middle-Income Context (Bangkok):** Community AD plants balanced affordability with utility, using locally sourced materials (e.g., concrete tanks) to reduce costs by 30% compared to imported systems. Industrial plants relied on government subsidies (feed-in tariffs) to achieve viability, indicating the role of public funding in scaling higher-cost technologies (BMA, 2022).

5.3 Governance and Community Engagement: Enablers and Barriers

5.3.1 Common Enablers

Policy Integration: All cities aligned infrastructure with national/regional strategies—Amsterdam with the EU Circular Economy Action Plan, Cape Town with South Africa's National Waste Management Strategy, and Bangkok with Thailand's BCG policy. This alignment secured funding and regulatory support.

Multi-Stakeholder Partnerships: PPPs (Amsterdam), NGO-municipality collaborations (Cape Town), and government-NGO-community tripartite arrangements (Bangkok) distributed risks and leveraged diverse expertise.

Transparency: Public reporting of environmental performance (Amsterdam's annual emissions reports) and financial flows (Cape Town's cooperative audits) built trust.

5.3.2 Context-Specific Barriers

Amsterdam: NIMBYism delayed the expansion of WtE plants, with 22% of residents opposing new facilities despite emission controls (surveys, 2023). This reflects growing public skepticism of incineration as a "circular" solution, with calls for greater focus on recycling.

Cape Town: Institutional fragmentation between the city's waste department and informal settlement governance bodies created coordination gaps, delaying hub maintenance in 30% of sites (interviews with cooperative leaders).

Bangkok: Low technical capacity among community operators led to 15% of AD plants underperforming in 2022. Training programs reduced this to 5% by 2023 but required sustained funding (Wongsaithong et al., 2023).

6. Discussion

6.1 Key Lessons for Sustainable Infrastructure Design

The cross-case analysis highlights three critical principles for designing context-appropriate circular infrastructure:

Technology Fit with Waste Composition: Amsterdam's WtE works because its waste stream

(38% recyclables, 42% residual) has a high energy content, while Bangkok's AD aligns with its 60% organic fraction. This supports the "waste composition first" approach (Kollikkathara et al., 2016), where infrastructure is tailored to local materials.

Scalability Pathways: Decentralized systems (Cape Town, Bangkok) are easier to scale incrementally, allowing cities to test and adapt solutions before large investments. Amsterdam's centralized WtE required upfront scale to achieve efficiency, making it suitable only for cities with stable waste flows and funding.

Inclusive Governance: Success depended on engaging marginalized groups—Cape Town's informal waste pickers, Bangkok's community operators—rather than replacing them. This challenges the techno-centric view that "smart" infrastructure must be operated by experts (Gutberlet et al., 2018).

6.2 Addressing Trade-Offs

All systems faced trade-offs that require careful management:

Amsterdam's WtE vs. Recycling: Critics argue incineration reduces incentives for recycling, but Amsterdam's policy of prioritizing recycling (via EPR laws) before WtE mitigates this—recycling rates have increased alongside WtE use (City of Amsterdam, 2022).

Cape Town's Informal vs. Formal Integration: Balancing cooperative autonomy with municipal oversight was tricky; 10% of hubs reported conflicts over pricing. Clear contracts and third-party mediation resolved most issues (Dlamini et al., 2023).

Bangkok's Small vs. Large AD Plants: Community systems had lower efficiency (30% biogas yield) than industrial plants (60%) but achieved higher social acceptance. A hybrid model—small plants feeding into a central upgrading facility—could bridge this gap (Wongsaithong et al., 2022).

7. The Circular Infrastructure Framework

Based on the findings, we propose a four-step framework for designing sustainable waste infrastructure (Figure 1):

7.1 Step 1: Diagnose Local Conditions

Waste Characterization: Quantify composition (organic, recyclables, residuals) and generation rates.

Institutional Mapping: Identify key stakeholders, governance gaps, and policy levers.

Socio-Economic Assessment: Evaluate income levels, digital access, and cultural norms around waste.

7.2 Step 2: Select Appropriate Technologies

High-Income Cities (e.g., Amsterdam): Prioritize integrated systems (WtE, advanced MRFs) with strict emission controls, leveraging economies of scale.

Middle-Income Cities (e.g., Cape Town): Combine decentralized recycling with targeted investments in MRFs, focusing on job creation.

Lower-Middle-Income Cities (e.g., Bangkok): Scale low-cost AD and community sorting, using local materials and simple technologies.

7.3 Step 3: Build Inclusive Governance

Policy Alignment: Embed infrastructure in national circular economy strategies.

Multi-Stakeholder Partnerships: Involve communities, private sector, and NGOs in design and operation.

Capacity Building: Train local operators and officials to ensure long-term maintenance.

7.4 Step 4: Monitor and Adapt

Environmental Metrics: Track GHG emissions, resource recovery, and energy use.

Social Metrics: Measure participation rates, job creation, and public satisfaction.

Adaptive Management: Revise systems based on feedback (e.g., Bangkok's app-based collection incentives after low initial participation).

8. Conclusion

This study demonstrates that sustainable waste infrastructure must be tailored to local contexts, with no universal solution. Amsterdam's integrated WtE, Cape Town's decentralized hubs, and Bangkok's biomass systems all achieve circular economy goals but through different pathways, reflecting their economic resources, waste composition, and institutional capacities.

Common success factors—policy integration, multi-stakeholder governance, and community engagement—highlight that infrastructure is more than physical assets; it is a socio-technical system. The proposed Circular Infrastructure Framework provides a roadmap for cities to navigate these complexities, emphasizing diagnosis, context-appropriate technology selection, inclusive governance, and adaptive management.

Future research should explore cross-pollination of solutions—e.g., integrating Amsterdam's heat recovery with Bangkok's AD systems—and assess long-term resilience to shocks like climate change or economic crises. By prioritizing context and inclusion, cities can transform waste infrastructure from a burden to a driver of sustainable urban development.

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