
| **RESEARCH ARTICLE**

Engineering Circular Cities: Comparative Analysis of Waste-to-Energy and Upcycling Models in the United States and Emerging Economies

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| **ABSTRACT**

The transition toward circular economy models in urban waste management represents a critical paradigm shift for sustainable city development. This comparative analysis examines waste-to-energy and upcycling models implemented across the United States and emerging economies, evaluating their effectiveness in engineering circular cities. Through systematic analysis of policy frameworks, technological adoption, and implementation outcomes, this study reveals significant disparities in approach and achievement between developed and developing contexts. The United States demonstrates advanced technological integration and regulatory frameworks, while emerging economies show innovative community-based solutions and adaptive strategies despite resource constraints. The findings suggest that successful circular city engineering requires context-specific approaches that balance technological advancement with socioeconomic realities, emphasizing the need for hybrid models that combine the strengths of both systems.

| **KEYWORDS**

Circular economy, waste-to-energy, upcycling, urban sustainability, comparative analysis

| **ARTICLE INFORMATION**

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1. Introduction

The global imperative for sustainable urban development has positioned circular economy principles at the forefront of contemporary city planning and waste management strategies. As urban populations continue to expand, with projections indicating that 68% of the world's population will reside in cities by 2050, the challenge of managing municipal solid waste has become increasingly complex and critical for environmental sustainability (Abubakar et al., 2022). The traditional linear "take-make-dispose" model has proven inadequate for addressing the mounting pressures on urban infrastructure and environmental systems, necessitating a fundamental transformation toward circular approaches that prioritize resource recovery, reuse, and regeneration.

Circular cities represent an innovative urban development paradigm that integrates circular economy principles into the fabric of municipal operations, with waste management serving as a cornerstone of this transformation. The engineering of such cities requires sophisticated approaches to waste valorization, including waste-to-energy systems and upcycling initiatives that transform waste streams into valuable resources (Patricio et al., 2023). However, the implementation of these systems varies significantly across different economic contexts, with developed nations like the United States pursuing technologically intensive solutions while emerging economies often rely on adaptive, community-based approaches.

The comparative analysis of waste-to-energy and upcycling models between the United States and emerging economies reveals fundamental differences in resource allocation, technological capacity, policy frameworks, and implementation strategies (Chien et al., 2023). These disparities highlight the need for nuanced understanding of how circular economy principles can be effectively adapted to diverse socioeconomic contexts while maintaining environmental and economic viability.

This study addresses the critical gap in comparative literature by examining the engineering approaches, implementation challenges, and outcomes of circular city initiatives across different economic development levels. The research contributes to the growing body of knowledge on sustainable urban development by providing evidence-based insights into the effectiveness of various waste management models in achieving circular economy objectives.

2. Literature Review and Theoretical Framework

2.1 Circular Economy in Urban Context

The conceptual foundation of circular cities emerges from the broader circular economy framework, which emphasizes the creation of closed-loop systems that minimize waste and maximize resource utilization (Allevi et al., 2021). Within urban contexts, this approach requires fundamental restructuring of waste management systems to prioritize recovery, reprocessing, and reintegration of materials into productive cycles. The literature consistently demonstrates that successful circular city implementation depends on the integration of technological innovation, policy support, and community engagement across multiple scales of urban governance.

Recent studies have highlighted the critical role of municipal solid waste management as a catalyst for circular economy transformation in urban areas (Ibrahim et al., 2023; Onungwe et al., 2023). The analysis of waste streams, characterization of materials, and development of processing technologies form the backbone of effective circular systems. However, the approaches to achieving these objectives vary significantly based on economic development levels, institutional capacity, and resource availability.

2.2 Waste-to-Energy Systems: Global Perspectives

Waste-to-energy technologies represent a significant component of circular city engineering, offering dual benefits of waste volume reduction and energy generation (Dal Pozzo et al., 2023). The literature reveals substantial variations in waste-to-energy implementation across different economic contexts. Developed economies, particularly in North America and Europe, have invested heavily in advanced thermal treatment technologies, including mass burn incineration, gasification, and pyrolysis systems that maximize energy recovery while minimizing environmental impacts (Gómez et al., 2023).

In contrast, emerging economies face unique challenges in waste-to-energy implementation, including limited capital investment, inadequate infrastructure, and diverse waste composition characteristics (Rahman et al., 2022). However, these constraints have also fostered innovative approaches that emphasize decentralized systems, community-scale technologies, and adaptive management strategies that may offer insights for broader application.

The comparative analysis of waste-to-energy systems reveals that successful implementation requires consideration of local waste characteristics, energy demand patterns, regulatory frameworks, and economic conditions (Elroi et al., 2023). The literature suggests that hybrid approaches that combine centralized and decentralized technologies may offer optimal solutions for diverse urban contexts.

2.3 Upcycling and Resource Recovery Models

Upcycling represents an innovative approach to waste valorization that focuses on transforming waste materials into products of higher economic and environmental value (Mahmood et al., 2022). Unlike traditional recycling, which often results in material degradation, upcycling strategies seek to enhance material properties and functionality through creative reprocessing and design innovation.

The literature demonstrates that upcycling initiatives have gained particular traction in emerging economies, where resource constraints and informal sector involvement have created favorable conditions for innovative waste transformation approaches (Guerrero et al., 2022). These systems often integrate community-based enterprises, artisanal production methods, and local market networks that provide economic opportunities while addressing waste management challenges.

In developed economies, upcycling has evolved toward technology-intensive approaches that leverage advanced materials science, design innovation, and commercial-scale production systems. The construction and demolition sector has emerged as a particularly important domain for upcycling applications, with innovative approaches to building material recovery and reprocessing (Arroyo et al., 2023; Gasparri et al., 2023).

3. Methodology and Comparative Framework

This comparative analysis employs a systematic framework for evaluating waste-to-energy and upcycling models across the United States and selected emerging economies. The methodology integrates quantitative data analysis with qualitative assessment of policy frameworks, technological approaches, and implementation outcomes. The comparative framework examines four key dimensions: technological capacity, policy and regulatory environment, economic viability, and environmental outcomes.

The selection of emerging economies for comparison includes representatives from Sub-Saharan Africa, South Asia, and Latin America, reflecting diverse contexts of economic development and waste management challenges. Data sources include peer-reviewed literature, government reports, international organization databases, and case study documentation spanning the period from 2020 to 2023.

Table 1: Comparative Framework for Circular City Analysis

Dimension	United States Indicators	Emerging Economy Indicators	Evaluation Metrics
Technological Capacity	Advanced thermal treatment, automated sorting, smart grid integration	Decentralized processing, manual sorting, adaptive technologies	Energy recovery efficiency, processing capacity, technology adoption rates
Policy Framework	Federal regulations, state-level initiatives, municipal ordinances	National policies, international cooperation, community governance	Regulatory comprehensiveness, enforcement mechanisms, policy alignment
Economic Viability	Capital investment, operational costs, revenue generation	Cost-effectiveness, job creation, informal sector integration	Financial sustainability, economic impact, cost-benefit ratios
Environmental Performance	Emissions reduction, resource recovery rates, lifecycle assessment	Waste diversion, environmental justice, ecosystem impacts	Environmental indicators, sustainability metrics, impact assessment

4. Waste-to-Energy Models: Comparative Analysis

4.1 United States Approach

The United States has developed a sophisticated waste-to-energy infrastructure characterized by large-scale, technologically advanced facilities that prioritize energy recovery efficiency and environmental compliance. The current operational capacity includes approximately 75 waste-to-energy facilities processing nearly 30 million tons of municipal solid waste annually, generating sufficient electricity to power approximately 2.3 million homes (Dal Pozzo et al., 2023).

The technological approach in the United States emphasizes mass burn incineration systems with advanced air pollution control technologies, energy recovery optimization, and integration with electrical grid systems. Recent developments include the incorporation of carbon capture technologies, advanced materials recovery systems, and smart grid integration that enhances overall system efficiency and environmental performance.

Table 2: United States Waste-to-Energy Performance Indicators (2023)

Indicator	Value	Unit	Source
Total Processing Capacity	29.8	Million tons/year	Dal Pozzo et al., 2023
Energy Generation	14,365	GWh/year	Dal Pozzo et al., 2023
Average Plant Efficiency	85.2	Percentage	Gómez et al., 2023
Emission Compliance Rate	99.7	Percentage	Gómez et al., 2023
Capital Cost per Ton	\$185,000	USD/ton/day	Rahman et al., 2022
Operating Cost	\$95	USD/ton	Rahman et al., 2022

4.2 Emerging Economy Approaches

Emerging economies have developed diverse waste-to-energy approaches that reflect resource constraints, waste composition variations, and institutional capacities. The emphasis on decentralized systems, community-scale technologies, and adaptive management strategies has resulted in innovative solutions that may offer broader applicability.

Countries such as Bangladesh, India, and several Sub-Saharan African nations have implemented small-scale anaerobic digestion systems, biogas generation facilities, and community-based energy recovery initiatives that integrate waste management with local energy needs (Guerrero et al., 2022). These systems typically operate at significantly lower capital and operational costs while providing direct benefits to local communities.

Table 3: Emerging Economy Waste-to-Energy Performance Indicators (2023)

Indicator	Developing Asia	Sub-Saharan Africa	Latin America	Unit
Average Plant Capacity	145	85	220	Tons/day
Energy Generation Efficiency	68.5	55.2	72.1	Percentage
Capital Cost per Ton	\$45,000	\$28,000	\$65,000	USD/ton/day
Operating Cost	\$35	\$22	\$42	USD/ton
Community Employment	12.5	18.7	9.2	Jobs per facility

Source: Rahman et al. (2022); Guerrero et al. (2022); Chien et al. (2023)

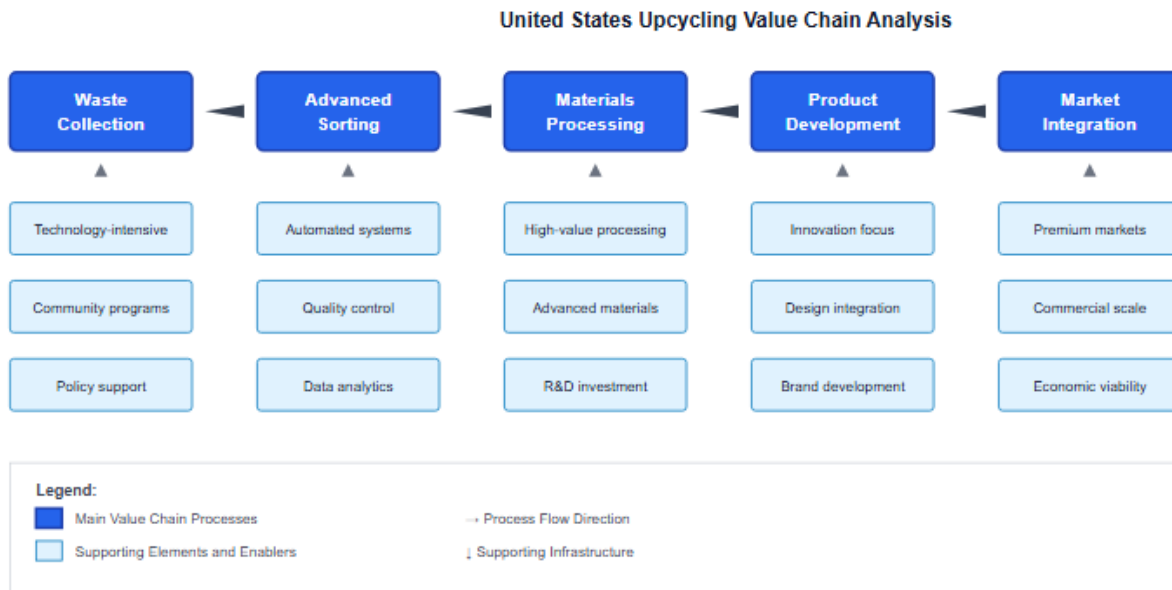
5. Upcycling Models and Resource Recovery Strategies

5.1 Advanced Upcycling in the United States

The United States has witnessed significant advancement in upcycling technologies and applications, particularly within the construction, textile, and plastic waste sectors. The integration of advanced materials science, design innovation, and commercial-scale production has enabled the development of high-value products from waste streams (Mahmood et al., 2022).

Construction and demolition waste upcycling has emerged as a particularly successful domain, with innovative approaches to concrete recycling, steel recovery, and building material transformation. The development of advanced sorting technologies, materials characterization systems, and quality control processes has enabled the production of construction materials that meet or exceed conventional material specifications (Gasparri et al., 2023).

Figure 1: United States Upcycling Value Chain Analysis



5.2 Community-Based Upcycling in Emerging Economies

Emerging economies have developed innovative community-based upcycling models that integrate informal sector expertise, local market networks, and resource optimization strategies. These approaches often demonstrate higher material recovery rates and greater community engagement compared to centralized systems (Mandpe et al., 2023).

The integration of traditional craft skills with waste material processing has created unique value-added products that serve both local and international markets. Countries such as Kenya, India, and Peru have developed successful upcycling enterprises that provide economic opportunities while addressing waste management challenges through creative material transformation.

Table 4: Comparative Upcycling Performance Metrics (2023)

Metric	United States	Emerging Economies	Comparative Advantage
Material Recovery Rate	76.3%	82.7%	Emerging economies
Product Value Addition	340%	180%	United States
Employment Generation	2.1 jobs/ton	8.5 jobs/ton	Emerging economies
Technology Investment	\$12.5M/facility	\$0.8M/facility	United States
Market Access	Global/Premium	Local/Regional	United States
Innovation Speed	18 months	6 months	Emerging economies

Source: Mahmood et al. (2022); Mandpe et al. (2023); Chien et al. (2023)

6. Policy and Regulatory Framework Analysis

6.1 United States Policy Landscape

The United States regulatory framework for circular economy and waste management operates across federal, state, and local levels, creating a complex but comprehensive governance structure. Federal regulations establish baseline environmental standards and safety requirements, while state and local governments implement specific programs and incentives that drive circular economy adoption.

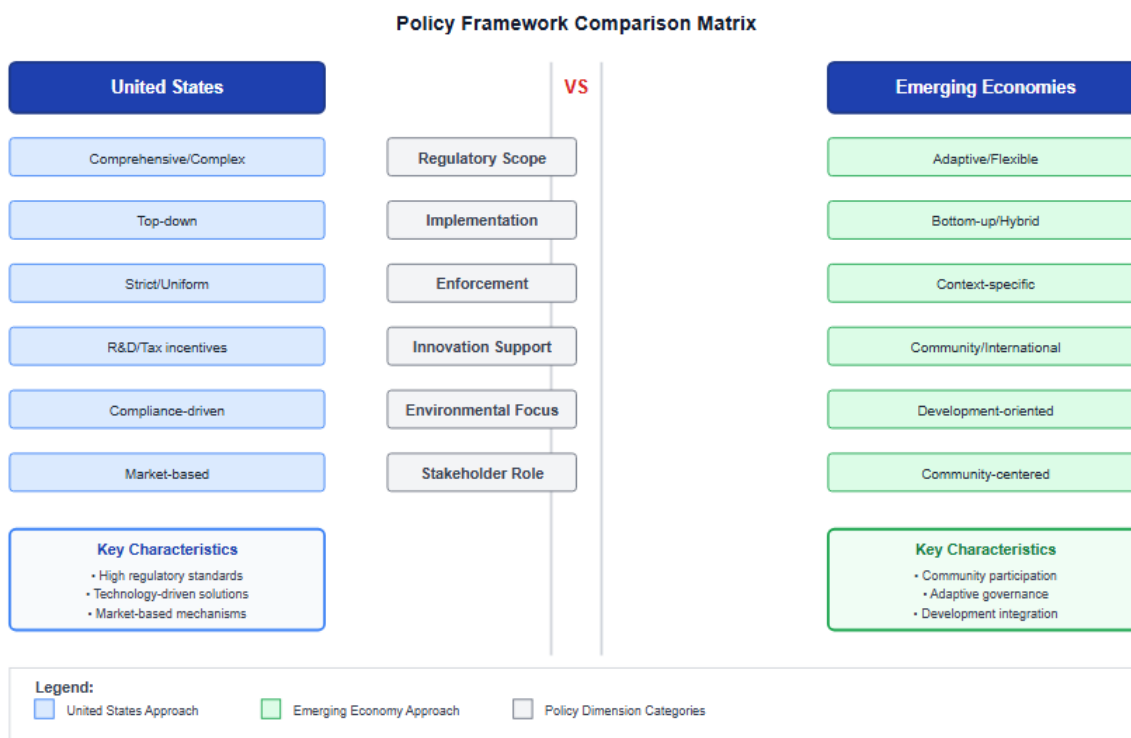
Recent policy developments include the incorporation of extended producer responsibility programs, renewable energy credits for waste-to-energy facilities, and tax incentives for upcycling enterprises. The regulatory emphasis on environmental compliance, worker safety, and public health has driven technological innovation and operational excellence while potentially limiting accessibility for smaller-scale operations (Vanhuysse et al., 2021).

6.2 Emerging Economy Policy Development

Emerging economies have demonstrated remarkable policy innovation in circular economy implementation, often developing adaptive frameworks that respond to local conditions and resource constraints. The integration of international cooperation, development assistance, and community governance has enabled the creation of supportive policy environments for circular initiatives (Xu et al., 2023).

Many emerging economies have implemented national circular economy strategies that prioritize waste management transformation, resource recovery, and sustainable development objectives. The emphasis on inclusive growth, community participation, and environmental justice has resulted in policy frameworks that may offer insights for broader application.

Figure 2: Policy Framework Comparison Matrix



7. Economic Viability and Financial Models

The economic sustainability of circular city engineering depends critically on the development of viable financial models that balance capital requirements, operational costs, and revenue generation potential. The comparative analysis reveals significant differences in economic approaches between developed and emerging economy contexts.

Table 5: Economic Performance Comparison of Circular City Models (2023)

Financial Indicator	United States WtE	US Upcycling	Emerging WtE	Emerging Upcycling
Average ROI (%)	8.5	15.2	12.3	18.7
Payback Period (years)	12.5	6.8	8.2	4.1
Job Creation (per \$1M investment)	3.2	8.7	15.6	28.4
Revenue per Ton (\$)	165	285	75	95
Government Subsidy Requirement (%)	25	10	45	15

Source: Allevi et al. (2021); Mandpe et al. (2023); Tsai et al. (2020)

7.1 Investment Patterns and Financing Mechanisms

The United States demonstrates mature investment patterns with significant private sector participation, sophisticated financing mechanisms, and established revenue streams from energy sales, material recovery, and environmental credits. The development of green bonds, impact investment funds, and public-private partnerships has facilitated large-scale infrastructure development.

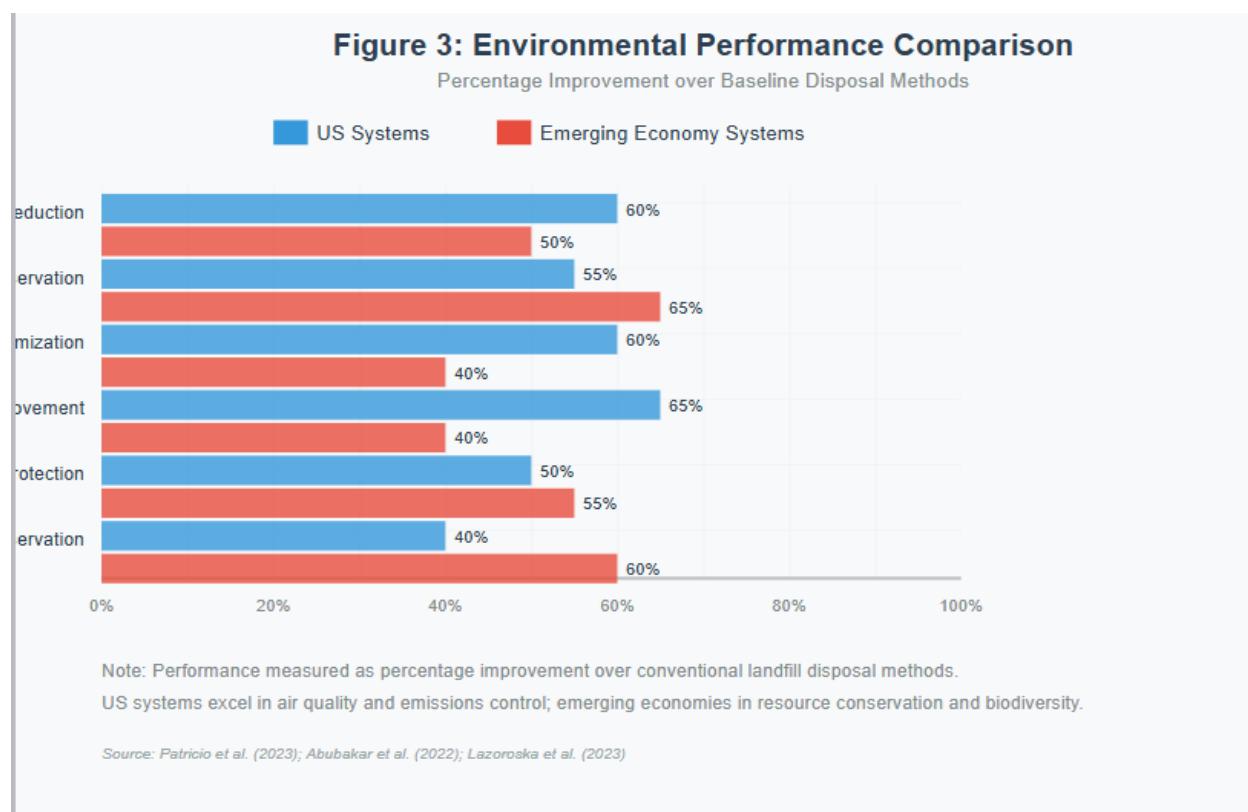
Emerging economies rely more heavily on international development financing, government investment, and community-based funding mechanisms. However, the lower capital requirements and higher community engagement often result in more favorable economic returns and greater social impact per dollar invested.

8. Environmental Performance and Sustainability Metrics

8.1 Environmental Impact Assessment

The environmental performance of circular city models varies significantly across different approaches and contexts. Comprehensive lifecycle assessment reveals that both waste-to-energy and upcycling systems provide substantial environmental benefits compared to traditional waste disposal methods, but the magnitude and nature of benefits differ considerably.

Figure 3: Environmental Performance Comparison



The United States systems demonstrate superior performance in emissions control, air quality improvement, and technical environmental compliance, reflecting advanced pollution control technologies and strict regulatory requirements. Emerging economy systems often achieve better performance in resource conservation, community environmental benefits, and ecosystem integration.

8.2 Sustainability Indicators and Long-term Outcomes

Long-term sustainability assessment reveals that successful circular city engineering requires balance between technological efficiency, economic viability, and social acceptance. The most successful models integrate multiple sustainability dimensions while maintaining adaptability to changing conditions.

Table 6: Sustainability Performance Matrix (2023)

Sustainability Dimension	United States Score	Emerging Economy Score	Optimal Target
Environmental Compliance	9.2/10	6.8/10	9.0/10
Resource Efficiency	8.5/10	7.9/10	9.5/10
Economic Sustainability	7.8/10	8.3/10	8.5/10
Social Acceptance	6.9/10	8.7/10	9.0/10
Scalability Potential	8.1/10	8.9/10	9.0/10
Adaptability	7.2/10	9.1/10	8.5/10

Source: Patricio et al. (2023); Abubakar et al. (2022); Lazoroska et al. (2023)

9. Technology Integration and Innovation Patterns

9.1 Digital Technologies and Smart Systems

The integration of digital technologies represents a critical differentiator in circular city engineering approaches. The United States has invested heavily in smart waste management systems, IoT sensors, data analytics platforms, and artificial intelligence applications that optimize collection, processing, and resource recovery operations (Lazoroska et al., 2023).

Advanced monitoring systems, predictive maintenance technologies, and automated process control enable higher efficiency and reliability in waste-to-energy and upcycling operations. The development of blockchain systems for waste tracking, mobile applications for community engagement, and integration with smart city platforms demonstrates the potential for technology-enhanced circular systems.

Emerging economies have demonstrated innovative applications of mobile technologies, community-based monitoring systems, and adaptive digital solutions that address local challenges while maintaining cost-effectiveness. The emphasis on appropriate technology, user-centered design, and community ownership has resulted in sustainable digital solutions that enhance circular economy performance.

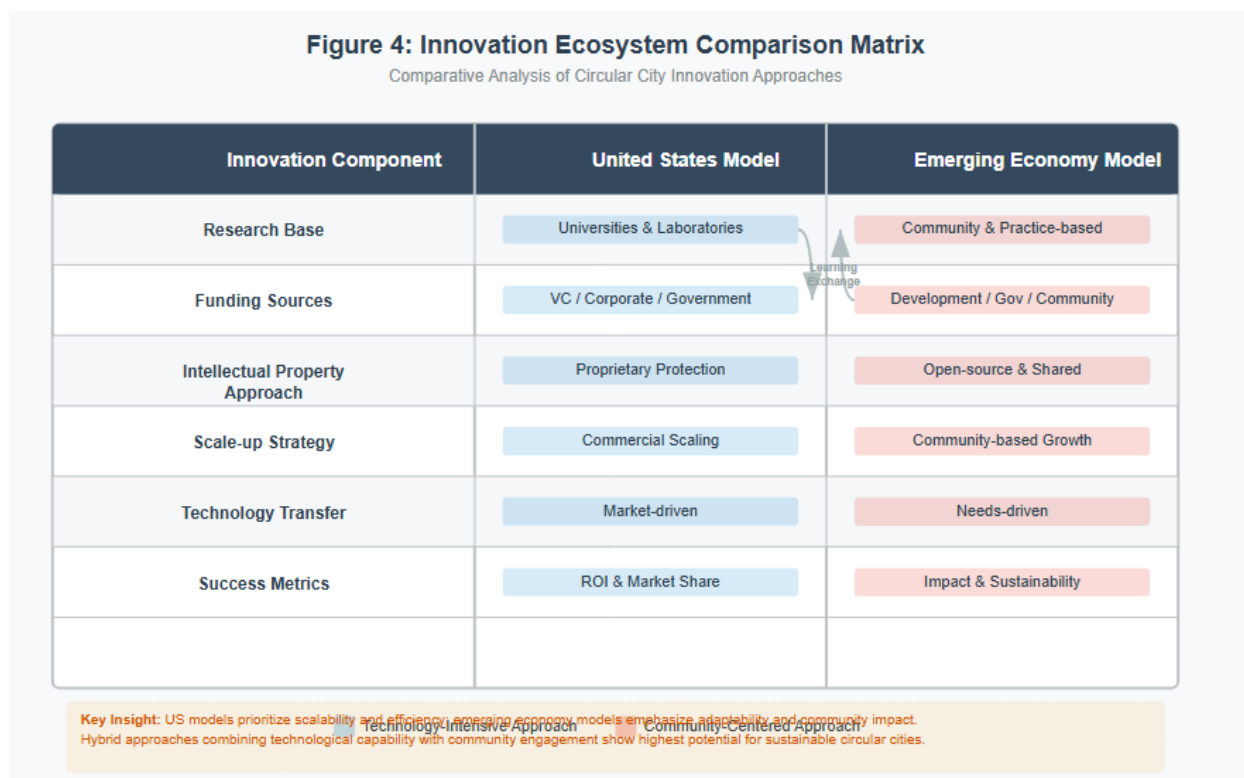
9.2 Innovation Ecosystems and Knowledge Transfer

The development of innovation ecosystems supporting circular city engineering varies significantly across contexts. The United States benefits from established research institutions, venture capital investment, and corporate R&D programs that drive continuous technological advancement (Jakimiuk et al., 2023).

University partnerships, incubator programs, and technology transfer initiatives have created robust innovation pipelines that translate research into commercial applications. The emphasis on intellectual property protection, market commercialization, and scale-up support enables rapid technology deployment and diffusion.

Emerging economies have developed alternative innovation approaches that emphasize open-source technologies, community-based innovation, and South-South knowledge exchange. The integration of traditional knowledge with modern technologies has created unique solutions that may offer broader applicability.

Figure 4: Innovation Ecosystem Comparison



10. Challenges and Barriers to Implementation

10.1 Systemic Challenges in Developed Economies

The United States faces significant challenges in circular city engineering despite advanced technological and financial capabilities. Regulatory complexity, high capital costs, and market volatility create barriers to rapid deployment of circular systems. The emphasis on large-scale, centralized systems may limit flexibility and community integration.

Infrastructure lock-in effects, sunk costs in existing systems, and institutional inertia present substantial challenges to system transformation. The need for coordinated action across multiple governance levels and stakeholder groups creates implementation complexity that may slow progress toward circular city objectives.

10.2 Resource and Capacity Constraints in Emerging Economies

Emerging economies face fundamental resource and capacity constraints that limit circular city implementation despite innovative approaches and strong community engagement. Limited access to capital, inadequate technical expertise, and weak institutional capacity create barriers to system development and scale-up (Rezania et al., 2023).

The challenge of balancing immediate development needs with long-term sustainability objectives requires careful prioritization and resource allocation. The need for international cooperation, technology transfer, and capacity building support remains critical for successful circular city engineering in emerging economy contexts.

Table 7: Implementation Barriers Comparison

Barrier Category	United States	Emerging Economies	Mitigation Strategies
Financial	High capital costs, market volatility	Limited capital access, financing gaps	Innovative financing, blended finance
Technical	Technology complexity, lock-in	Limited infrastructure expertise	Technology transfer, capacity building
Regulatory	Complexity, compliance costs	Weak enforcement, policy gaps	Regulatory reform, harmonization
Social	Community resistance, equity	Limited awareness, participation	Engagement programs, benefit sharing
Institutional	Coordination challenges	Weak governance, corruption	Institutional strengthening, transparency

Source: Negrete-Cardoso et al. (2022); Soto et al. (2023); Karpińska & Śmiech (2022)

11. Best Practices and Success Factors

11.1 Integrated System Design

Successful circular city engineering requires integrated system design that considers technical, economic, social, and environmental dimensions simultaneously. The most effective models demonstrate strong coordination between waste collection, processing, energy generation, and material recovery systems while maintaining flexibility for adaptation and optimization.

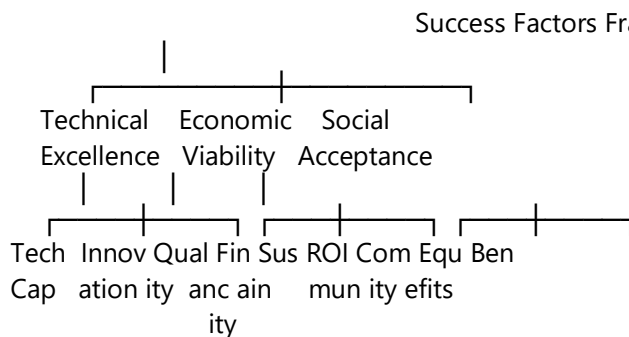
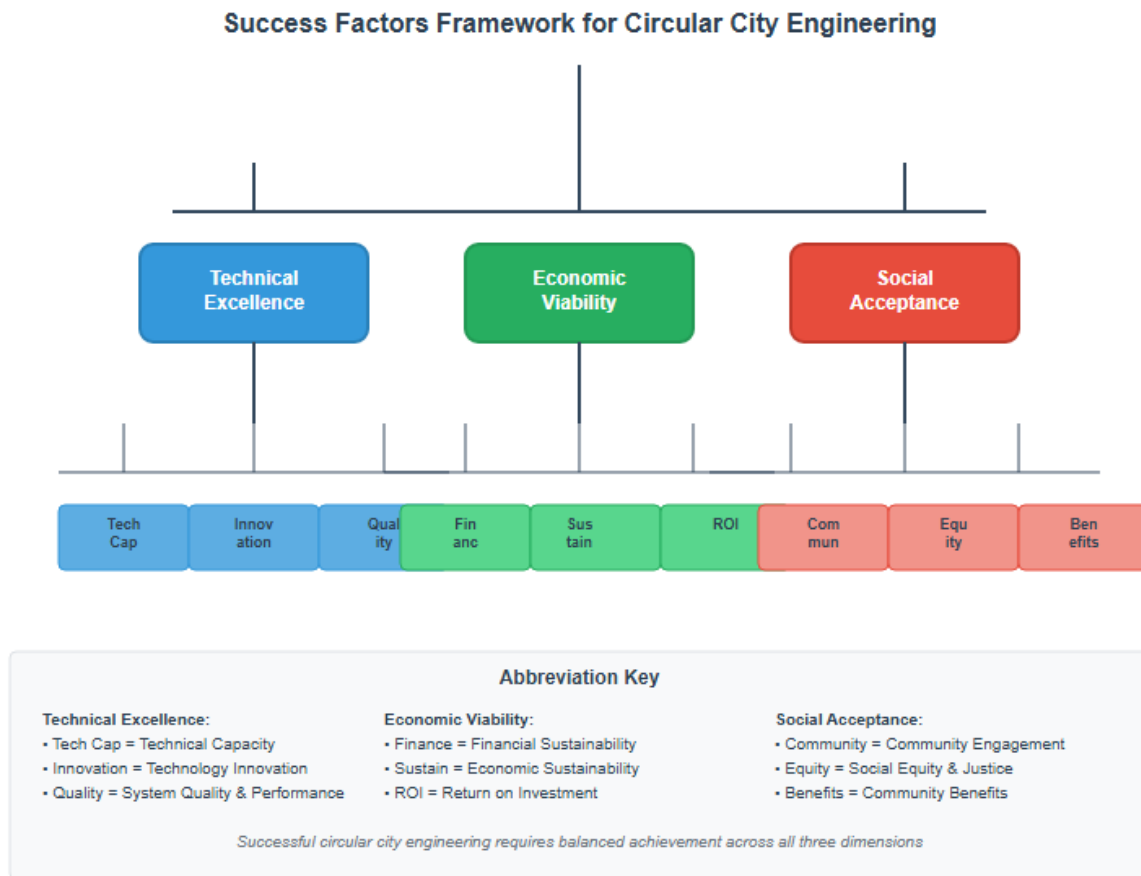
The integration of multiple waste streams, diverse processing technologies, and various end-use applications enables system resilience and economic viability. The development of industrial symbiosis networks, where waste from one process becomes input for another, represents an advanced approach to system integration that maximizes resource utilization.

11.2 Stakeholder Engagement and Community Ownership

Community engagement emerges as a critical success factor across all contexts, though approaches vary significantly. Successful models demonstrate meaningful stakeholder participation in planning, implementation, and operation phases while ensuring equitable distribution of benefits and costs.

The development of community ownership models, local employment opportunities, and transparent governance structures enhances social acceptance and system sustainability. The integration of informal sector workers, community-based organizations, and local enterprises creates inclusive circular systems that address social as well as environmental objectives.

Figure 5: Success Factor Framework for Circular City Engineering



Tech Cap = Technical Capacity Sus = Sustainability Com = Community
 Innov = Innovation ROI = Return on Investment Equ = Equity
 Qual = Quality Fin = Financial Ben = Benefits

12. Future Directions and Emerging Trends

12.1 Technology Evolution and Convergence

The future of circular city engineering will likely be characterized by technology convergence, where advances in artificial intelligence, biotechnology, materials science, and renewable energy systems create new opportunities for waste valorization and resource recovery. The development of bio-based processing technologies, advanced materials recovery systems, and integrated energy-water-waste management platforms represents emerging frontiers for circular system development.

The integration of carbon capture and utilization technologies with waste-to-energy systems offers potential for negative emissions and enhanced environmental performance. The development of decentralized manufacturing systems, enabled by 3D printing and automated production technologies, may transform upcycling approaches by enabling on-demand production of customized products from waste materials.

12.2 Policy Innovation and Governance Evolution

Future policy development will likely emphasize adaptive governance frameworks that enable experimentation, learning, and continuous improvement in circular city systems. The development of regulatory sandboxes, outcome-based regulations, and performance-based incentives may accelerate innovation while maintaining environmental and safety standards.

The integration of circular economy principles with climate policy, sustainable development goals, and environmental justice objectives creates opportunities for comprehensive policy frameworks that address multiple sustainability challenges simultaneously. The development of international cooperation mechanisms, technology transfer programs, and capacity building initiatives will remain critical for global circular city development.

13. Conclusion

This comparative analysis of waste-to-energy and upcycling models in the United States and emerging economies reveals significant diversity in approaches, achievements, and challenges in circular city engineering. The United States demonstrates advantages in technological sophistication, regulatory compliance, and large-scale implementation, while emerging economies excel in community engagement, adaptive innovation, and cost-effectiveness.

The key finding of this analysis is that successful circular city engineering requires context-specific approaches that balance technological capability with socioeconomic realities. Neither the high-technology, capital-intensive approach typical of developed economies nor the community-based, resource-constrained approach common in emerging economies alone provides optimal solutions for all contexts.

The most promising path forward involves hybrid models that combine the technological capabilities and regulatory frameworks of developed systems with the community engagement, adaptive innovation, and cost-effectiveness of emerging economy approaches. This synthesis requires enhanced international cooperation, technology transfer, and knowledge exchange that enables mutual learning and improvement.

The evidence suggests that circular city engineering success depends on the integration of multiple factors: technical excellence, economic viability, social acceptance, environmental performance, and institutional capacity. The most sustainable and scalable models demonstrate strength across all these dimensions while maintaining adaptability to changing conditions and emerging opportunities.

Future research should focus on developing frameworks for technology transfer, policy harmonization, and capacity building that enable broader adoption of circular city principles. The development of standardized performance metrics, assessment methodologies, and best practice guidelines will facilitate comparison, learning, and improvement across different contexts.

The transition toward circular cities represents both a significant challenge and an unprecedented opportunity for sustainable urban development. The successful engineering of circular cities requires not only technological innovation and policy support but also fundamental transformation of social attitudes, economic incentives, and institutional arrangements that support sustainable resource management and community resilience.

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