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Bridging circularity and inclusion in urban metabolic transitions: Through the lens of waste system evolution in Almere, the Netherlands

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ABSTRACT

Waste is a key material stock and flow in urban metabolism, and circular economy (CE) strategies are increasingly promoted to enhance resource efficiency and reduce environmental burdens. Yet CE practices do not always evolve in harmony with dynamic social needs, leading to exclusionary outcomes. To examine how circularity and inclusion interact in urban metabolic transitions, this paper analyses the evolution of Almere's waste system from the 1970s to the 2020s as a longitudinal case study. Using the Municipal Solid Waste Infrastructure System (MSWIS) model and a combination of qualitative and quantitative indicators, we identify three phases of sociotechnical system change. The findings reveal that while regulatory reforms and infrastructure upgrades advanced material recovery, more transformative outcomes emerged where inclusive governance arrangements and grassroots innovations were integrated into the waste system. Almere's experience demonstrates that when technological efficiency is aligned with social equity, waste systems can become engines of circular and inclusive urban transitions.

1. Introduction

Cities function as complex urban metabolisms, where materials and energy circulate through infrastructure and human activities (Lanau et al., 2021). Within this metabolic system, municipal solid waste (MSW) is both an outcome of urban consumption and a latent resource stream that, if recovered, can be reintroduced into urban cycles rather than accumulate as pollution (Kennedy et al., 2007). However, cities are grappling with the dual pressures of rapid urbanization and shifting consumption patterns, which strain existing municipal solid waste infrastructures (MSWIs). Globally, by 2018 over two billion people lacked waste collection services, and three billion had no access to controlled waste disposal facilities, predominantly in developing countries (UNDP, 2018).

To address these growing waste challenges, circular economy (CE) strategies are widely promoted to narrow, slow, close, and regenerate material loops (Dong et al., 2021; Kirchherr et al., 2017; Kirchherr et al., 2023; Liu et al., 2023a). Leading economies such as the European Union (EU) and China have been at the forefront of CE adoption, albeit through distinct approaches. The EU emphasizes environmental legislation and economic competitiveness through innovation, reflected in policies like the Green New Deal (Furlan et al., 2024; McDowall et al., 2017). China's CE model relies on state-driven initiatives, exemplified by the Circular Economy Promotion Law of 2008, which enforces top-down regulations and funds large-scale pilot zones (Geng et al., 2012; Ma et al., 2022). Despite these efforts, translating CE ambitions into practice has produced mixed outcomes: capital-intensive infrastructure upgrades and waste-to-energy projects have improved recovery rates in some contexts

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but also produce metabolic inequalities: uneven exposure to pollution (Ferdous et al., 2021; Purnell, 2019), uneven access to resource-recovery knowledge and opportunities (Ma et al., 2018; Nevrly et al., 2019; Wang et al., 2016), and unequal distribution of economic benefits from circular practices (Wainaina et al., 2023; Yalçın et al., 2024).

A central shortcoming in the existing literature is that urban metabolic and CE studies tend to emphasize material and technical performance while paying insufficient attention to who participates in, and who benefits from, metabolic transitions (Jaeger-Erben et al., 2021; Liu et al., 2023a; Mies & Gold, 2021; Piao et al., 2023). Informal and community-based actors, such as waste pickers, repair collectives, upcycle practices, grassroots reuse initiatives, frequently perform essential metabolic functions (collecting, sorting, repairing, reintroducing materials), yet their creativity and roles are often marginalized by formal policy frameworks (Tong & Tao, 2016; Steuer et al., 2018; Zisopoulos et al., 2023; Parajuly et al., 2024). Research on the Global South often categorizes informal actors as a group operating independently from formal systems, and emphasizes the formalization processes (Aparcana, 2017; Cook et al., 2024; Kashyap & Visvanathan, 2013). This approach overlooks key issues: (a) the constraints and exclusion (e.g., licensing, taxes) imposed by formal systems, (b) the neglected knowledge and creativity of informal actors in advancing high-level circularity (e.g., reuse, repurposing), and (c) the lack of a systemic framework to analyze how formal-informal interactions reshape the MSWI system and their broader impacts on cities. This highlights a critical gap in understanding how to align material circularity and social inclusion in MSWI upgrading so that metabolic transitions are both efficient and just.

This study addresses these gaps through a longitudinal analysis of Almere, a city in the Netherlands that has undergone a remarkable transition from landfill dependence in the 1970s to becoming a European leader in zero-waste initiatives by 2023. Almere is analytically useful for metabolic inquiry because its MSWIS evolution entailed sequential changes in material flows (from landfilling to recovery), staged infrastructure investments, and evolving actor networks that span municipal agencies, private firms, and grassroots initiatives. By tracing these changes we can observe how technical upgrades, policy shifts, and social practices jointly reconfigure local metabolic cycles.

To structure the analysis we apply the Municipal Solid Waste Infrastructure System (MSWIS) model developed in an earlier work (Liu et al., 2023b). This model conceptualizes MSWIs as a coupled socio-technical system in which technical subsystems (collection networks, sorting facilities, treatment plants, transport logistics) and social subsystems (municipal authorities, firms, civic groups, informal actors, markets and norms) jointly shape material flows and their distribution across urban space. Using this model together with mixed qualitative–quantitative indicators of circularity and inclusion, the study maps how Almere's MSWIS evolved between 1976 and 2022 and assesses the implications for urban metabolic transitions. The research is organized around three guiding questions:

- RQ1: What are the main changes in the social and technical components underpinning MSWI development?
- RQ2: How do formal and informal actors in the MSWIS interact to drive these sociotechnical transitions?
- RQ3: What impacts has the development of Almere's MSWI had on promoting urban circularity and inclusion, and what lessons can be drawn for other cities?

The following section presents the theoretical and conceptual framework, introducing the MSWIS model and clarifying how circularity and inclusion are operationalized for metabolic assessment. Section 3 outlines the research design and data sources, including the mixed qualitative–quantitative approach. Section 4 reconstructs the longitudinal evolution of Almere's MSWIS and addresses the three research questions. Section 5 discusses the mechanisms that drove the observed metabolic transitions and draws broader implications, and synthesizes lessons for policy and future research on inclusive and circular urban metabolic transitions.

2. Theoretical and conceptual framework

2.1. Cities as organisms: waste systems as engines of urban transition

Cities can be conceived as living organisms: nested, interdependent networks of infrastructures, institutions, markets, and social practices that together govern the stocks and flows of people, energy, materials and information (Inostroza & Zepp, 2021; Lanau et al., 2021). This organism can therefore be considered as a system-of-systems (SoS), because: (a) each subsystem (e.g. transport, water, energy, waste) has its own internal logic and functions, (b) subsystems are coupled by material and information flows, and (c) the overall performance of the city emerges from interactions among subsystems rather than from any single component (Dagli & Kilicay-Ergin, 2008; Jamshidi, 2008; Keating et al., 2003; Mo & Beckett, 2019). Recent interdisciplinary urban sustainability research further emphasizes that environmental, social, economic, and governance dimensions are deeply interconnected in shaping urban transitions, highlighting the need for systemic and cross-sectoral approaches to urban sustainability and metabolism (Hezardastan & Shmelev, 2025; Reijtenbagh et al., 2025; Shmelev et al., 2023).

Socio-technical transition theory, through frameworks such as the Multi-Level Perspective (MLP) (Geels, 2002) and Strategic Niche Management (SNM) (Schot & Geels, 2008), complements SoS theory by explaining how sustained change occurs in such complex settings. The MLP distinguishes three analytically useful strata: (i) the landscape (slow, exogenous pressures such as demographic change, climate risk or national legislation), (ii) the regime (the dominant configuration of technologies, institutions, markets, norms and infrastructures that stabilizes current practice), and (iii) niches (protected or experimental spaces where novel practices and technologies develop) (Geels, 2002; Smith, 2007). Transitions occur when landscape pressures destabilize regimes and niche innovations gain traction, highlighting the co-evolution of technical (facilities, processes) and social (governance, practices) subsystems that reconfigure each other (Derwort et al., 2022; Geels, 2012; Geels, 2019).

Viewed through these combined lenses, waste systems occupy a privileged position as engines of urban transition. Waste systems handle dense, continuous material flows and aggregate dispersed resource potentials (paper, plastics, bio-waste, textiles, e-waste) into manageable stocks (Arora et al., 2021; Wiedenhofer et al., 2024; Xavier et al., 2023). Therefore, how infrastructures and policies govern its redistribution determines who captures value and how power relations among actors shift. Interventions such as landfill bans, deposit-return schemes, or community reuse hubs make these dynamics visible by reallocating material flows, economic benefits, and environmental impacts. Mechanisms by which MSW interventions drive broader urban transitions include:

(1) Material leverage: redirecting waste flows into recovery channels alters resource availability and market incentives (Matter et al., 2015).
(2) Institutional realignment: new regulations, associations, or contracts reshape actor incentives and power relations (Hacking & Flynn, 2014; Lawhon, 2012).
(3) Practice change: infrastructure that makes sorting or reuse easier can shift everyday behaviors (Timlett & Williams, 2011).
(4) Niche upscaling: community experiments (repair cafés, worm-composting, upcycle centers) can be institutionalized when supportive policy and markets emerge (Ma et al., 2023; Wang et al., 2024).

In short, treating the city as an SoS and using socio-technical transition concepts highlights three central analytical points for this study: (a) waste systems are not peripheral operational details but core metabolic subsystems with high leverage on urban stocks and flows; (b) transitions in waste systems require coordinated change across technical and social domains; and (c) waste systems can function as catalytic engines that accelerate and enable sustainable transitions at the urban scale.

2.2. Municipal solid waste infrastructure system (MSWIS) – a conceptual model

Building on the SoS and socio-technical transition perspectives outlined above, the Municipal Solid Waste Infrastructure System (MSWIS) model was developed (Fig. 1) (Liu et al., 2023b). The model conceptualizes MSWI not as isolated facilities, but as interdependent socio-technical subsystems that combine technical elements (e.g., sorting plants, recycling centers, incinerators) with social ones (e.g., households, municipalities, entrepreneurs, informal actors). These subsystems are connected by flows of waste, resources, and practices, together forming a dynamic system embedded in the broader urban metabolism.

A key advantage of the MSWIS model is that it enables researchers to map transitions over time. By distinguishing technical and social subsystems and analyzing their interconnections, the model makes visible how changes in one domain (e.g., regulatory bans on landfill) can trigger adjustments in others (e.g., household separation behavior, business opportunities in recycling, or informal sector adaptations) (Hacking & Flynn, 2014; Lawhon, 2012; Schraven et al., 2025). Equally, it helps to identify how niche innovations (e.g., repair cafés or community composting) emerge, interact with mainstream infrastructures, and potentially scale when aligned with supportive policies or market demand (Spekkink et al., 2022; Wang et al., 2024).

For this reason, the MSWIS model is particularly suited for longitudinal case analysis. It highlights the adaptive dynamics of municipal waste systems, including both top-down interventions and bottom-up innovations, and situates them within broader urban metabolic transitions. In this paper, the MSWIS model is used to trace the evolution of Almere's waste system from the 1970s to the 2020s, focusing on how interactions between infrastructures, actors, and policies have driven shifts in urban circularity and inclusion.

2.3. Bridging urban circularity and inclusion through waste management

In urban metabolism studies, circularity is often framed as the technical optimization of material flows: reducing inputs, minimizing waste, and closing loops through recovery and recycling (Cui et al., 2019; Kennedy et al., 2007; Kirchherr et al., 2017; Purnell, 2019). However, such circular strategies alone do not guarantee socially just or sustainable outcomes. Without attention to inclusion, policies can generate uneven benefits, exclude vulnerable groups, or reinforce existing inequalities (Rootes, 2009; Kim et al., 2020). For example, landfill bans or waste-to-energy investments may reduce environmental impacts but simultaneously marginalize community reuse initiatives or limit income opportunities for informal waste workers (Gallagher et al., 2008; Zisopoulos et al., 2023). In Fig. 2, we present the interdependencies between urban circularity and urban inclusion viewed through the lens of MSWI.

To address this, scholars increasingly argue for coupling circularity with inclusion, defined here as the equitable participation of diverse social actors, including households, governments, communities, small enterprises, and informal initiatives, in shaping and benefiting from circular transitions (Cook et al., 2024; Henry et al., 2024; Kirkman & Voulvoulis, 2017; Liu et al., 2020; Pekdemir et al., 2025). In the waste sector, inclusion extends the scope of metabolism beyond technical loops, capturing how waste systems influence wellbeing, access to services, employment, and social cohesion (Gutberlet, 2023; Liu et al., 2023a).

Within the MSWIS model, this coupling can be operationalized by mapping not only material flows and facilities but also the actor networks, governance arrangements, and knowledge exchanges that shape system evolution. This dual focus reveals how technical upgrades (e.g., new waste collecting facilities) interact with social innovations (e.g., repair cafés, reuse networks), producing synergies or tensions between efficiency and equity. Studying circularity and inclusion together thus allows us to understand MSWIS not just as an operational infrastructure system, but as engines of sustainable metabolic transitions.

3. Research design

This research adopts a qualitative–quantitative case study approach to investigate how Almere's MSWIS evolved as part of its broader urban circular and inclusive transition. The case study was scrutinized in-depth through a combination of expert interviews, document content analysis, on-site surveys, and a stakeholder workshop. The MSWIS conceptual model (Section 2.2, Fig. 1) guided both the design of data collection and the coding framework. The model highlights technical facilities with material flows, and social actors as interdependent subsystems whose

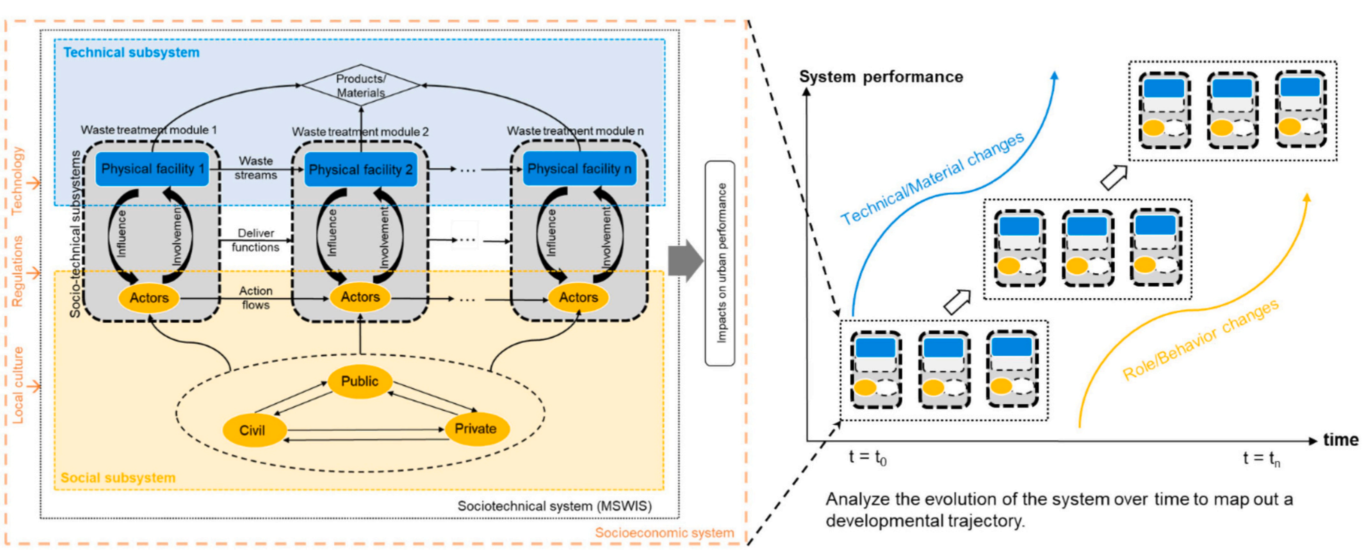

Fig. 1. Conceptual model of a municipal solid waste infrastructure system (MSWIS) (Liu et al., 2023b).

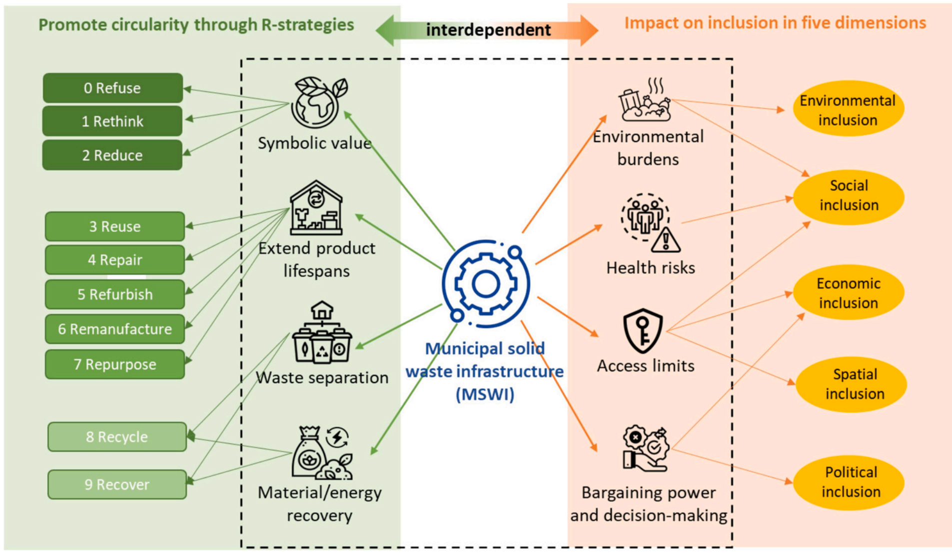

Fig. 2. The interdependencies between urban circularity and urban inclusion viewed through the lens of MSWI.

co-evolution shapes waste system performance. Applying this model allowed us to move beyond descriptive accounts of waste management, systematically tracing how a city's MSWIS adapted to regulatory pressures, infrastructural innovations, and social mobilization across different phases.

The overall research design, including case selection, data collection, coding strategy, and analytical flow, is presented in Fig. 3.

3.1. Case selection

This study employs a case study of MSWI upgrading in the City of Almere, the Netherlands. In the late 1960s, the world's largest artificial island, named Flevoland and spanning nearly 1000 km^2, was reclaimed from the sea. It was created for agriculture and to accommodate the population of the overcrowded Randstad cities such as Amsterdam and Utrecht. This island laid the foundation for the city of Almere, which saw its first residents arrive in the late 1970s. The municipality of Almere was officially established in 1984 with a projected capacity of 250,000 residents, however by 2030 the population is expected to reach 350,000 (MoA, 2021). With accelerated urbanization and population growth, many cities are exploring future models for sustainable urban development, such as Xiong'an New Area in China, Milton Keynes in the United Kingdom, and Marne-la-Vallee in France, with Almere being the Dutch version of the laboratory for future urban living.

With respect to MSWI upgrading and its relationship with urban transition goals, Almere is a compelling case study. Over fifty years, Almere has witnessed its MSWI growing from an uncontrolled landfill to an advanced waste treatment system. The nature of Almere as a newly born city has provided urban planners and many other stakeholders with the opportunity to experiment with innovative MSWI upgrading programs. Meanwhile, exceeding expected population growth and unique geographic advantages give Almere the ambition to become an internationally competitive European city, but also presents the challenge of bringing together the various stakeholders to realize the changing needs of society. In this context, the Almere Municipality has taken steps to enhance MSWI and promote public involvement and innovation through a range of initiatives and projects, including the "City Deal Circular City," "Almere Green & Healthy," and "Inclusive City of Almere." These efforts have positioned Almere as a leader in the Netherlands and Europe when it comes to advancing circular and inclusive urban transitions, and

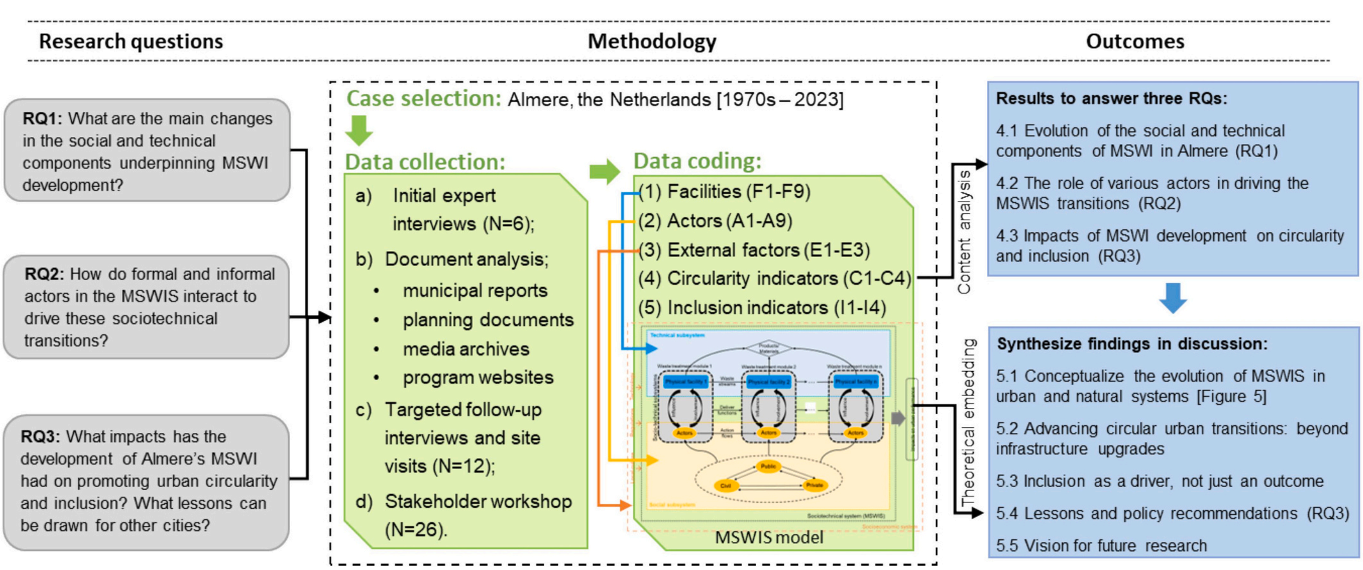

Fig. 3. Research design.

effectively made Almere a testing ground for exploring how MSWI upgrading can contribute to sustainable transitions at the city level.

3.2. Data analysis

3.2.1. Data collection

Data were collected in Almere between August 2021 and August 2023 in four steps:

1. Initial expert interviews (N = 6) with municipal officials provided an overview of system development, existing facilities, and regulatory context.
2. Document analysis of municipal reports, policy documents, historical archives, and CBS (Statistics Netherlands) provided longitudinal data on infrastructure, regulations, actor involvement, and waste collection and separation data.
3. Targeted follow-up interviews (N = 12) with contractors, entrepreneurs, artists, and residents captured perceptions of circularity and inclusion impacts, supplemented by field observations of facilities and initiatives.
4. Stakeholder workshop (N = 26) validated preliminary findings and provided expert advice on the selection of circularity and inclusion indicators.

All interviews and workshops were conducted with informed consent, and participants were assured of anonymity in reporting. Details on interviewees' professional roles, document names, data types, and sample size are provided in Appendix A.

This iterative and multi-sourced approach aligns with community-based and participatory research principles (Eisenhardt & Graebner, 2007; Henry et al., 2024), allowing us to triangulate data, engage diverse voices, and reflect the complex dynamics of sociotechnical transition in urban waste systems.

3.2.2. Data coding

We used five categories of codes for data coding (see Table 1). Three categories of codes were predetermined by the MSWIS conceptual model introduced earlier and developed in our previous study (Liu et al., 2023b): facilities in the technical subsystem (F1–F9), actors in the social subsystem (A1–A9), and external factors (E1–E3). These categories (FAE) are therefore not newly constructed in this study but form the baseline structure for tracing how the MSWIS evolves over time.

For the circularity (C1–C4) and inclusion (I1–I4) indicators, we adopted a deductive–inductive approach. Deductively, codes from the literature were used to define the scope of potential indicators (see Appendices B and C). Inductively, these initial codes were screened, revised, and supplemented through expert interviews and the stakeholder workshop. This ensured that the selected indicators were not only theoretically grounded but also contextually relevant to Almere.

4. Results

Structured around the study's three research questions, the results highlight the technical and social transformations of the MSWI system, the role of formal and informal actors in shaping these transitions, and the implications for circularity and inclusion in urban waste management.

4.1. Evolution of the social and technical components of MSWIS in Almere

The development of Almere's MSWIS over the past five decades can be divided into three phases, each marked by distinct interactions between technical facilities, social actors, and external pressures. Fig. 4 gives an overview of the evolution of MSWI in Almere, namely the location and duration of waste facilities in Almere from 1970 to 2020. We have illustrated the key elements in the three phases in Fig. 5.

4.1.1. Phase I: landfill dependence and informal waste trading (1970s–1980s)

Almere's early MSW management relied almost exclusively on landfill, reflecting limited infrastructure and low public awareness. Grassroots initiatives, such as schools and sports clubs collecting paper or local farmers organizing bottle reuse, played a complementary but small-scale role. External pressures grew as national legislation tightened, culminating in the Chemical Waste Act (1977) and the Waste Act (1979), which forced the municipality to begin upgrading its system. At this stage, the technical subsystem remained rudimentary, but regulatory and health concerns at the landscape level destabilized the existing regime. Recycling remained informal, fragmented, and uncoordinated, limited by a lack of policy support and centralized infrastructure.

Table 1
Data coding framework.

Facilities in the technical subsystem	Actors in the social subsystem	External factors	Circularity indicators	Inclusion indicators
F1. Waste generation sites	A1. Municipality	E1. Regulations including laws, policies, rules that regulate actors' activities and the process of developing and using physical facilities	C1. The influence of MSWI upgrading on MSW generation	I1. Adoption of social innovations in MSWI upgrading
F2. Waste reuse and upcycle platforms	A2. Industries	E2. Local culture that shapes the interactions, awareness, and behaviors of actors in relation to waste treatment	C2. The influence of MSWI upgrading on MSW separation	I2. Habitat- and nature-friendly MSWI
F3. Waste collection containers	A3. Businesses	E3. Technologies that are applied in physical facilities and social activities	C3. The R-strategies adopted in the MSWI upgrading process	I3. Affordability and accessibility of MSWI and related waste services
F4. Waste sorting facilities	A4. Households		C4. The presence of MSWI upgrading-related circular initiatives	I4. Public evolvement in the decision-making and operational processes of MWSI
F5. Waste transportation tools	A5. Communities			
F6. Waste storage sites	A6. Waste traders			
F7. Waste-to-resource conversion facilities	A7. Waste recycling companies			
F8. Waste-to-energy recovery facilities	A8. Waste recovery companies			
F9. Landfill sites	A9. Landfill management company			

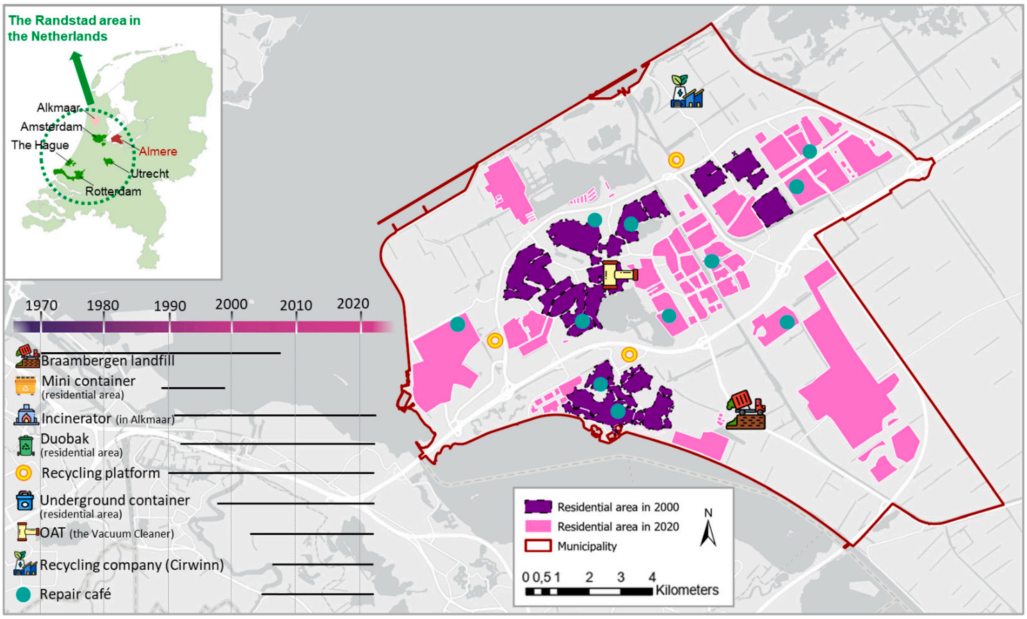

Fig. 4. Location and duration of various waste facilities in Almere (1970–2020).

4.1.2. Phase II: infrastructure expansion and centralized recycling (1980s–2000s)

Responding to landfill saturation and rising waste volumes, Almere invested in capital-intensive facilities, including chemical waste collection ("Chemocar"), multi-compartment bins, and partnerships with companies such as VAR (bio-waste composting) and HVC (waste incineration). These moves illustrate the mechanism of *material leverage* and *practice change*, redirecting waste flows into recycling and recovery channels. Social actors, however, became increasingly dependent on centralized infrastructures, and many earlier grassroots collection schemes declined. The regime shifted toward municipal–business cooperation, but inclusiveness remained limited as facilities often conflicted with residential space and generated community resistance.

4.1.3. Phase III: systematic design and multi-actor collaboration (post-2000)

With population growth and densification, Almere introduced systematic five-year waste management plans and diversified infrastructures, including underground containers, pneumatic collection (Ondergronds Afvaltransportsysteem, OAT), and recycling platforms. At the same time, community innovations such as Repair Cafés and Worm Hotels emerged, addressing gaps in municipal service and advancing higher-level circular strategies (reuse, repair). This phase demonstrates *institutional realignment* and *niche upscaling*: municipal policies increasingly incorporated citizen-led experiments, and regional initiatives such as the Raw Material Collective and PRICE Center connected municipalities, businesses, and knowledge institutions. The MSWIS thus evolved into a more integrated socio-technical system, balancing efficiency with inclusiveness.

4.2. The role of various actors in driving the MSWIS transitions

The evolution of Almere's MSWIS was not only a technical process but also the result of dynamic interactions among government agencies, businesses, community organizations, and residents. These interactions shifted over time, reflecting changing power relations, cooperation patterns, and social inclusion. The role changing and interactions have also been reflected in Fig. 3.

4.2.1. Phase I: state-led regulation and limited engagement

In the early years, municipal agencies dominated MSW management, focusing on basic collection and landfill operations. Non-state actors participated mainly through ad hoc grassroots recycling (e.g., paper collection by schools, bottle reuse by farmers), driven by economic incentives rather than environmental concerns. Their role remained marginal in decision-making, as governance was top-down and oriented toward compliance with emerging national regulations.

4.2.2. Phase II: government–business partnerships and centralization

As landfill bans and environmental laws came into force, the municipality increasingly collaborated with large waste companies such as VAR and HVC to develop capital-intensive facilities. Businesses brought investment and expertise, while the municipality coordinated planning and contracts. This partnership marked a shift toward privatization of treatment services, though collection remained under municipal control. Civil society's earlier role diminished, as centralized infrastructures crowded out small-scale initiatives. Inclusion was limited, with community concerns over truck traffic and space conflicts often sidelined.

4.2.3. Phase III: multi-actor cooperation and networked governance

From the 2000s onward, Almere embraced more systematic and participatory governance. The municipality launched education campaigns, supported startups through the Upcycle Center, and incentivized household separation. Meanwhile, community-led initiatives such as Repair Cafés and Worm Hotels complemented formal services by promoting reuse and decentralized composting. Importantly, regional networks such as the Raw Material Collective and PRICE Center institutionalized collaboration between municipalities, businesses, knowledge institutions, and citizens. These platforms facilitated knowledge sharing and scaling of innovations, reflecting a transition from hierarchical governance toward cooperative networks.

It is worth to note that several municipal mechanisms facilitated the integration of grassroots circular initiatives into Almere's evolving waste system. Interviewees highlighted that the municipality increasingly adopted a facilitating role by providing working spaces and facilities for circular experiments, supporting networking events, and incorporating community initiatives into broader urban sustainability programs. For example, initiatives such as the Upcycle Center and Repair Café benefited from municipal visibility, collaborative platforms, and

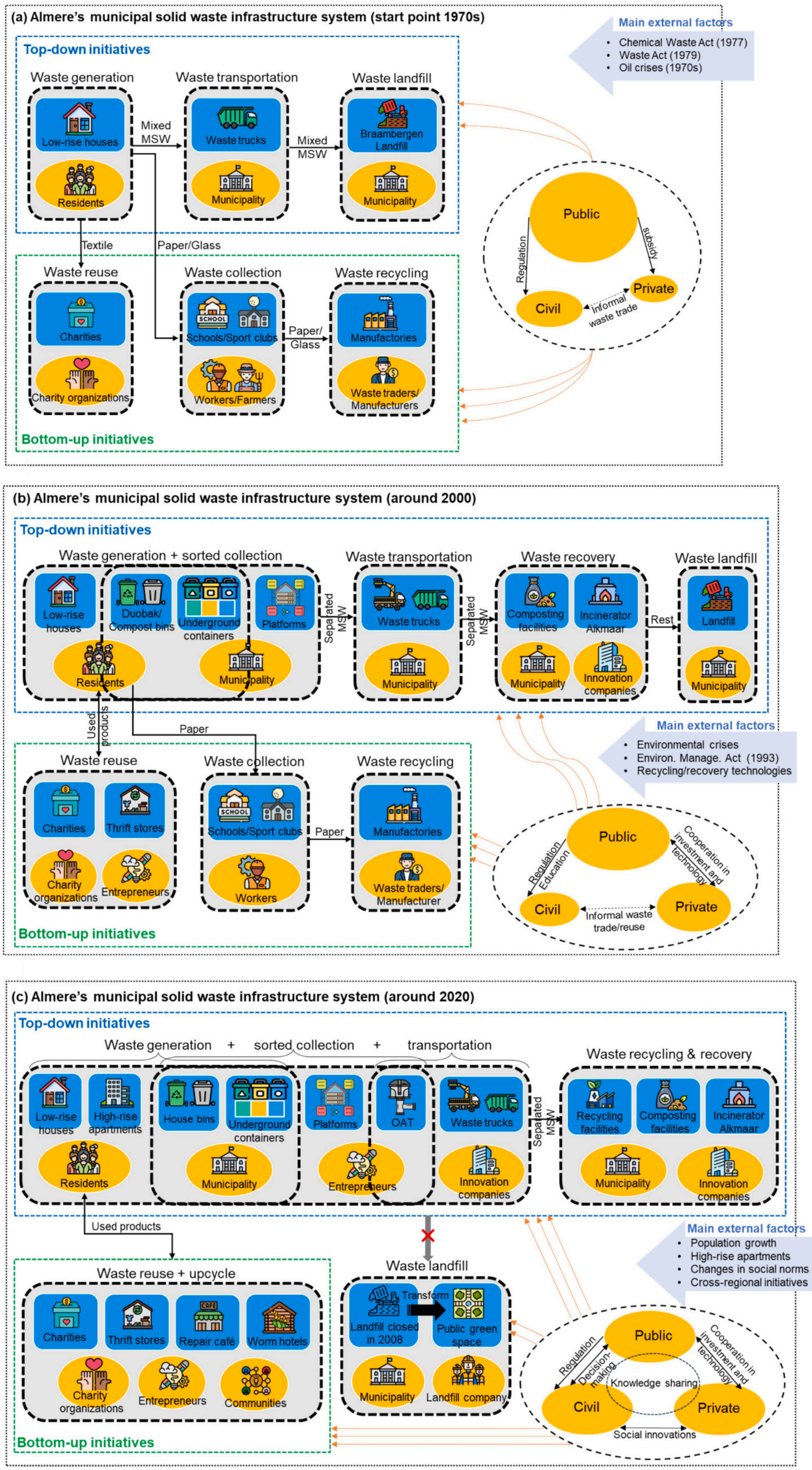

Fig. 5. The MSWIS in Almere in 1970s (a), 2000 (b), and 2020 (c).

connections with local businesses and educational institutions. Rather than fully formalizing or centralizing grassroots activities, these arrangements enabled community-based initiatives to operate alongside formal waste infrastructures while contributing to broader circularity goals.

4.3. Impacts of MSWI development on circularity and inclusion

Over time, Almere's MSWIS shifted from landfill dependency to an integrated circular system, leading to measurable reductions in waste generation, increased material recovery, and expanded public participation and equitable benefits. Using indicators developed in Table 1, Table 2 gives an overview of how Almere MSWIS evolution, both technically and socially, has impacted urban circularity and inclusion at three stages.

As illustrated in Fig. 6, Almere experienced rapid population growth between 2001 and 2021, while total MSW generation remained relatively stable overall. At the same time, per-capita MSW generation showed a gradual declining trend, suggesting a partial decoupling between urban growth and waste generation. Waste separation rates also improved significantly during this period, reflecting the combined effects of infrastructure upgrades, policy interventions, and increasing public participation in waste sorting practices. A temporary reversal can be observed around 2020, when both total and per-capita waste generation increased and separation rates declined slightly, likely associated with changes in household consumption and waste practices during the COVID-19 pandemic. However, the indicators shifted again in 2021 toward pre-pandemic levels.

Overall, Almere demonstrates that circularity and inclusion are mutually dependent in urban metabolic transitions. Technological upgrades alone can raise recovery rates but risk exclusion, and social inclusion without adequate infrastructures risks stagnation. For example, some interviewees noted that underground waste containers occasionally caused odor, noise, and concentrated waste-related nuisances for nearby residents, redistributing environmental burdens unevenly across neighborhoods. In addition, the expansion of pneumatic collection systems improved urban cleanliness and collection efficiency but required substantial infrastructure investments, contributing to concerns over rising municipal waste management costs and waste taxes. Several interviewees also highlighted that increasingly complex sorting systems, digitalized collection arrangements, and Dutch-language communication materials could create accessibility challenges for newcomers, elderly residents, and non-Dutch-speaking groups. These examples illustrate that circular infrastructure transitions may simultaneously improve system efficiency while generating new inequalities, frictions, and differentiated experiences across urban communities. The pursuit of circularity therefore required continuous adjustments and negotiations to reconcile infrastructural efficiency with affordability, accessibility, and everyday urban life. The most transformative outcomes occur when technical facilities, policies, and social practices align to redirect material flows and redistribute economic and social value.

5. Discussion and conclusions

5.1. Conceptualize the evolution of MSWIS in urban and natural systems

This research applies the MSWIS model to Almere to analyze how waste infrastructures are assembled, reconfigured, and embedded in broader urban and ecological contexts. It demonstrates how technical and social elements interact—competing, adapting, and reconfiguring—to shape sustainable urban transitions. As illustrated in Fig. 7, we conceptualize the dynamic evolution of MSWIS within three interconnected layers: MSWIS, the urban system, and the ecosystem. These interactions highlight adaptive feedbacks between waste management, governance, and ecological sustainability.

At the MSWIS level, the framework focuses on the co-optimization of technical and social subsystems. MSWI facilities interact through waste flows, with ongoing modifications to system components. Formal and informal actors engage in co-creation of value and benefit from knowledge sharing, ensuring more inclusive and adaptive solutions.

At the urban system level, circular and inclusive goals emerge in response to environmental crises, economic dynamics, and urban expansion. These pressures drive regulatory, technological, and cultural changes, which, in turn, shape MSWIS through learning, aggregation, and innovation. The inclusion of diverse actors and the mobilization of financial and knowledge resources further reinforce system evolution.

At the ecosystem level, environmental pressures such as climate change and resource scarcity cascade into cities, motivating adaptation and transformation. Innovations and pilot projects contribute to system learning, while lessons from failed experiments inform refined strategies. This multi-layered perspective underscores MSWIS as a dynamic socio-ecological subsystem that both shapes and is shaped by its urban and natural environment.

Table 2
Impact of Almere MSWIS evolution on urban circularity and inclusion.

Time		1970s (start point)	1980s to 2000	Post-2000
Circularity indicators	C1. MSW generation	Uncontrolled waste generation ended up in landfill	MSW generation (per household) increased by 22% during the years 1989–1999	MSW generation (per resident) decreased by 18.5% during the years 2001–2021
	C2. MSW separation	MSW separation was not conducted	MSW separation rate climbed from 14% in 1989 to 42% in 1999	MSW separation rate rose steadily and reached 60% in 2021
	C3. Adopted R-strategies	Reuse and recycle at small scale	Reuse, recycle, and centralized recovery	Reduce, reuse, repair, and upscaled recycling and recovery
	C4. Presence of circular initiatives.	Informal waste trading among civil and private actors.	Top-down waste reduction and separation initiatives.	Various top-down and bottom-up circular initiatives, even cross city regions.
Inclusion indicators	I1. Adoption of social innovations	Limited local initiatives driven by economic incentives	Innovation companies contributed to reuse and recovery facilities	Innovation/Startup companies and communities engage in initiatives
	I2. Habitat- and nature-friendly projects	Environmental and health risks posed by landfilling	Waste collection/transport caused noise and safety concerns	The underground waste transportation system reduced disruption to city center; landfill site became a public green space; employment of vulnerable groups
	I3. Affordability and accessibility of facilities and services	Accessible but basic waste treatment services	Lack of knowledge restricted effective utilization of facilities	Accessible waste services but high waste taxes
	I4. Public involvement in decision-making and operational processes	Civil and private actors were not involved in decision-making process	Top-down decision-making but involvement of private sectors	Broader public participation in the decision-making and operational process

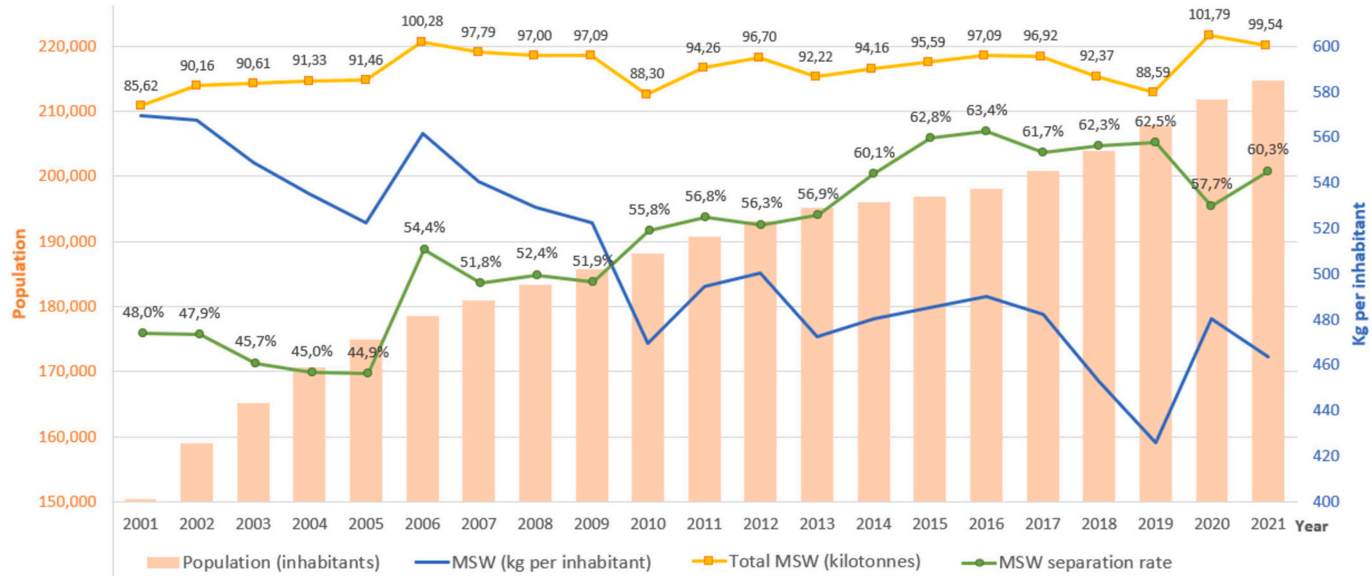

Fig. 6. Trends in population, MSW generation (in total and per-capita), and MSW separation rate in Almere from 2001 to 2021 (data source (CBS, 2023)).

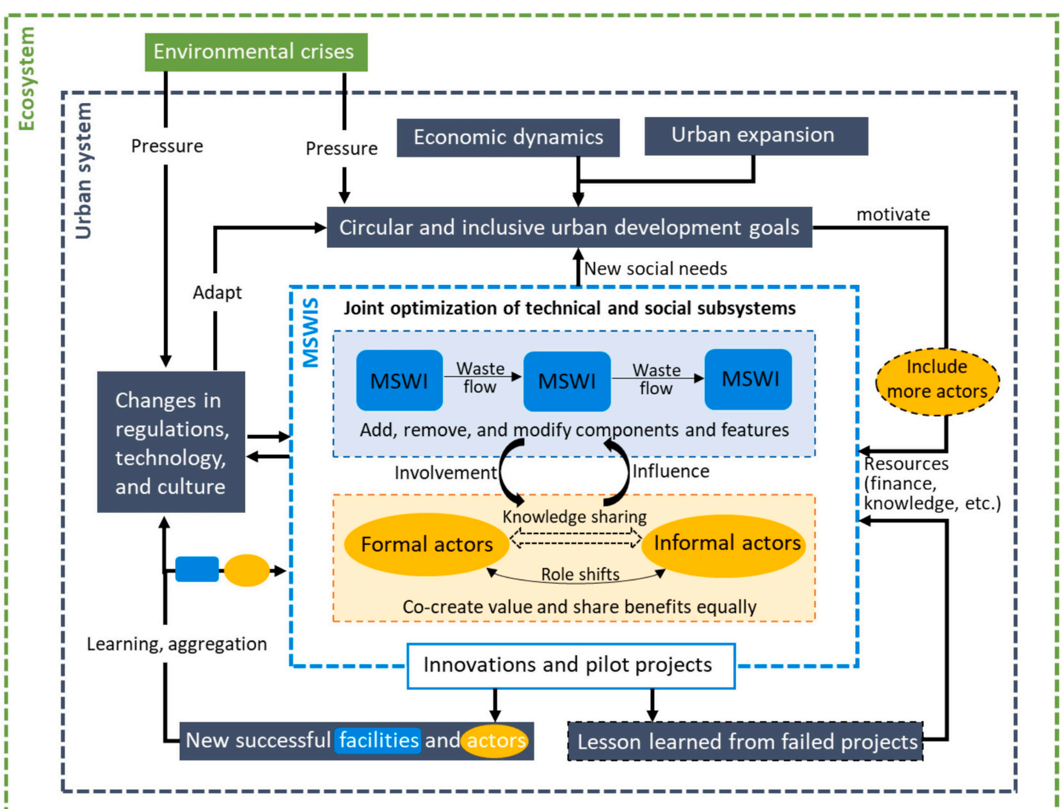

Fig. 7. Dynamic evolution of MSWIS in urban and natural systems.

5.2. Advancing circular urban transitions: beyond infrastructure upgrades

The findings confirm that infrastructure upgrades alone are insufficient to achieve circular urban transitions. Social recognition, systematic governance, and cross-sector collaboration play equally critical. Almere's experience aligns with CE research emphasizing multi-actor involvement (Geissdoerfer et al., 2017; Kirchherr et al., 2017) but extends this understanding by showing that technical efficiency must be matched with social acceptance and legitimacy.

As illustrated in Fig. 7, Almere's trajectory was not linear but iterative: regulatory pressures, social needs, and pilot projects continuously interacted. While some innovations succeeded, others failed and were discarded. Over time, Almere's focus shifted from narrow waste management to a broader mission of building a circular and inclusive city. This involved modifying technical components, mobilizing both formal actors (government, businesses) and informal actors (community organizations, knowledge networks), and embedding waste into a wider vision of urban sustainability.

Moreover, policy continuity and adaptability were essential in reshaping the Dutch waste system. Fiscal policy instruments such as the landfill tax increased pressure to divert waste away from landfill disposal and accelerated investments in recycling and energy recovery infrastructures. In contrast, taxes and levies on waste incineration were introduced to discourage excessive reliance on waste-to-energy systems and stimulate higher-order circular strategies. However, their implementation and adjustment became subjects of ongoing political and economic debate concerning international competitiveness, waste trade, and the balance between recycling and energy recovery. These shifts illustrate how urban metabolic transitions are shaped not only by technological innovation, but also by evolving policy priorities, economic pressures, and political trade-offs. Recent studies similarly argue that policy instruments, including taxation, extended producer responsibility, and public awareness programs, are most effective when implemented as integrated governance frameworks rather than isolated interventions (Steuer & Chen, 2023)(Hezardastan & Shmelev, 2025). The Almere case supports this argument by demonstrating that long-term circular transitions depend on adaptive governance arrangements capable of aligning economic incentives, social participation, and infrastructural change over time.

5.3. Inclusion as a driver, not just an outcome

This study demonstrates that inclusion is not merely an outcome of waste infrastructure upgrades but a driver of circular transitions. Almere's evolution shows how shifts in roles, responsibilities, and power relations, moving from hierarchical governance to collaborative co-creation, generated both material and social value. Volunteer networks, social enterprises, and employment programs for marginalized groups reinforced CE objectives by embedding circular behaviors across social groups.

Yet earlier phases of Almere's development mirrored global patterns where MSWI disproportionately impacted low-income residents (Wilson et al., 2012) and marginalized informal recyclers despite their contributions. Subsequently, when technological upgrades improved material recovery and urban cleanliness, they also redistributed environmental burdens, accessibility conditions, and economic costs unevenly across social groups and neighborhoods. These findings suggest that inclusive urban governance should not be understood as a frictionless alignment of technical and social goals, but rather as an ongoing process of balancing environmental performance, economic feasibility, and differentiated social impacts.

Globally, many governments frame informal waste pickers primarily as low-cost labor, with formalization policies aimed at efficiency gains (Kasinja & Tilley, 2018; Zisopoulos et al., 2023). This risks suppressing the creativity of informal actors in reuse, repair, and upcycling. In contrast, Almere illustrates the potential of grassroots initiatives to generate not only economic value (resource recovery, job creation) but also social cohesion. Supporting such bottom-up initiatives ensures that circularity is pursued in tandem with social inclusion, creating more resilient urban economies.

The Almere case further suggests that integrating grassroots initiatives into urban waste systems requires governance approaches that move beyond centralized infrastructure provision. Flexible institutional arrangements, intermediary networks, and municipal support for experimental spaces enabled decentralized circular initiatives to interact with formal infrastructures without being fully absorbed into bureaucratic structures. These findings highlight the importance of enabling and coordinating roles for municipalities in fostering inclusive urban metabolic transitions.

5.4. Lessons and policy recommendations

MSW management is a classic "wicked problem," shaped by historical legacies, socio-economic structures, and cultural norms. While no universal solution exists, Almere offers transferable lessons for cities pursuing circular and inclusive transitions.

1. **Adaptive policy frameworks:** Waste policies must remain flexible to avoid constraining innovation. For example, restrictive reuse laws can hinder entrepreneurs in scaling up upcycling operations. Regulatory frameworks should support experimentation and circular business models rather than inhibit them.
2. **Economic incentives beyond infrastructure:** Financial support should extend beyond centralized facilities to include grassroots initiatives such as Repair Cafés, composting schemes, and reuse hubs. Non-monetary support (e.g., facilities, tools, logistical aid) can further empower community-driven solutions.
3. **Communication and knowledge sharing:** Networks and platforms that connect diverse actors can accelerate the diffusion of low-cost, community innovations such as worm hotels and repair networks, embedding them into wider sustainability strategies.
4. **Integrated governance frameworks:** Waste management must be aligned with energy, food, housing, and mobility strategies to avoid fragmentation. Cross-sectoral leadership structures can strengthen coordination and link grassroots circular efforts to broader urban sustainability transitions.

5.5. Vision for future research

Based on the findings and limitations of this research, we propose four directions for future research.

First, the long historical scope meant relying heavily on archival documents and official reports. Future research should incorporate oral histories and participatory methods to capture diverse perspectives, especially from informal recyclers, residents, and grassroots innovators.

Second, while this study underscores the importance of social mobilization, it does not fully disentangle the mechanisms of multi-stakeholder involvement. Future work could examine which groups drive socio-technical change, under what conditions, and with what distributional impacts.

Third, more research is needed on how specific policy instruments, such as financial incentives, regulations, or bans, shape actor behavior and infrastructure adaptation. For instance, the 2023 Dutch deposit-return policy (Rijksoverheid, 2023) spurred both new formal collection systems and informal recovery networks, illustrating how regulatory shifts can catalyze multi-actor responses. How to design adaptive instruments that guide such responses without unintended exclusion remains an open question.

Finally, future research should further examine the limitations of infrastructure-led circularity across different waste streams and explore how upstream interventions at the production and consumption stages influence urban metabolic transitions. Interviewees in Almere noted that, despite long-term investments in source separation infrastructures, the recyclability and sorting quality of certain waste streams, particularly plastics, remained inconsistent, contributing to recent PMD+ post-separation initiatives in the city (MoA, 2024). This suggests that downstream waste collection and processing systems alone may not fully resolve the complexity of contemporary material flows. Future studies could therefore investigate how measures such as packaging standardization, extended producer responsibility, bio-based material innovation, and emerging international plastics governance frameworks interact with local waste infrastructure systems to support more systemic circular transitions.

CRediT authorship contribution statement

Zhaowen Liu: Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Daan Schraven:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Martin de Jong:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Xin Tong:** Writing – review & editing, Supervision, Methodology. **Ling Han:** Writing – review & editing. **Marcel Hertogh:** Writing – review & editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Data collection procedure

Steps and methods	Interviewees/documents	Type of data	Sample size
(1) Initial expert interviews	• Public servants from the Municipality of Almere, including the Head of the City Cleaning Department and manager of the Infrastructure and Mobility Section • Several employees involved in waste management initiatives in Almere	• Type, function, and location of the existing facilities, • Main governmental agencies and social organizations in waste sector, • National policies, regional regulations, and local cultures relayed to MSW.	6 interviewees
(2) Document content analysis	Historical textual information and quantitative data from the principals, databases, and the program's website, including: • Yearly Waste Management Report of Almere, • Five-year Waste Management Plan of Almere, • Sustainable Development Agenda of Almere (2050), • Historical newspaper stored in City Archive of Almere (1980–2004), • Waste policy in the EU and the Netherlands, • CBS (Statistics Netherlands)	Historical data of: • Type, function, and location of the MSWI, • Stakeholders' role and networks, • Waste-related projects and initiatives, • Waste-related law, policy, and regulations, • Economic, social, environmental dynamics, • Population, waste collection quantity, and waste separation rate	25 policy documents and government reports; 230 archived news articles
(3) Targeted follow-up interviews and site visits	• Contractors of the MSWI, • Employees of the waste treatment companies, • Waste-related start-ups, • Upcycling artists, • Local residents	• Type, function, and location of the MSWI, • Motivation for developing the MSWI, • Methods and challenges of cooperation among stakeholders, • Stakeholders' perceptions of their impact on the circularity and inclusion of the city.	12 interviewees
(4) Stakeholder workshop ('Towards inclusive and circular urban waste management systems' on 14th June 2022)	• Academics in the field of CE, • Businesses in waste treatment, • Think-tanks work with Almere CE initiatives, • Public organizations involved in CE initiatives in Almere	• Verification of the preliminary data analysis, • Supplementary data on MSWI and stakeholders, • Advices on selecting circularity and inclusion indicators.	26 workshop participants

Appendix B. Methods and indicators for measuring circularity at various levels

Level	Scope	Approach	Circular indicators
Micro	Products, individual enterprises, and consumers	• Life Cycle Analysis (LCA) • Material Flow Analysis (MFA) • Resource Efficiency Assessment • Product Composition Analysis • Emergy analysis • Survey/Fuzzy methods	• Carbon footprint & emissions (Fang et al., 2017; Yang et al., 2023) • Depletion of non-renewable resources (Szargut et al., 2002) • Energy/Water use (Eberhardt et al., 2019; Fregonara et al., 2017) • Longevity & durability of products (Akanbi et al., 2019; Franklin-Johnson et al., 2016) • Resource efficiency/eco-efficiency (Pfaff et al., 2018; Liu et al., 2019) • **Waste generation (C1)** (Haupt et al., 2017)
Meso	Industrial ecosystems, regional level	• MFA & Substance Flow Analysis • Multi-regional input-output (MRIO)	• Recycling & reuse rates (Hotta et al., 2016) • Resource productivity (Wen & Meng, 2015) • Material input/output balance (Liu et al., 2019) • Material flow index (Sun et al., 2017) • **Material separation rate (C2)** (Haupt et al., 2017; Struk, 2017)

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Level	Scope	Approach	Circular indicators
Macro	Global and/or national level, overall industry/economic structure	• Economy-wide MFA • Domestic Material Consumption analysis • Circular Policy & Indicator Frameworks (e.g., China's CE Index System, EU CE monitoring)	• Network symbiosis intensity & by-product exchange (Sun et al., 2017; Wen & Meng, 2015) • Adoption rate of the R-strategies (C3) (Dong et al., 2021; Geng et al., 2012) • Circular material rate (Haas et al., 2015) • Contribution to SDGs (Panchal et al., 2021) • Presence and effectiveness of circular initiatives (C4) (Konietzko et al., 2020) • Recycling/utilization rate of waste (Berglund & Söderholm, 2003)

Appendix C. Five dimensions of inclusion in CE and relevant indicators

Dimensions of inclusion	Description in the context of CE (Liu et al., 2023a)	Inclusive indicators (Liu et al., 2023a)
Social inclusion	Maximizing the value of products and services while ensuring the satisfaction of consumer needs and the well-being of employees and nearby residents.	• Green transformation of traditional manufacturing • Green customers and product preferences • **Adoption of social innovations on practicing CE strategies (I1)** • Integration with the informal waste sector • Knowledge sharing channels among actors
Environmental inclusion	Eco-friendly production and consumption, minimizing natural resource use and environmental impact while promoting waste-to-resource processes that benefit habitats.	• Air/water/soil emissions and resident well-being • Local solutions for end-of-life waste treatment • **Habitat- and nature-friendly waste infrastructure (I2)** • Natural regeneration technologies and initiatives
Economic inclusion	Ensuring equitable economic opportunities for all during the transition to a circular economy, encompassing labor markets, finance, entrepreneurship, and trade.	• Financial sustainability of different actors • **Affordable CE products and waste services (I3)** • Products-sharing business models • Green jobs in CE • Recyclable trading platforms
Spatial inclusion	Providing equitable access to resources for active participation and fair benefits in the CE transition.	• Access to CE products, facilities, and knowledge • Cross-region cooperation framework of CE • Local resource recovery and land restoration
Political inclusion	Ensuring equal political rights and responsibilities for both governments and citizens in shaping and advancing favorable policies for the CE transition.	• **Decision-making process with the participation of all stakeholders (I4)** • Taxation and CE behaviors of actors • Frameworks for monitoring the inclusion of CE initiatives

Data availability

Data will be made available on request.

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