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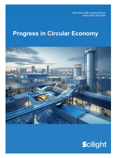

Review

Urban Intelligence for a Circular Future: Advanced Digital Technologies for Waste Prevention, Reuse, and Wise Construction

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Abstract: Urban areas generate growing volumes of waste and material flows that increasingly challenge the sustainability of current linear management models in cities. This paper examines how advanced digital technologies can enable a systemic transition toward circular urban systems, with a particular focus on waste prevention, reuse, and high value recycling. Building on insights from recent developments in smart energy systems, digitalized building management, and resource efficient construction practices, the study argues that urban intelligence—understood as the integration of IoT sensors, real time data analytics, artificial intelligence, and digital platforms—plays a pivotal role in optimizing material cycles across the city. The analysis identifies key mechanisms through which digital innovation enhances circularity: early detection of inefficiencies that lead to waste generation, improved tracing and valorization of materials, automation supported sorting and recovery processes, and data driven coordination among urban stakeholders. While digital tools significantly improve operational performance and environmental outcomes, the findings also highlight persistent challenges related to data governance, interoperability, institutional capacity, and social equity. The paper concludes that urban intelligence is not merely supportive but foundational for scaling circular economy strategies in cities, and calls for integrated policies, investment in digital infrastructures, and future research aimed at quantifying long term circular benefits at the urban scale.

Keywords: circular economy; urban intelligence; digital technologies; waste prevention; resource recovery; smart cities; material flow analysis

JEL Classification: Q53; Q55; Q58; O33; R11; R58

1. Introduction

Urban areas are increasingly recognized as critical nodes in the global resource system. By 2050, cities are projected to house nearly 70% of the world's population, intensifying the pressure they already place on material, energy flows [1], and greenhouse gas emissions. After the growth and expansion of the population, traditional methods will become hard to sustain. The built environment alone accounts for approximately 34% of global energy demand and 37% of energy- and process-related CO_2 emissions [1], while EU citizens generated an average of 511 kg of municipal waste per person in recent years [2]. Despite decades of policy ambition, the process of extracting, consuming, and disposing is economically and environmentally unsustainable and still remains dominant in most urban systems, and progress toward circular targets has stabilized [3], the emerge of technologies that provide a circular economic strategy to prevent unnecessary waste, extend product lifecycles, and recover materials of high residual value in place.

Achieving true circularity at a city scale isn't just a structural challenge, it's a coordination challenge. It requires an 'intelligent bridge' that can connect and balance the complex web of resources flowing through every building and district in our systems.

The concept of the circular economy offers a structural alternative to this trajectory, one that emphasizes waste prevention, material reuse, and high-value resource recovery. However, circularity at urban scale is not simply a design or infrastructure problem, it means it is fundamentally a coordination and information problem. Cities involve thousands of simultaneous material flows, distributed actors, and regulatory obligations that cannot be managed through conventional, reactive approaches. This paper argues that urban intelligence—understood as the purposeful integration of IoT sensors, real-time data analytics, artificial intelligence, and digital platforms across urban systems—has emerged as the operational backbone needed to make circular urbanism functional.

Smart systems are already showing very tangible results, helping to reduce the daily energy consumption of buildings, and emissions associated with the materials used in construction or maintenance. Insights from recent studies on zero-carbon improve in efficiency and supports a better understanding of decision-making, increasing productivity and information of how resources are used and where inefficiencies occur with a broader circular-economy goal. The intersection of these fields—specifically, how digital intelligence enables the practical mechanisms of waste prevention, systematic reuse, and high-quality material recovery—remains underexplored. Many cities still depend on waste-management practices that are fragmented, making it difficult to anticipate inefficiencies, track how materials move through the urban environment, or recover value from resources before they are lost.

Bringing digital intelligence into these systems offers a way to close that gap for an early detection of waste-generation patterns, automated sorting technologies, and better coordination and management in an effective way. Smart cities must find a path to handle and protect data, ensure that different digital systems can work together, and secure the long-term investments needed to support modern digital infrastructure.

This paper addresses that gap by posing three interconnected research questions:

RQ1: Through what specific mechanisms does urban intelligence enable waste prevention, material reuse, and high-value recovery at the city scale?

RQ2: What empirical evidence exists from real-world deployments to support the circular performance of these digital technologies?

RQ3: Under what governance, regulatory, and institutional conditions is urban intelligence most effective in advancing circular urban transitions?

To address these questions, the study conducts a narrative review of evidence across five thematic domains: energy-efficient construction based on Passive House and EnerPHit standards, digital deposit return systems, smart waste sensor networks, urban digital twins, and sustainable materials. The analysis prioritizes real-world deployments with documented, quantifiable performance data and situates the findings within the European regulatory context, including the EU Taxonomy, the Packaging and Packaging Waste Regulation, and the 2030 circular economy targets. Our aim is to translate technical evidence into actionable implications for policy and investment, emphasizing measurable performance (capture, purity, avoided CO_{2e}, energy demand) and the data-governance conditions needed to scale. The analysis is selective and prioritizes cases with clear relevance to European regulatory frameworks.

The remainder of the paper is structured as follows. Section 2 reviews the literature and identifies key gaps. Section 3 describes the review methodology and case selection criteria. Section 4 presents results organized by thematic domain. Section 5 discusses implications for theory, policy, and practice. Section 6 concludes and identifies directions for future research.

2. Literature Review

According to the UN Environment Programme and the Global Alliance for Buildings and Construction [1], buildings accounted for roughly one-third of the world's resource footprint—34% of global energy demand and 37% of energy- and process-related CO_2 emissions in 2022. Since the Paris Agreement in 2015, sector-wide emissions have still risen by about 5%, while the pathway to net zero calls for an approximate 28% reduction by 2030—evidence that current efforts are falling short of the pace and scale required.

This trajectory reveals that we cannot build a sustainable future using the reactive and fragmented methods of the past, a decisive transition toward urban intelligence is necessary. Through the integration of advanced digital capabilities such as artificial intelligence, the Internet of Things, and digital twins, cities can evolve static assets into dynamic, self-optimizing systems. These infrastructures can anticipate demand, optimize resources, and maintain a cycle of continuous performance enhancement.

As highlighted in the World Energy Outlook 2025 [4], the transition to an 'Age of Electricity' demands not only cleaner generation but also a fundamental shift in how resources are managed through digitalization, particularly to secure critical mineral supply chains through enhanced circularity, with demand projected to accelerate, the International Energy Agency identifies circularity and secondary recovery as vital mechanisms to mitigate supply chain vulnerabilities. In this context, Urban Intelligence provides the digital architecture necessary to transform cities into 'urban mines', leveraging high-fidelity data to recover strategic materials, such as copper and rare earth elements, ensuring they remain within the economic loop and reducing the environmental pressure of primary extraction.

To reach decarbonization targets by 2035, scaling up low-emissions electricity generation and significantly reducing methane emissions will be critical (Figure 1). The data from this scenario underscores that the rate of energy efficiency improvement must double to 4% annually by 2030 to remain consistent with the NZE Scenario. Achieving this benchmark, alongside a projected increase in electricity's share of energy consumption to one-third by 2035, necessitates a sophisticated digital infrastructure. Urban Intelligence serves as the critical enabler for this transition, providing the real-time coordination required for heat pump deployment, EV charging networks, and the 80% reduction in methane emissions through advanced sensing and predictive analytics.

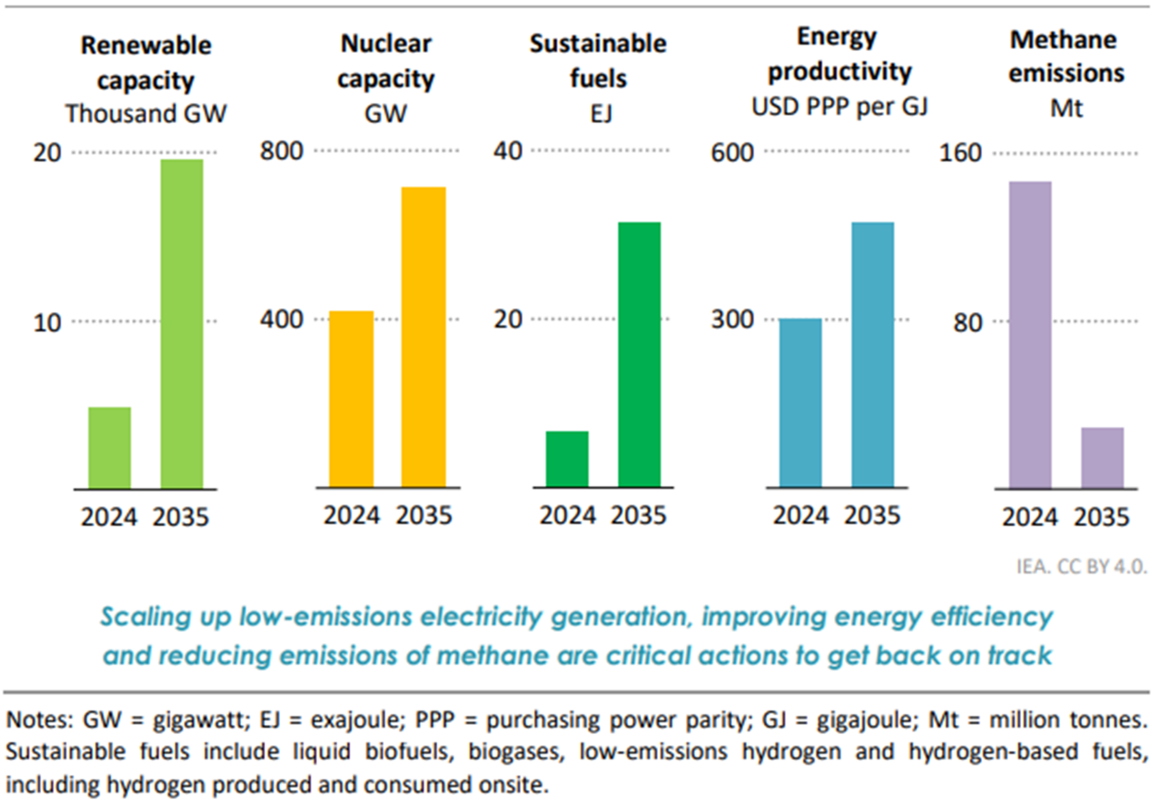

Figure 1. Key indicators of energy transitions in the NZE Scenario, 2024–2035. Source: IEA 2025.

The constructions have been evolving, and a wise construction building is the new concept of Passivhaus, where the research institute of Passive House Institute (PHI) [5] represents a fundamental shift in how we conceive the relationship between residents and their built environment. Instead of relying on energy-intensive mechanical systems to fight external climates, a Passive House leverages the laws of physics to create stability. By prioritizing superior thermal insulation, airtightness, and high-performance windows, these structures minimize energy demand by up to 90% compared to traditional builds and where standard Central European buildings average ~100 W/m^2 heating loads, a Passive House keeps peak load below 10 W/m^2, enabling supply-air heating via a small post-heater and eliminating the need for traditional large heating or cooling systems.

The description defines clear performance thresholds verified in Passive House Planning Package and on site. New buildings must limit space heating demand to ≤15 kWh/(m^2·year) or peak load to ≤10 W/m^2; following the five principles for the construction of PHI (Figure 2) [6]: the superior thermal insulation acts as a continuous protective skin, significantly reducing the energy needed to maintain a stable internal climate with passive house windows fitted with low-e glazings mostly filled with argon or krypton which brings natural light while preventing the warmth from escaping, and it is important to avoid invisible gaps where heat often leaks out getting better the airtightness of the building and a ventilation with heat recovery serves as the system's lungs. It provides a constant flow of filtered fresh air while reclaiming over 75% of the heat from the outgoing air.

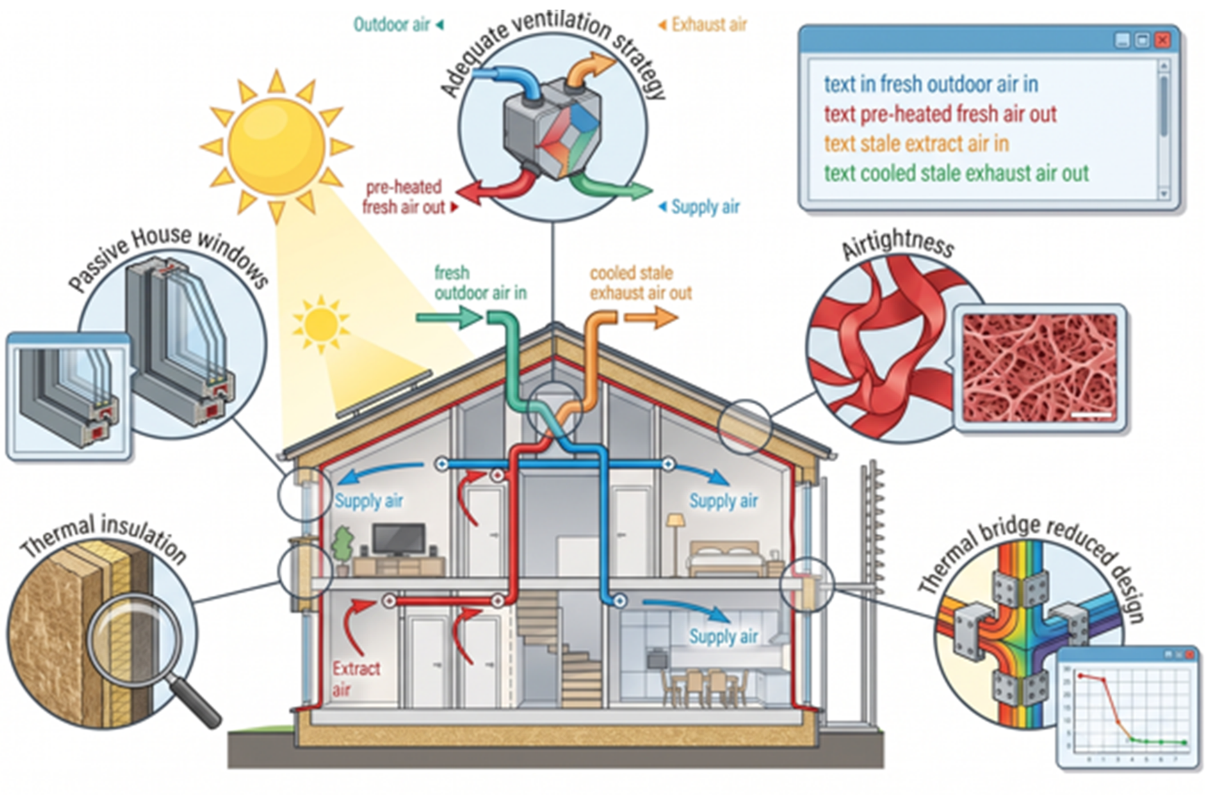

Figure 2. Five principles applied for Passive House. Source: Adapted from Passive House Institute. (2025).

The International Council for Research and Innovation in Building and Construction [5] for the Global Practices of Net Zero Carbon Building Design and Construction make a shifting of our focus toward a more symbiotic relationship with nature by embracing bio-based and low-carbon materials, we are moving beyond mere efficiency toward the possibility of carbon-negative architecture. To achieve this commitment the United Kingdom's roadmap toward carbon neutrality prioritizes building envelope integrity over mechanical fixes, placing a strategic emphasis on fabric-first methodologies and the adoption of Passivhaus principles to minimize baseline energy demand, involving diverse ecosystem of stakeholders, spanning the entire value chain from regulatory bodies and institutional actors to industry practitioners and civil society propose hemp-lime bio-composites, offsite construction, and alternatives solutions like clay and limestone for concrete production. Furthermore, most builders still rely on a narrow set of familiar technologies that fit easily into existing business models, such as thermal storage and grid-responsive controls, which offer significant potential, yet their adoption is often stalled by rigid institutional habits and technical traditions. Moving forward, achieving real decarbonization at scale requires more than just better hardware; it demands a holistic approach where different technologies work in synergy and diverse stakeholders collaborate to break old industry patterns.

Additionally, aspects in the growth of the population reflect the importance of residual waste in the daily routine. Eurostat [2] shows in their recent municipal waste statistics that EU citizens generated an average of 511 kg of municipal waste per person, and the highest generation comes from Austria (803 kg), Denmark (802 kg), Luxembourg (712 kg), while recycling stood at 48% (246 kg per person), a long-term improvement but still insufficient against 2030 ambitions.

In Figure 3 from the European Environment Agency [7], between 2004 and 2022, residual waste decreased by 16%, but progress has plateaued since 2015. The EU is currently unlikely to achieve the 50% residual waste reduction target by 2030 because municipal waste generation continues to increase, and requires 60% of municipal waste to be prepared for reuse or recycled by 2030.

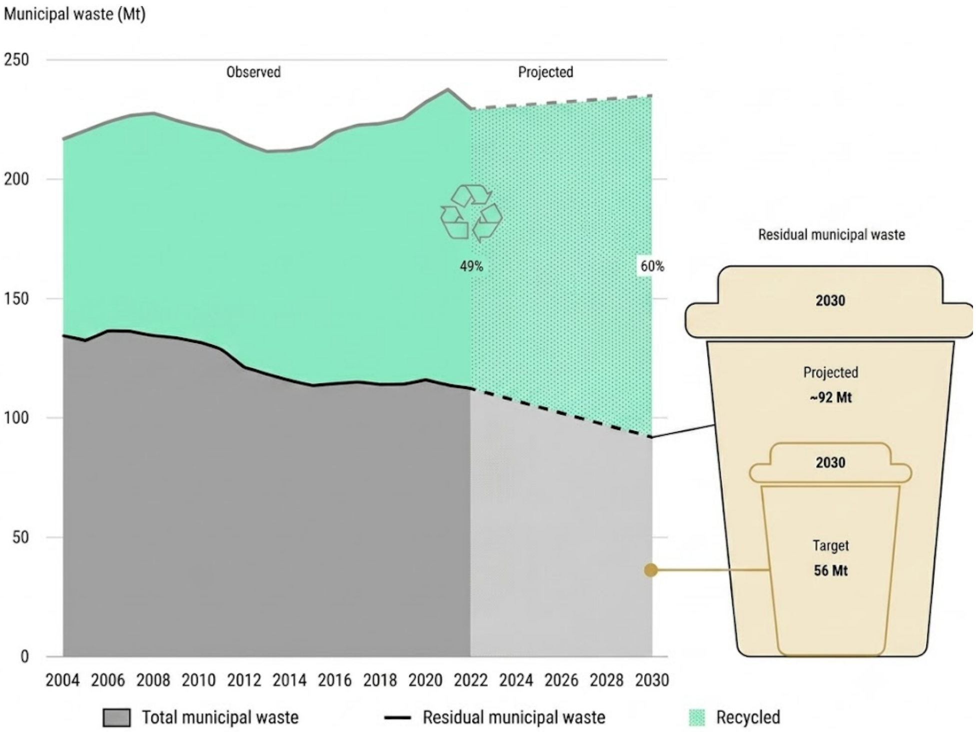

Figure 3. Past trends and distance to target residual municipal waste. Source: Adapted from European Environment Agency (2025).

The implications of cities getting smarter and improving their measurement and manage is gaining value by reporting against residual-waste KPIs alongside recycling quality, so that interventions translate into real reductions for systemic prevention and quality recycling needed to get back on track for 2030.

Another aspect to take into consideration is the sustainable materials and construction techniques. The use of low-carbon materials can significantly reduce the embodied carbon of a project, ensuring that the environmental impact is minimized throughout the entire life cycle of the building. For the following materials:

Steel: Willeke [8] shows that global manufacturing incorporates 630 million tons of recycled steel annually. This process saves energy and natural resources while cutting of CO_2 emissions by nearly 950 million tons. Furthermore, using the term 'recycled steel' highlights the vital role this material plays in the transition to eco-friendly steel production. Referring to ODI Europe [9] steel contributes ~8% of energy-related global GHG emissions; switching to secondary steel and clean power is a key lever in a city's embodied-carbon strategy. To effectively lower carbon emissions in steelmaking, the foremost solution is to leverage scrap-based EAF technology to its full potential.

Glass: it is taking importance with an effectiveness of Close the Glass Loop [10], an European action platform in the process of Glass Cullet Recycling in 93% of all materials, 85% of which was reused to re-elaborate new bottles and jars. The platform's goal is to achieve a collection rate of 90% by 2030 in the European Union, covering data from 81 recycling plants in 20 countries, representing 62% of all glass collected in the EU, the United Kingdom, and Norway.

Plastics: Tamam and Wafaa Mahdi [11] show the possibility that properties of recycled PET (r-PET) can be used as a building material (specifically in concrete), reinforcing it with natural and synthetic fibers to mitigate the accumulation of plastic waste after curing periods of 7, 14, and 28 days. Companies also support the movement beyond conventional recycling into a sophisticated system of reverse logistics like Jcoplastic in the European Circular Economy Stakeholder Platform [12] in Italy serves as a compelling example of a successful transition from linear to circular industrial models. Their approach should be strategic opportunity to manage the entire product lifecycle by focusing on High-Density Polyethylene (HDPE)

The holistic decarbonization of the built environment requires a synergy between structural biomaterials and their binding agents. By combining certified wood and hempcrete with natural additives and eco-friendly mortars, developers can create high-performance building envelopes that are not only low impact during construction but also fully biodegradable or recyclable at the end of their lifecycle.

3. Method

This study adopts a narrative review methodology, appropriate for synthesizing evidence across an emergent multi-disciplinary field where the heterogeneity of outcome measures and study designs precludes formal meta-analysis. The narrative approach permits the integration of peer-reviewed academic literature with authoritative institutional reports and documented real-world deployments, organised around five thematic domains of urban intelligence: energy-efficient construction (Passive House/EnerPHit), digital deposit return systems, smart waste sensor networks, urban digital twins, and sustainable materials. Literature and evidence were sourced primarily from academic databases including Scopus, Web of Science, and Google Scholar, supplemented by authoritative institutional reports from the European Environment Agency, the International Energy Agency, the Passive House Institute, and the United Nations Environment Programme. The selection of sources prioritised: (i) peer-reviewed publications from 2018 onwards, with particular emphasis on studies published between 2020 and 2026; (ii) real-world deployments with documented, quantifiable performance outcomes (energy savings, CO_{2e} reductions, material recovery rates, or operational cost data); and (iii) relevance to the European regulatory context, including the EU Taxonomy, the Packaging and Packaging Waste Regulation, and the 2030 circular economy targets. Case studies were selected on the basis of technological representativeness, geographic diversity within the European context, and availability of verifiable performance data.

Evidence from each domain was analyzed against a common three-dimensional framework: (a) the specific mechanism through which the digital technology contributes to circular performance—prevention, traceability, sorting accuracy, coordination, or regulatory verification; (b) the quantified outcome achieved in documented real-world deployments; and (c) the regulatory or institutional conditions under which the deployment occurred. This structured approach enables cross-domain comparison and supports the development of theoretical propositions and practical implications in subsequent sections.

3.1. Waste Stream Differentiation, AI-Enabled Classification, and Urban Mining

Municipal solid waste is not a homogeneous category: it encompasses distinct streams—including household solid waste, construction and demolition debris, industrial residues, and waste electrical and electronic equipment (WEEE)—each of which presents different compositional profiles, contamination risks, and recovery pathways. Effective circular urbanism requires that these streams be managed not collectively but with precision, and this is precisely where artificial intelligence offers transformative potential. Deep learning architectures, particularly convolutional neural networks (CNNs) and hybrid models combining image recognition with sensor data, have demonstrated classification accuracy exceeding 90% across mixed municipal waste streams [13]. A systematic review of machine learning applications in waste classification documents a 47.6% increase in relevant publications between 2023 and 2024, reflecting the rapid maturation of this field [14]. In construction and demolition contexts, transfer learning models have been applied to augment training datasets and improve the detection of heterogeneous materials, enabling more targeted recovery of concrete, metals, and timber [15].

Beyond logistical optimization, the integration of urban intelligence significantly enhances the identification and differentiation of municipal and industrial waste streams. AI-powered vision systems and advanced sensors now offer the sensitivity required to distinguish high-value fractions—such as metallic components in construction debris or electronic waste—from general residual flows [16]. Urban mining and the recovery of critical minerals from secondary sources are increasingly important for sustainability and resource security [17] and highlight the opportunities associated with rare earth element recovery from urban wastes. These findings are consistent with previous evidence showing that waste recovery can contribute to offsetting waste management costs and improve the economic sustainability of recovery systems [18]. The integration of IoT-enabled smart containers with on-device AI inference further enables real-time, point-of-disposal classification. According to recent systematic evidence, advanced deep learning architectures can identify waste fractions with high precision [19]. By automating the separation of these materials, urban intelligence reduces the loss of recyclables and lowers the overall collection costs for municipalities [20]. This capability aligns with the growing strategic importance of urban mining, whereby cities function as secondary sources for critical raw materials such as rare earth elements and precious metals, essential for the global transition to electric mobility, changing the vision of waste as valuable resource. Furthermore, recovering strategic minerals from waste tailings and urban deposits can fundamentally improve the economic feasibility of municipal waste enterprises by creating new revenue streams from high-purity feedstocks [21,22]. Despite this progress, a significant gap persists between technological capability and operational deployment: most AI classification systems have been validated under controlled laboratory conditions rather than at the scale and variability characteristic of urban waste flows, underscoring the need for context-specific validation frameworks

3.2. Critical Raw Materials and the Strategic Imperative of Urban Mining

As stated in the Global E-waste Monitor 2024, while the secondary raw materials recovered through urban mining have an estimated value of USD 28 billion, the formal collection rate remains at only 22.3%, highlighting a significant recovery gap that urban intelligence technologies can address [23]. Only in Europe, 62 million tonnes of WEEE were generated, with a similarly low recovery rate, despite the substantial concentrations of recoverable metals: one tonne of mobile phones, for instance, can yield up to 340 g of gold and 3.5 kg of silver [24]. A study assessing 43 categories of electrical and electronic equipment placed on the Spanish market between 2016 and 2021 identified urban mining potential of 1.4 million tonnes of metals valued at USD 2.43 billion, representing 80% of the mass placed in the primary market during that period [25]. The EU Critical Raw Materials Act (Regulation 2024/1252) establishes a binding target of sourcing at least 25% of annual strategic material consumption through domestic recycling by 2030, creating a direct regulatory driver for the expansion of WEEE collection and processing infrastructure [26]. Urban intelligence systems, including IoT-enabled WEEE collection networks, AI-driven sorting platforms, and digital traceability tools, are well positioned to close the gap between collection capacity and this strategic mandate by enabling more precise identification, routing, and valorization of high-value waste fractions at the city scale.

3.3. Organic Waste Recovery and Soil Amendment

The organic fraction of municipal solid waste—estimated to represent a maximum of 55% of total household waste generation in most urban contexts—constitutes a significant yet underexploited resource stream within circular urban systems [27]. Composting, as a biologically driven valorization pathway, transforms this fraction into stable humus-rich soil amendments that improve soil water retention, restore microbial diversity, reduce reliance on synthetic fertilizers, and contribute to carbon sequestration in agricultural soils [28]. Beyond conventional composting, recent studies have highlighted the potential of combining municipal and household waste with selected mining residues to produce technosols and soil amendments capable of enhancing soil fertility, nutrient availability, and land reclamation. These approaches contribute to nutrient recycling and support sustainable agricultural practices while providing an environmentally sound destination for waste streams that would otherwise require disposal [29,30]. Municipal solid waste compost applications have been shown to increase soil organic carbon content by up to 2.8% and to sustain biological activity at rates compatible with commercial vegetable production [31]. The integration of smart waste monitoring systems into organic waste collection can substantially reduce contamination rates in the organic stream, which is a primary quality constraint for compost end-use in agriculture

3.4. Economic Feasibility of Urban Intelligence Technologies

The economic viability of urban intelligence technologies is as critical as their environmental performance, yet cost data remains unevenly reported across the literature. For smart waste sensor systems, research demonstrates that IoT node hardware can be deployed at costs below US$70 per unit [32], the system operates in continuous monitoring mode, where sensor readings are recorded at predefined intervals and sent to the platform, while city-level deployments have demonstrated tangible operational gains: Copenhagen has implemented a smart waste management system in which IoT sensors monitor container fill levels and optimize collection routes in real time, achieving a 20% reduction in operational costs alongside a significant decrease in carbon emissions [33] Route optimization deployments by Sensoneo have documented collection cost reductions of 43% to 63% depending on urban context [34].

For Passive House and EnerPHit retrofits, the Passivhaus Trust reports that the construction cost uplift is now generally below 8% when economies of scale are applied. This initial premium is more than repaid through long-term energy bill savings and whole-life costs, providing a robust business case even in the face of fluctuating material prices [27]. Furthermore, a 2025 lifecycle assessment of EnerPHit retrofits further confirms total carbon savings of 80–83% compared to the existing building's original performance, noting that embodied carbon from retrofit materials accounts for a mere 8–14% of the building's total lifecycle impact. The study indicates that while initial rehabilitation costs are substantial—representing 71–75% of the total lifecycle expenditure—the resulting financial benefits from reduced utility and maintenance costs yield a net lifecycle saving of between 7% and 15% [35].

Digital Deposit Return Systems offer a structural cost advantage over conventional DRS by significantly reducing capital investment in physical return infrastructure, as evidenced by an economic impact assessment conducted by Resource Futures for the UK context [36] At the largest scale, urban digital twin platforms require the highest capital commitment—Virtual Singapore alone involved an investment of approximately $73 million [37]—though ABI Research projects that city-wide adoption of digital twins could generate global urban planning savings of US$280 billion by 2030 [38], suggesting a compelling long-term return on public investment. Across all technology categories, the absence of standardised cost-reporting frameworks makes cross-city comparison difficult, and this represents an important gap for future research and policy design.

3.5. Regulatory Frameworks and Economic Incentives for Circular Urban Technologies

The adoption of urban intelligence technologies for waste management does not occur in a regulatory vacuum: the pace and scale of deployment are substantially shaped by the policy frameworks within which municipalities operate. Extended Producer Responsibility (EPR) represents one of the most consequential instruments in this regard, shifting financial responsibility for end-of-life product management from municipalities to producers and thereby creating market incentives for circular product design and investment in collection infrastructure [39]. A study of EPR systems in 2023 across seven jurisdictions found that collection and recycling rates for targeted packaging exceeded 75% in regions with established producer responsibility frameworks, significantly outperforming jurisdictions without such mechanisms [40]. At the European level, the revised Waste Framework Directive introduces eco-modulation of EPR fees linked to sustainability criteria, including durability and recyclability, thereby directly incentivizing manufacturers to design products compatible with smart sorting and high-value recovery systems [41]. Beyond EPR, public procurement policies, green bond frameworks, and EU Taxonomy-aligned financing instruments are increasingly being deployed to lower the capital cost of circular infrastructure for municipal governments. Research examining the transition to smart waste management in developing economies identifies the absence of supportive regulatory policy and financial planning as the most critical systemic barriers to IoT-enabled waste system adoption [42], confirming that technology availability alone is insufficient without a coherent governance architecture.

4. Results

4.1. Case Study 1: PassivHaus/EnerPHit

Addressing RQ1 and RQ2, this case documents the circular mechanisms enabled by physics-led building design and their verified performance outcomes. The project of Barrio do Cura [43] in Vigo (Spain) is set on the steep urban fabric between O Berbés and Paseo de Alfonso XII to re-stitches the historic center with new and redesigned streets, a large plaza-mirador overlooking the estuary, vertical mobility (elevators and escalators) to overcome topographic barriers, a mid-slope urban park, and resident-oriented public parking—placing pedestrian comfort and public space at the core of the intervention. On the real-estate side, developer materials describe three residential buildings (Lúa, Estrela, Ardora) and ~265 dwellings framing the public square. Works formally started in 2024, with foundations and superstructure phases advancing through 2025 and indicative deliveries reported around 2027–2028.

The development of Barrio do Cura aligns with global decarbonization goals through an operational model that promotes a circular economy and high-level energy efficiency and integrates renewable production and water management, providing a scalable model for how intelligent cities can synchronize energy demand with low-carbon supply and more than 2000 m^2 of photovoltaic panels.

According to simulations, the buildings will save up to 43% water and 40% energy compared to an ordinary building.

Adding value with circular "wise construction," a Passivhaus EnerPHit retrofit demonstrates how digitalized, quality-assured deep renovation prevents construction waste, preserves embodied carbon, and delivers measurable gains in energy and indoor environmental quality. In Madrid, from outPHit [44], the Cartagena50 residential building renovation, a certified EnerPHit social-housing project, reduced heating demand to 20 $kWh/m^2 \cdot a$ with airtightness $n50 = 0.8\ h^{-1}$ and integrated rooftop PV for common loads; helping apartments with the monitoring for energy, comfort, and air quality, closing the loop between design assumptions and lived performance. When coupled with BIM-LCA and material passports, EnerPHit enables traceability and reuse at end-of-life, reducing residual waste flows and aligning building operations with urban circularity targets.

The significance of the integration of urban development serves the European Green Deal's objectives. Projects like Barrio do Cura or Cartagena50 residential building renovation act as critical proof-points for the EU Taxonomy for Sustainable Activities, which in 2024 the European Commission [45] establishes a rigorous mandatory framework where urban developments must demonstrate not only energy efficiency but also a 70% circularity rate in waste management. This regulatory pressure reinforces the need for Urban Intelligence platforms, which act as the 'digital auditor' required to validate these sustainability claims for institutional investors.

4.2. Case Study 2: Digital Deposit Return Systems

This case addresses RQ1 by examining how serialized digital identifiers enable traceable container flows, and RQ2 through documented collection outcomes in operational pilots. According to Reloop [46] the Digital Deposit Return Systems (DDRS), also known as "smart" or "serialized" DRS, there are 56 operational deposit systems (DRS) worldwide, serving over 346 million people where the European Union's new Packaging and Packaging Waste Regulation (PPWR) requiring Member States to achieve a 90% separate collection rate for plastic bottles and metal cans up to 3L by 2029.

Unlike classic DRS, where consumers return physical containers to designated points for a refund, DDRS introduces alternative digital pathways. The system relies on the following core components: Each container is printed or labeled with a unique serialized barcode or QR code with applications in users' smartphones. The model assumes that consumers will deposit scanned containers into existing municipal kerbside/curbside recycling bins rather than returning them to a retailer. It is emphasized in several international pilots like Blenheim Palace (UK), with a DDRS deposit for reusable coffee cups, achieving onsite reuse and real-time tracking via a digital platform or like Kedarnath (India) reporting the return of over 1,600,000 units by 2023 through the use of QR-coded stickers. Similar perspective the Ecoembes project of Reciclos [47] in Spain that offer a digital alternative to the containers or machines expanded to over 100 Spanish cities and integrated collection points in high-traffic hubs such as train stations and shopping centers, this digital incentive model encourages circular behavior through "tokens" redeemable for sustainable rewards or social donations.

4.3. Case Study 3: Smart Waste Sensors in Containers

This case provides direct empirical evidence for RQ2, documenting verified CO_{2e} savings, cost reductions, and overflow reduction across multiple European deployments. Being predictive in data-driven operations, for a net climate impact of the digital solution using the European Green Digital Coalition (EGDC) [48] methodology a case in the municipality of Nicosia, Cyprus of smart cities applied ex-post to the deployment of Sensoneo Quatro ultrasonic sensors connected by LoRaWAN/GPRS and integrated into the Nokia Integrated Operations Center (IOC) platform, to optimize collection stops (emptying threshold: >50% full) in 42 containers (25 underground and 17 glass) with a result of less stops without changing the route, capturing savings of 1.92 tCO_{2e}/year for 42 containers, with 0.078 tCO_{2e}/container/year in underground containers and −0.002 tCO_{2e}/bin/year in glass recycling bins.

Urban modernization is improving street cleanliness and the efficiency of waste collection while reducing the carbon footprint. In Bratislava, Slovakia, initiatives led by Sensoneo [49] and OLO a.s. have digitized approximately 85,000 bins and containers with RFID for full life-cycle traceability and deployed more than 1500 smart sensors that record fill levels up to 12 times per day. Complementing these efforts, AI-enabled dumpster sensors from SmartEnds have shown measurable impact: in Ghent, Belgium, a deployment across 200 public dumpsters cut collection runs by 35%, delivered around €100,000 in annual savings, and halved overflow incidents, illustrating how real-time fill-level data and vision-based contamination detection can drive both operational and environmental gains.

4.4. Case Study 4: Urban Digital Twins

This case addresses RQ1 by identifying the coordination mechanisms enabled by city-scale digital twins, and RQ3 through the institutional conditions of each deployment. Different cities have implemented a continuously updated, data-rich virtual replica of city assets and processes that supports real-time monitoring, forecasting, and policy simulation. Experion Technologies [37] shows the cases of Virtual Singapore, a 3D digital twin that prepares urban scenarios for helping in the planning, testing, optimizing the decisions with a real-time data sets estimated with an investment of $73 million in a collaboration with the National Research Foundation Singapore, the Singapore Land Authority, and the Infocomm Development Authority of Singapore, for developing and highlights geospatial acquisition with aerial photography and terrestrial LiDAR; other technical reports document large volumes of data (tens of terabytes) and the combination of aerial LiDAR and vehicle scanning to obtain a high-resolution national model. Another important case is from the Seoul Metropolitan Government [50] the Virtual Seoul (S-Map) where planners can see where pipes actually run, which bridges or overpasses are affected by a storm, or how a station's indoor circulation behaves at rush hour with a data of 605.23 km^2 from Seoul combing the AI technologies for dam–river twins, automated risk alerts, wind path or closed circuit television (CCTVs). Finally, the strategic off from the Government of Dubai [51], the platform Dubai Here powered by AI, IoT, and machine learning, Dubai Here produces 3D mapping and uses predictive analytics to anticipate energy consumption and detect potential faults in advance.

4.5. Case Study 5: Sustainable Materials

This case addresses RQ2 by documenting verified circular performance in steel and glass material streams enabled by digital traceability. Companies such as ArcelorMittal [12] are scaling up "recycled and renewably produced" steel via the Electric Arc Furnaces (EAF) route, using renewable electricity, with the result of 75% of steel being recycled. This method moves the industry away from coal and significantly cuts pollution. In fact, this process produces only about 300 kg of CO_2 per ton of steel, compared to the 2000 kg produced by traditional methods. Meanwhile, Close the Glass Loop [8] represents the DRS are often highlighted in public policy debates, their actual contribution to the European glass recycling stream remains marginal for now. According to the data, glass acquired via DRS accounts for only 0.96% of the total input at treatment facilities. Interestingly, this recovery method shows extreme geographic concentration: Denmark and Finland together represent 88% of all glass recovered through DRS in the survey, while in the rest of Europe, the system is either non-existent or statistically insignificant. This suggests that the backbone of European glass circularity is not a single 'silver bullet' solution, but rather the continued strength of traditional municipal collection, which provides 87% of the total volume.

Across all five domains, the evidence consistently identifies four operational pathways through which urban intelligence delivers circular outcomes: early detection and upstream prevention; high-quality material recovery through digital sorting and classification; real-time coordination enabled by shared data platforms and digital twins; and regulatory verifiability through machine-readable performance data that satisfies EU Taxonomy and PPWR audit requirements. Table 1 summarizes the verified performance metrics across all case studies.

Table 1. Comparative Summary of Urban Intelligence Case Studies.

Case Study	Technology Type	Location/Scale	Key Performance Indicators	Verified Outcomes	Regulatory Alignment
Case 1 PassivHaus/ EnerPHit	Passive House envelope design; EnerPHit deep retrofit; rooftop PV	Vigo, Spain (Barrio do Cura) Madrid, Spain (Cartagena50)	Heating demand ($kWh/m^2·year$) Airtightness (n50, h^{-1}) Energy savings (%) Water savings (%)	Heating demand: 20 $kWh/m^2·a$ Airtightness: n50 = 0.8 h^{-1} Water savings: 43% Energy savings Vigo: 40%	EU Taxonomy (70% circularity rate) European Green Deal Fabric-first policy (UK roadmap) PHI certification standards
Case 2 Digital Deposit Return Systems (DDRS)	Serialized QR/barcode containers; smartphone scanning; kerbside integration; digital incentive tokens	Blenheim Palace, UK Kedarnath, India Spain (Reciclos) 56 DRS systems worldwide	Collection rate (%) Units returned Capture rate vs. conventional DRS Infrastructure cost vs. conventional DRS	Target: 90% collection rate (plastic bottles/cans by 2029) Kedarnath: 1,600,000+ units returned by 2023 Reciclos: deployed in 100+ Spanish cities	EU Packaging & Packaging Waste Regulation (PPWR) 90% separate collection target by 2029
Case 3 Smart Waste Sensors in Containers	Sensoneo ultrasonic sensors; LoRaWAN/GPRS; Nokia IOC platform; RFID lifecycle tracking; SmartEnds AI vision	Nicosia, Cyprus Bratislava, Slovakia Ghent, Belgium	CO_{2e} savings (tCO_{2e}/container/year) Overflow incidents (%)	Nicosia: 1.92 tCO_{2e}/year (42 containers) Bratislava: 85,000 bins digitized; 1500+ sensors Ghent: 35% reduction in collection runs Ghent: €100,000 annual savings Ghent: 50% reduction in overflow incidents Route optimisation: 43–63% cost reduction (Sensoneo)	EU 2030 residual waste targets European Green Digital Coalition (EGDC) methodology EU Circular Economy

Table 1. *Cont.*

Case Study	Technology Type	Location/Scale	Key Performance Indicators	Verified Outcomes	Regulatory Alignment
Case 4 Urban Digital Twins	3D city models; LiDAR + aerial photography; AI analytics; IoT sensor integration; real-time simulation; predictive analytics	Singapore (national) Seoul, South Korea (605 km^2) Dubai, UAE (city-wide)	Investment (USD million) Coverage (km^2) Global projected savings (USD bn, 2030)	Virtual Singapore: USD 73M investment S-Map Seoul: 605.23 km^2 coverage Dubai Here: AI + IoT predictive fault detection Enables real-time monitoring, risk alerts, and energy forecasting	EU Taxonomy for Sustainable Finance Smart Cities frameworks (UN-Habitat) National digital infrastructure strategies
Case 5 Sustainable Materials	(EAF) steel; glass cullet recycling	Europe-wide (ArcelorMittal, Close the Glass Loop) Global (steel EAF route)	CO_2/tonne steel (kg) Recycled content (%) Glass collection rate (%) GHG savings (million tCO_2)	EAF steel: 300 kg CO_2/tonne vs. 2000 kg (conventional) ArcelorMittal: 75% recycled steel Close the Glass Loop: 93% cullet recycling; 85% into new bottles/jars Glass target: 90% collection rate by 2030 (EU)	EU Circular Economy Action Plan Steel sector decarbonisation targets Close the Glass Loop 2030 target EU Taxonomy embodied carbon criteria

Note: All performance data are drawn from verified deployments cited in the manuscript; EAF = Electric Arc Furnace; PHI = Passive House Institute; PPWR = Packaging and Packaging Waste Regulation; RFID = Radio Frequency Identification.

5. Implications

The findings presented in the previous chapter carry implications at three levels: theoretical, policy, and managerial.

Theoretically, the cross-domain evidence supports the proposition that urban intelligence functions as more than an operational efficiency tool, which constitutes the informational infrastructure without which circular urbanism cannot be verified, financed, or governed at scale. This advances an integrative framework that neither the smart city nor the circular economy literature has previously articulated with empirical grounding across multiple technology domains.

For policymakers, the evidence confirms that digital technologies deliver the strongest circular outcomes when embedded in coherent regulatory architectures. EPR eco-modulation, the PPWR's separate collection mandates, and the EU Taxonomy's verifiable sustainability criteria create the demand signals and accountability structures that make investment in smart waste systems, digital twins, and building monitoring rational and financeable [39–41,45].

For practitioners, including municipal waste managers, developers, and technology procurement officers, three principles emerge: (i) establish performance baselines and harmonized KPIs before procuring technology, as the absence of standardized metrics is the most consistent barrier to evidence-based investment; (ii) design for interoperability using open standards to prevent vendor lock-in and enable cross-agency coordination; (iii) invest in institutional capacity alongside technology, since the evidence confirms that the bottleneck is rarely the technology itself but the municipal capacity to operate and interpret it [42].

This section looks ahead to how urban intelligence can accelerate waste prevention, systematic reuse, and high-value recycling at city scale. In practical terms, it frames urban intelligence as the operating system that links very-low-demand buildings, digital twins, DDRS/DRS, and smart waste operations with the European transition frameworks for energy and circularity—so that cities can move from reactive management to continuous, evidence-based optimization [1,4,45–47].

Over the next decade, cities will increasingly combine IoT, real-time analytics, and digital twins to coordinate energy, materials, and urban services from a single operational picture. The direction of travel is clear: programs such as Virtual Singapore, Seoul's S-Map, and Dubai Here already demonstrate the technical maturity and predictive power of city-scale platforms—allowing planners and operators to simulate scenarios, anticipate demand, and prioritize interventions that deliver measurable circular benefits [37,50,51].

What changes in practice is the cadence of decision-making: instead of annual planning cycles, cities act on hourly or daily signals about fill levels, contamination risks, building loads, or mobility patterns, reducing resource use and residual waste before it materializes [37,50,51].

On the built-environment front, Passive House/EnerPHit will continue to scale in both new construction and deep retrofit, anchored in physics-led envelopes, airtightness, and heat-recovery ventilation [6,7,44]. The next leap is to couple envelope performance with post-occupancy monitoring and material passports, so each building not only consumes far less energy but also proves its comfort, indoor air quality, and end-of-life recoverability. That data-rich approach strengthens urban circularity by preserving embodied carbon during renovation, tracking components for future reuse, and aligning retrofits with city-level targets for efficiency and waste reduction [6,7,44].

Equally, DDRS/DRS and smart waste operations are poised to lift capture rates, improve fraction purity, and cut truck-kilometers through route optimization and contamination detection. As the EU pushes toward higher separate collection and lower residual waste per capita, digital systems offer the audit-grade, machine-readable evidence needed to show progress and correct course quickly [7,46,48]. Success will hinge not only on technology but also on citizen experience (simple returns, transparent incentives) and on data governance that protects privacy while enabling cross-agency collaboration [7,46,48].

From an investment perspective, digital proof of performance is becoming the ticket to capital for circular projects under the EU Taxonomy. Cities and developers will need to demonstrate capture, purity, avoided CO_{2e}, and indoor environmental quality with traceable data and technical audits—favoring performance contracts and PPP models where repayment is tied to verified outcomes [44,45,48]. That shifts risk and accountability: financing flows to projects that can show, not just claim, circular impact. It also rewards teams that build interoperable data pipelines, strengthen municipal capacity, and keep procurement open to avoid vendor lock-in [44,45,48].

Looking ahead, two human factors deserve equal attention. First, workforce transition: operators, maintenance crews, and auditors will need upskilling to manage sensors, interpret analytics, and maintain cyber-secure infrastructure; these are high-value skills that create local jobs and raise service quality [4,48]. Second, equity and social license: pervasive sensing and digital incentives must be transparent, inclusive, and responsive to community input, or the trust needed for scale will erode [7,46,48].

The evidence synthesized in this review draws predominantly from deployments in high-income European urban contexts, where digital infrastructure, regulatory maturity, and access to green finance converge to make circular urban technologies viable. It is important to acknowledge, however, that the applicability of these findings is geographically and institutionally conditioned. Research on smart waste management adoption in developing economies consistently identifies a lack of regulatory policy, insufficient financial planning, and limited technical capacity as the primary systemic barriers to IoT-enabled waste system implementation [42]. The performance gap between cities in high- and low-income contexts is not primarily a function of technological unavailability but rather of differences in governance structures, regulatory maturity, and financing mechanisms. Similar observations have been reported in the broader resource recovery and urban mining literature, where the level of economic development and institutional capacity strongly influence the sustainability outcomes achieved by waste valorization systems [17]. Future research should therefore investigate context-sensitive deployment models that could extend the reach of circular urban intelligence to municipalities with constrained fiscal capacity.

If cities focus the next 3–5 years on establishing robust baselines and harmonized KPIs, securing data governance and interoperability, running evidence-rich pilots that integrate buildings, waste, and twins, and aligning finance with performance reporting, then circular outcomes become predictable, financeable, and repeatable at scale [3,37,44–46,48,50,51]. Urban intelligence is not the destination; it is the instrument that turns circular ambitions into daily operational practice—and into verifiable progress that investors, regulators, and citizens can trust [1,4,7,45,46].

Several directions for future research emerge from this review. First, longitudinal studies tracking the performance of smart waste systems over multi-year periods are needed to assess technological durability, maintenance cost trajectories, and behavioral adaptation. Second, comparative analyses across different governance regimes and income contexts would enable the identification of the institutional conditions most conducive to successful circular urban technology adoption. Third, the development of standardized cost-reporting frameworks for smart waste infrastructure would significantly improve the comparability of deployments and support evidence-based public procurement. Fourth, the integration of organic waste digital tracking with downstream composting and agricultural application monitoring represents an underexplored frontier in closed-loop urban nutrient management. Finally, the role of citizen engagement platforms in improving waste stream purity—and the conditions under which behavioral incentives and digital tools are complementary or substitutive—merits dedicated investigation.

6. Conclusions and Discussion

Cities cannot meet their circular-economy ambitions with linear, reactive practices. The evidence and cases in this paper point to a clear inflection: urban intelligence, the purposeful integration of sensors, real-time analytics, AI and digital platforms, has moved from a helpful add-on to the operating core of circular urbanism. It enables cities to see material and energy flow as they happen, to act before waste is created, and to coordinate stakeholders around shared performance signals.

Three mechanisms stand out. First, early detection and prevention: data-rich systems reveal where and why waste arises (from buildings to packaging), so cities can target design changes, service schedules and citizen incentives upstream. Second, high-quality recovery: digital IDs, automated sorting and verified tracking lift the purity and value of recovered streams, turning "recyclables" into reliable feedstocks. Third, coordination at scale: urban digital twins and shared data spaces align agencies and operators on the same real-time picture, so policy tests and operational tweaks can be run virtually and implemented only when they work.

While this paper focuses on municipal waste management, the applicability of urban intelligence extends considerably beyond the urban residential context. The same technological architecture can be deployed with meaningful adaptation in organized industrial zones, where heterogeneous waste streams from manufacturing processes share comparable challenges of volume, compositional variability, and regulatory traceability. The conditions under which these cross-sectoral applications are most viable include: the presence of sufficiently large and consistent waste volumes to justify sensor infrastructure investment; regulatory frameworks that mandate material traceability and recovery targets. Exploring the transferability of urban intelligence models to these industrial and peri-urban contexts represents a promising frontier for future research and for extending the economic case for AI-powered circular systems beyond the municipal domain.

The findings of this study suggest that the integration of urban intelligence not only optimizes logistics but also redefines the economic viability of waste management. By implementing fill-level sensors and computer vision, municipalities can transition from fixed collection routes to dynamic, demand-based models. This enables more cost-effective waste collection, reducing operational and fuel costs by up to 35%, as observed in case studies where trips to empty containers were eliminated. Furthermore, AI's early detection capabilities address the issue of undetected waste. Through real-time data analysis, the system can identify accidental overflows or critical accumulation points that traditional methods overlook, ensuring a higher material capture rate and reducing visual and environmental pollution in urban areas

The building cases show how "wise construction" delivers circular gains today. Passive House/EnerPHit projects demonstrate that physics-led envelopes, airtightness and heat-recovery ventilation avoid waste in construction, preserve embodied carbon, and make operations measurably cleaner and cheaper. The Cartagena50 EnerPHit retrofit in Madrid exemplifies a quality-assured approach that links design, monitoring and rooftop renewables for reuse at end-of-life.

At the urban scale, the maturation of digital twins confirms that visualization is no longer cosmetic. Platforms such as Virtual Singapore, S-Map in Seoul, or Dubai's 3D geospatial stack integrate above- and below-ground assets, fuse environmental and operational telemetry, and support predictive planning for energy, mobility and risk. In parallel, smart waste systems are translating data into measurable operational and environmental gains: fill-level sensing, contamination detection, and route optimization have reduced truck-kilometers, cut overflow incidents, and delivered verified cost savings in multiple deployments. On the consumer side, Digital Deposit Return Systems and incentive-based programs (e.g., Spain's Reciclos) demonstrate that digital channels can lift capture rates, improve fraction purity, and furnish real-time evidence to regulators and investors. Across these domains, the pattern is consistent: when regulations and financing instruments demand verifiable performance, digital infrastructures supply machine-auditable proof.

On consumer packaging, DDRS and modern DRS models offer credible pathways to higher capture and better material quality, and they align with the EU's new Packaging and Packaging Waste Regulation, which accelerates separate collection and design for recyclability. The message is consistent: where the rules demand verifiable performance, digital systems supply the evidence.

We also acknowledge limitations and areas for caution. Data governance remains uneven, with persistent questions about ownership, sharing and trust. Technical interoperability is still challenged by legacy systems and proprietary interfaces. Municipal capacity is often the bottleneck: expertise to procure, integrate, and operate advanced systems is scarce and must be cultivated. Finally, the social license for pervasive sensing depends on transparent safeguards and meaningful avenues for citizen participation for a long-term durability of circular transformations.

This study makes three identifiable contributions. Theoretically, it advances a unified analytical framework, bridging smart city and circular economy literature by mapping the informational mechanisms through which digital systems close material loops; this framework provides a foundation for future research that moves beyond domain-specific studies. Methodologically, it demonstrates that narrative synthesis across multiple complementary technology domains anchored in verified performance metrics generates insights that isolated technology reviews cannot produce, and it proposes a replicable three-dimensional analytical framework (mechanism/quantified outcome/governance condition) for future comparative studies. Practically, it delivers a structured roadmap connecting digital infrastructure choices to European regulatory requirements and to financeable performance outcomes, enabling municipalities and developers to identify where digital investment yields verifiable circular gains.

From EnerPHit retrofits to national and city twins and DRS/PPWR show that when data, physics and governance work together, cities can prevent waste, enable systematic reuse, and maximize high-value recovery while decarbonizing operations with the standards, infrastructure and institutions to make circular performance measurable, financeable and fair.

This work acknowledges persistent challenges: data governance, interoperability. institutional capacity, and social equity. While the cases show operational and environmental gains, longitudinal evaluations are needed to quantify circular benefits at city scale over multi-year horizons.

Author Contributions

F.P.G.: Conceptualization, project administration, supervision, writing—review and editing, validation; W.M.N.: Methodology, investigation, formal analysis, data curation, visualization, writing—original draft preparation. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Google's Gemini-1.5 multimodal AI model to redraft and adapt key visual figures (specifically Figures 2 and 3). This tool was employed to enhance the resolution, legibility, and artistic distinctiveness of the original diagrams, ensuring high-quality academic output and addressing potential copyright concerns. After using this tool, the authors reviewed and edited the content of the generated figures as needed and take full responsibility for the content of the published article.

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