Journal of Environmental Science Studies; Vol. 7, No. 2, 2024
ISSN 2591-779X E-ISSN 2630-4821
Published by July Press

# Redesigning Urban Infrastructure for Circularity: The Role of Smart Cities in Reducing Waste

Williams Chibueze Munonye[1] & George Oche Ajonye[2]

[1] Department of Thematic Studies, Science For Sustainable Development, Linköping University, Sweden

[2] Department of Design, Linköping University, Sweden

Correspondence: Williams Chibueze Munonye, Department of Thematic Studies, Science For Sustainable Development, Linköping University, Sweden. E-mail: williamsmunonye@gmail.com; George Oche Ajonye, Department of Design, Linköping University, Sweden. E-mail: ajonyego@gmail.com

Received: October 13, 2024 Accepted: November 28, 2024 Online Published: December 5, 2024

doi:10.20849/jess.v7i2.1468 URL: https://doi.org/10.20849/jess.v7i2.1468

**Abstract**

Rapid global urbanization has prompted cities to rethink their development strategies in the context of sustainability. One of the most promising paradigms is the transition toward a circular economy (CE), where resources are reused, recycled, and regenerated. This perspective article explores how the integration of smart city technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), and data analytics, can drive urban infrastructure toward circularity. Through the process of analyzing current research and case studies, the article highlights the potential of these technologies to reduce waste, optimize resource use, and enhance energy efficiency in urban settings. This article focuses particularly on the role of smart waste management, intelligent building design, and real- time data analysis in fostering circular practices in cities. Through these themes, this article offers insights into how smart cities can bridge the gap between linear urban development models and a sustainable, regenerative urban economy.

**Keywords:** circular economy, waste management, smart cities, sustainability, infrastructure, urbanization

## 1. Introduction

Currently the world has become more urbanized, cities are under increasing pressure to address the environmental impacts of their rapid growth. However, this has led to rising levels of waste generation, resource consumption, and greenhouse gas emissions, prompting a need for more sustainable urban development models (Szpilko et al., 2023; Simon et al., 2024). The traditional linear economy, which follows the "take-make-dispose" approach, has exacerbated environmental degradation by encouraging the extraction of finite resources and promoting waste generation without consideration for response, the concept of a circular economy (CE) has emerged as a promising solution.

The CE model aims to decouple economic growth from resource consumption by promoting reuse, recycling, and regeneration of resources, thereby reducing waste and minimizing environmental impact (Ellen MacArthur Foundation, 2017).

While the circular economy offers a compelling vision for sustainability, its implementation in urban settings presents unique challenges (Kitchin, 2014; Bocken et al., 2016). Cities are complex systems with diverse stakeholders, ranging from municipal authorities and private sector organizations to citizens, all of whom need to collaborate to foster circular practices (Kitchin, 2014; Reindl et al., 2024). Traditional infrastructure, designed for a linear economy, often lacks the flexibility needed to support resource loops and closed systems (Evans et al., 2019; Esfandi et al., 2024). However, the rise of smart city technologies present a significant opportunity to overcome these challenges. By leveraging the Internet of Things (IoT), Artificial Intelligence (AI), and big data analytics, smart cities can optimize urban operations and create systems that facilitate the circular economy (Kitchin, 2014; Esfandi et al., 2024; Parks C Rohracher, 2019).

Smart city technologies have the potential to transform urban infrastructure by enabling real-time data monitoring, predictive analytics, and automation. These technologies allow cities to collect detailed information about resource flows, waste generation, and energy consumption, making it easier to identify inefficiencies and implement strategies to reduce waste and enhance resource efficiency (Szpilko et al., 2023; Simon et al., 2024).

For example, IoT-enabled waste management systems can optimize waste collection routes, while AI-driven systems can reduce energy consumption in buildings through predictive energy management (Simon et al., 2024; Geng et al., 2013). These innovations not only reduce operational costs but also promote circular practices by minimizing waste and facilitating the reuse of materials (Giffinger et al., 2007; Angelidou, 2014). This article seeks to explore the role of smart city technologies in redesigning urban infrastructure to align with circular economy principles, focusing on key areas such as waste management, energy efficiency, and material reuse.

## 2. Smart City Technologies and Circular Economy Alignment

The parallels between smart city technologies and circular economy principles presents a groundbreaking approach for reimagining urban infrastructure in ways that reduce waste and resource consumption. A circular economy (CE) revolves around the regenerative cycle of resources, promoting reuse, recycling, and extending the life of materials and products (Ellen MacArthur Foundation, 2017; Chertow, 2000). In contrast, urban systems have traditionally operated on a linear economic model, which emphasizes extraction, use, and disposal (Geissdoerfer et al., 2017; EU, 2014). However, with increasing urbanization and the environmental impacts of waste generation and resource scarcity, progressive cities, especially in the global north, are now exploring how to transition from a make-use-dispose system toward a circular economy model (Szpilko et al., 2023; Simon et al., 2024).

Smart city technologies, including the Internet of Things (IoT), Artificial Intelligence (AI), and big data analytics, have emerged as powerful tools for enabling this transition (Allam C Dhunny, 2019; Angelidou, 2014; Bocken et al., 2016). These technologies enhance urban efficiency by collecting, analyzing, and responding to real-time data, thus optimizing the use of resources and improving the flow of materials within cities (Allam C Dhunny, 2019; Kitchin, 2014). The concept of the smart city relies on interconnectivity between urban systems, which allows for streamlined processes across sectors such as transportation, energy, and waste management (Giffinger et al., 2007; Geissdoerfer et al., 2017).

A key aspect of this synergy lies in the ability of smart cities to monitor and manage resource flows more effectively. Through real-time data analysis, smart cities can track consumption patterns and identify inefficiencies, which can then be addressed to minimize waste generation and maximize resource recovery (Ferronato et al., 2019; Rathi, 2006). For instance, IoT sensors embedded in urban infrastructure can monitor water usage, energy consumption, and waste generation, providing detailed insights into where and how materials can be reused or recycled (Parks C Rohracher, 2019). This data can be processed by AI-driven systems to forecast demand and optimize resource allocation, further supporting circularity (Allam C Dhunny, 2019; Evans et al., 2019).

The intersection of smart city technologies and CE principles also opens opportunities for designing urban systems that are inherently circular. For example, the development of smart grids allows for energy to be generated, distributed, and reused more efficiently, reducing the reliance on finite resources and lowering the carbon footprint of cities (Esfandi et al., 2024; Parks C Rohracher, 2019). Moreover, the integration of smart technologies into urban planning enables cities to adopt flexible and adaptive reuse strategies, where materials from deconstructed buildings can be repurposed for new construction projects (Bocken et al., 2016; Chertow, 2000).

To this end, the potential for smart cities to accelerate the adoption of circular economy practices are immense. However, the realization of this potential requires a concerted effort by city planners, policymakers, and technologists to ensure that smart city initiatives prioritize circularity from the outset. Therefore, by fostering cross-sector collaboration and aligning technological innovation with circular goals, cities can create resilient and regenerative urban environments that reduce waste and promote sustainable resource use (Geissdoerfer et al., 2017; Simon et al., 2024).

## 3. The Role of IoT in Waste Management

One of the most important applications of IoT technologies in the context of circular cities is in waste management. Smart waste management systems, underpinned by IoT sensors and data analytics, provide a highly efficient solution for tracking and reducing municipal waste (Pires et al., 2011; Ferronato et al., 2019). Traditional waste collection systems operate on a fixed schedule, regardless of actual waste levels. This often results in overfilled bins in high- traffic areas or inefficient collection of half-empty bins in other locations. IoT-enabled waste bins solve this inefficiency by utilizing sensors that detect the fill levels of waste containers, allowing for more targeted and efficient waste collection routes (Ferronato et al., 2019; Rathi, 2006). The data generated by these sensors are transmitted in real-time to a central management system, where collection routes can be dynamically adjusted to prioritize areas with high waste levels and avoid unnecessary collections in less critical zones (Angelidou, 2014; Allam C Dhunny, 2019). This not only reduces fuel consumption and carbon emissions from collection vehicles but also minimizes operational costs for waste management companies. For example, Barcelona has implemented a smart waste management system that uses IoT technology to monitor waste bins throughout the city. The system has led to a significant reduction in collection costs and a noticeable decrease in the volume of waste being sent to landfills (Angelidou, 2014; Szpilko et al., 2023). IoT-enabled waste management also enhances recycling efforts by improving waste segregation at the source. Sensors can identify different types of waste materials, such as plastics, metals, and organic matter, and send alerts to inform users about proper disposal methods (Szpilko et al., 2023; Simon et al., 2024). This real-time feedback not only improves recycling rates but also reduces contamination in recycling streams, making it easier for materials to be processed and reused in the circular economy (Ferronato C Torretta, 2019; Allam C Dhunny, 2019). In cities like Seoul, smart waste management systems have been integrated with digital payment systems that reward residents for correctly separating recyclables, further incentivizing participation in circular practices (Rathi, 2006). Another emerging trend is the use of IoT in optimizing industrial waste management. IoT sensors embedded in manufacturing plants can monitor the production process and track waste generation in real-time (Giffinger et al., 2007; Kitchin, 2014). This allows companies to identify inefficiencies in the production process and find opportunities to reuse or recycle materials (Ferronato et al., 2019). For example, industrial symbiosis networks enable companies to share waste materials, turning one company’s waste into another’s resource. This form of industrial symbiosis is a key principle of the circular economy and is increasingly being supported by IoT technologies that facilitate material flow tracking and optimization (Chertow, 2000; Esfandi et al., 2024; Parks et al., 2019). The integration of IoT into urban waste management systems is thus a critical component of circular city strategies. Concepts like reducing waste, improving recycling rates, and optimizing material flows, IoT technologies are helping cities move away from the traditional linear “take-make-dispose” model toward a more circular and regenerative urban economy (Pires et al., 2011; Ferronato et al., 2019; Ferronato C Torretta, 2019).

## 4. AI and Data Analytics for Resource Efficiency

Artificial Intelligence (AI) and data analytics play a critical role in optimizing resource efficiency in urban environments (Simon et al., 2024). AI driven systems for smart citiesare increasingly being used to manage and optimize energy consumption, improve resource allocation, and reduce waste (Szpilko et al., 2023; Angelidou, 2014; Allam C Dhunny, 2019). One of the primary applications of AI in this regard is predictive energy management, where AI algorithms analyze real-time data from sensors and meters to optimize energy use in buildings and urban infrastructure (Angelidou, 2014; Allam C Dhunny, 2019). Smart buildings, for instance, are equipped with AI-enabled systems that monitor energy consumption in real-time and adjust heating, cooling, and lighting systems to reduce energy waste (Allam C Dhunny, 2019; Kitchin, 2014; Giffinger et al., 2007). These systems can predict energy demand based on patterns in occupant behavior and external factors such as weather conditions. This allows for dynamic energy management, where energy is allocated more efficiently to meet actual demand, reducing unnecessary energy consumption and lowering operational costs (Bocken et al., 2016; EU, 2014). In this way, AI- driven energy management systems contribute to the circular economy by minimizing the amount of energy wasted and ensuring that resources are used as efficiently as possible (Reindl et al., 2024; Esfandi et al., 2024; Parks et al., 2019). AI also plays a key role in managing urban transportation systems, which are major consumers of energy and sources of pollution. Through data analytics, AI can optimize traffic flow, reduce congestion, and improve the efficiency of public transportation systems. This, in turn, reduces fuel consumption and lowers greenhouse gas emissions, contributing to the overall sustainability of the city (Kitchin, 2014). For example, AI powered traffic management systems in cities like London have been shown to reduce congestion and improve the efficiency of public transportation, leading to significant reductions in energy use and emissions (Allam C Dhunny, 2019). Another important application of AI in the context of resource efficiency is predictive maintenance. Urban infrastructure, such as bridges, roads, and public transportation systems, requires regular maintenance to remain functional (Geissdoerfer et al., 2017; Kitchin, 2014). AI-driven predictive maintenance systems use data from sensors embedded in infrastructure to monitor its condition and predict when repairs will be needed. This allows for timely maintenance, preventing breakdowns and extending the life cycle of infrastructure. Further, ensuring that infrastructure lasts longer, cities can reduce the need for new materials and minimize waste, aligning with the principles of the circular economy (Ferronato et al., 2019; Giffinger et al., 2007).

AI and data analytics also play a critical role in optimizing material flows within cities. In the context of the circular economy, material reuse and recycling are essential for reducing waste and minimizing resource extraction (Allam C Dhunny, 2019; Simon et al., 2024). AI- driven systems can analyze data on material usage and identify opportunities for material reuse and recycling (Esfandi et al., 2024). For instance, AI can be used to track the materials used in construction projects and identify materials that can be repurposed in future projects. This not only reduces the demand for new materials but also prevents construction waste from ending up in landfills (Parks et al., 2019; Reindl et al., 2024). AI and data analytics are powerful tools for improving resource efficiency in urban environments (Kitchin, 2014). Through predictive energy management, optimized transportation systems, predictive maintenance, and material flow tracking, AI-driven systems are helping cities reduce waste, improve resource use, and transition toward a more circular and sustainable urban economy (Allam C Dhunny, 2019).

## 5. Final Remarks

Smart city technologies offer a transformative pathway for urban centers to transition towards a circular economy, reducing waste, optimizing resource use, and promoting sustainability. This can be achieved by integrating IoT, AI, and data analytics, smart cities can enable real-time monitoring, predictive analytics, and automated decision-making to improve the efficiency of waste management, energy use, and material flows. IoTenabled systems play a pivotal role in optimizing waste collection, enhancing recycling rates, and supporting industrial symbiosis, all of which are fundamental principles of the circular economy. AI, on the other hand, enhances resource efficiency through predictive energy management, optimized transportation systems, and predictive maintenance, ensuring that resources are used more efficiently, and waste is minimized. However, while the potential for smart cities to support the circular economy is significant, realizing this potential requires coordinated efforts across multiple sectors. Policymakers, city planners, and technologists must work together to ensure that smart city initiatives prioritize circularity from the outset. This includes designing urban systems that are inherently circular, leveraging smart technologies to extend the life of materials and products, and fostering collaboration between industries to promote resource sharing and waste reduction. Ultimately, the integration of smart city technologies and circular economy principles presents a unique opportunity to create more sustainable and resilient urban environments. A roadmap can be developed through aligning technological innovation with circular goals, cities can not only reduce their environmental impact but also improve the quality of life for their residents, laying the foundation for a more sustainable future. However, as cities continue to grow and evolve, smart city technologies will play an increasingly important role in shaping the circular economy of tomorrow.

## Author Contributions

Williams Chibueze Munonye: Responsible for the conceptualisation, data collection, writing of draft, review C editing, and supervision. George Oche Ajonye: Responsible for the proof reading, reading of drafts, writing and data collection.

## Declarations

Competing interests: The author declares no competing interests.

## References

Allam, Z., & Dhunny, Z. A. (2019). On big data, artificial intelligence and smart cities. *Cities*, *89*, 80-91. https://doi.org/10.1016/j.cities.2019.01.032

Angelidou, M. (2014). Smart city policies: A spatial approach. *Cities*, *41*, S3-S11. https://doi.org/10.1016/j.cities.2014.06.007

Bibri, S. E., Krogstie, K., Kaboli, A., & Alahi, A. (2024). Smarter eco-cities and their leading-edge artificial intelligence of things solutions for environmental sustainability: A comprehensive systematic review. *Environmental Science and Ecotechnology, 19,* 100330. https://doi.org/10.1016/j.ese.2023.100330

Bocken, N. M., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308-320. https://doi.org/10.1080/21681015.2016.1172124

Chertow, M. R. (2000). Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy and the Environment*, *25*(1), 313-337. https://doi.org/10.1146/annurev.energy.25.1.313

Ellen MacArthur Foundation. (2017). *Concept: What is a circular economy?.*

Energy solutions for smart cities and communities. (2014). Retrieved from https://op.europa.eu/publication-detail/-/publication/a700e825-18a5-41f9-be4e-6cf10405d50c

Esfandi, S., Tayebi, S., Byrne, J., Taminiau, J., Giyahchi, G., & Alavi, S. A. (2024). Smart Cities and Urban Energy Planning: An Advanced Review of Promises and Challenges. *Smart Cities*, *7*, 414-444. https://doi.org/10.3390/smartcities7010016

Evans, J., Karvonen, A., Luque-Ayala, A., Martin, C., Mccormick, K., Raven, R., & Voytenko Palgan, Y. (2019). Smart and sustainable cities? pipedreams, practicalities and possibilities. *Local Environment, 24*(7), 557-564. https://doi.org/10.1080/13549839.2019.1624701

Ferronato, N., & Torretta, V. (2019). Waste mismanagement in developing countries: A review of global issues. *International Journal of Environmental Research and Public Health, 16*(6), 1060. https://doi.org/10.3390/ijerph16061060

Ferronato, N., Rada, E. C., Gorritty Portillo, M. A., Cioca, L. I., Ragazzi, M., & Torretta, V. (2019, January). Introduction of the circular economy within developing regions: A comparative analysis of advantages and opportunities for waste valorization. *J Environ Manage, 230,* 366-378. https://doi.org/10.1016/j.jenvman.2018.09.095

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The circular economy–A new sustainability paradigm?. *Journal of Cleaner Production, 143,* 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geng, Y., Sarkis, J., Ulgiati, S., & Zhang, P. (2013, March). Environment and development. Measuring China's circular economy. *Science, 339*(6127), 1526-7. https://doi.org/10.1126/science.1227059

Giffinger, R., Fertner, C., Kramar, H., Kalasek, R., Pichler-Milanović, N., & Meijers, E. (2007). Smart cities: Ranking of European medium-sized cities.

Kitchin, R. (2014). The real-time city? Big data and smart urbanism. *GeoJournal*, *79*(1), 1-14. https://doi.org/10.1007/s10708-013-9516-8

Parks, D., & Rohracher, H. (2019). From sustainable to smart: Re-branding or re-assembling urban energy infrastructure?. *Geoforum, 100*, 51-59. https://doi.org/10.1016/j.geoforum.2019.02.012

Pires, A., Martinho, G., & Chang, N. B. (2011). Solid waste management in European countries: A review of systems analysis techniques. *Journal of Environmental Management*, *92*(4), 1033-1050. https://doi.org/10.1016/j.jenvman.2010.11.024

Rathi, S. (2006). Alternative approaches for better municipal solid waste management in Mumbai, India. *Waste Management*, *26*(10), 1192-1200. https://doi.org/10.1016/j.wasman.2005.09.006

Reindl, K., Dalhammar, C., & Broden, E. (2024). Circular Economy Integration in Smart Grids: A Nexus for Sustainability. *Circular Economy and Sustainability, 4,* 2119-2145. https://doi.org/10.1007/s43615-024-00375-5

Szpilko, D., de la Torre Gallegos, A., Jimenez Naharro, F., Rzepka, A., & Remiszewska, A. (2023). Waste Management in the Smart City: Current Practices and Future Directions. *Resources*, *12,* 115. https://doi.org/10.3390/resources12100115