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Digital accountability for circular economy: a case study of Alia Servizi Ambientali's smart waste management

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Abstract

The aim of this paper is to examine how the integrated use of AI, GIS, IoT, and blockchain technologies can enable digital accountability frameworks that enhance transparency, operational efficiency, and circular economy outcomes in urban waste management. An interventionist case study of Alia Servizi Ambientali shows that combining sensor networks, spatial analytics, and blockchain notarisation transforms waste collection into a transparent, participatory service. The findings indicate that digital accountability can support operational improvements and social-impact objectives, while providing empirical insights into circular economy implementation in public–private service contexts.

Keywords: Digital accountability, Circular economy, Social impact, Smart waste management, Blockchain, Stakeholder engagement

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1. Introduction

Urban waste management represents one of the most pressing challenges in modern infrastructure, located at the crossroads of technological innovation, environmental sustainability, and social responsibility (Sohag & Podder, 2020). As urban populations grow and waste volumes increase, cities face mounting pressures not only to improve operational efficiency and reduce costs, but also to promote equity in public services, enhance the quality of life, and minimize environmental impacts. These priorities call for a shift toward inclusive, transparent, and data-driven systems capable of engaging citizens and local institutions in the co-creation of sustainable urban environments (Szpilko et al., 2023; Esmaeilian et al., 2018).

Persistent inefficiencies in traditional waste management systems—such as static route planning, delayed feedback, fragmented data, low recycling rates, and limited citizen involvement—hinder progress toward these goals (Teoh Ji Sheng et al. 2020). In response, the integration of digital technologies such as geographic information systems, artificial intelligence, and the internet of things has emerged as a promising solution. These tools enable real-time monitoring, predictive analytics, and process optimisation. Yet, their full potential remains underexploited, particularly when it comes to supporting circular economy strategies and reinforcing organisational accountability frameworks (Palagan et al. 2025). While transparency may involve granting access to real-time data, true accountability requires verifiable, auditable systems that align operational activities with sustainability, regulatory, and social impact objectives (Mason 2019).

The waste management sector still faces several systemic obstacles. GIS is often confined to static planning, with little dynamic analysis. Relationships with municipalities are frequently challenged by misaligned priorities and reluctance to adopt new technologies. Meanwhile, citizens are typically positioned as passive users rather than active partners in circular practices. These limitations highlight the need for integrated systems that facilitate stakeholder collaboration, elevate public participation, and make data actionable across governance levels. Embracing this transformation means not only improving logistical performance but also reinforcing social engagement, environmental accountability, and long-term value creation.

In this context, digital transformation introduces complex managerial challenges. Organisations must balance the optimisation of operations with the development of internal capabilities that ensure data integrity and cross-sector trust. Digital accountability, in particular, cannot be reduced to the digitisation of services—it must include tools and processes that support real-time monitoring, reliable data traceability, and transparent reporting. These elements are essential for building systems that meet growing demands for ESG (Environmental, Social, and Governance) compliance, improve non-financial reporting, and align technological innovation with long-term institutional goals.

To explore these dynamics, this research adopts a case study approach focused on Alia Servizi Ambientali S.p.A., a public-private company operating in central Tuscany. With a service area of 58 municipalities and 1.5 million residents, Alia manages the full waste cycle—from collection to treatment—while aligning its operations with sustainability and circular economy principles. Its scale and organisational complexity make it a relevant regional case for examining digital transformation in waste management. Its scale and organisational complexity make it a relevant regional case for examining digital transformation in waste management. In the Italian waste management sector, service provision is highly fragmented. While the three largest national multi-utilities (A2A, Iren, Hera) together serve over 11 million people across more than 870 municipalities, the average

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service area in the Italian waste sector covers only about 61,988 residents, with considerable territorial fragmentation in service delivery models. In this context, Alia represents an intermediate case: sufficiently large to provide insight into data-driven transformation, yet still embedded in a local governance framework typical of many regional operators. Its ongoing digital transformation provides a useful empirical setting for analysing the strategic role of integrated technologies in improving accountability, decision-making, and stakeholder relationships in a semi-public, multi-stakeholder environment.

Alia's digital strategy includes IoT-enabled sensors, AI-powered monitoring boards, GIS-based spatial management, and blockchain infrastructure for data certification. This framework allows for real-time tracking of waste levels, user behaviour, and service performance. It not only enhances process efficiency and operational governance but also reinforces ESG compliance by enabling verifiable reporting and reducing information asymmetries among stakeholders.

While this digital strategy offers significant potential in terms of efficiency, transparency, and data integrity, its implementation also revealed organis ational and managerial challenges that are central to understanding the dynamics of digital transformation. Despite the benefits, implementation was not without challenges. Internal resistance among technical staff and management revealed organis ational concerns regarding the complexity of new systems and a lack of familiarity with digital tools. These frictions underscore the need for continuous investment in digital literacy, process redesign, and change management strategies that align technology deployment with long-term stakeholder trust and institutional capacity building.

Similar initiatives across Europe confirm that the Alia case is part of a broader trend in smart waste management. The experience in Barcelona, Stockholm, and Amsterdam have shown how digital technologies and citizen engagement models support the transition towards circular economy practices (Johansson & Corvellec, 2018, Barca et. al 2024, Laureti et. al 2024, Krúpová, 2025). At the same time, companies such as Enevo in Finland and FCC Environment in Spain have implemented IoT-based collection systems and predictive models to improve efficiency and accountability. Positioning the Italian case within this dual landscape of research and practice reinforces its international relevance and highlights its contribution to the European debate on digital transformation in waste management.

The Alia case illustrates how the integration of digital technologies can move beyond operational improvement to support organis ational transparency and circular economy goals. Notably, the adoption of blockchain ensures the integrity of regulatory and operational data, transforming digital traceability into a tool for ESG-oriented governance. In doing so, it offers a replicable framework for other urban waste systems aiming to combine environmental responsibility, citizen engagement, and data-driven decision-making.

In addition to organis ational and environmental considerations, recent research has highlighted that the financial sustainability of digital innovation represents a crucial factor for public service adoption. Smart waste management systems often require significant upfront investment in infrastructure, sensors, and digital platforms, followed by long-term maintenance costs. While such investments can generate efficiency gains and reduce operational expenses, the challenge of balancing costs and benefits is particularly acute for small and medium-sized municipalities, which may lack the necessary financial and managerial resources (Romero-Hernández & Romero, 2018; Das et al., 2019).

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Although the potential of digital transformation in waste management is increasingly recognized, significant research gaps remain, especially in understanding how the synergy between GIS, AI, IoT, and blockchain can support comprehensive accountability systems (Banujan et al., 2024; Abdallah et al., 2020). By analysing Alia Servizi Ambientali's experience, this study contributes to filling those gaps, demonstrating how integrated digital accountability frameworks can serve as both managerial tools and enablers of sustainable, inclusive, and circular public services. Accordingly, the aim of this study is to investigate how the convergence of AI, GIS, IoT, and blockchain technologies supports digital accountability, stakeholder engagement, and circular economy practices in a complex public–private waste management context.

This paper proceeds as follows: Section 2 provides a comprehensive review of existing literature on digital transformation in waste management, with attention to accountability, transparency, circular economy and stakeholder engagement. Section 3 outlines the research methodology and analytical framework. Section 4 presents the findings and analysis, highlighting how advanced technologies contribute to overcoming traditional system limitations. Section 5 discusses the implications for theory and practice, and Section 6 concludes with recommendations for future research and operational implementation. To address these gaps, the study focuses on two core research questions concerning the organis ational and technical challenges of implementing digital accountability frameworks in waste management, and the role of AI, GIS, IoT, and blockchain in enhancing transparency, operational efficiency, and stakeholder accountability.

2. Literature review

2.1 Accountability in the era of digital transformation

Digital transformation has emerged as a fundamental force reshaping organis ational structures, operational models, and governance frameworks across sectors (Hanelt et al., 2020). Its manifestations differ between the public and private spheres, requiring conceptual frameworks that address such nuances without oversimplification (Muehlburger & Krumay, 2023). In the public sector, the evolution of e-government highlights how digital change is often driven by political, social, and environmental imperatives (Janowski, 2015). Crucially, digital transformation extends beyond technological deployment to include shifts in culture, processes, and leadership, enabling organis ations to increase adaptability, transparency, and service responsiveness (Vial, 2019). The success of these transformations depends on internal capacities, particularly employee digital literacy and cross-functional collaboration (Kozanoglu & Abedin, 2020).

Within this broader context, digital accountability has gained prominence as a strategic framework for aligning technological innovation with ethical governance and sustainability outcomes. Defined by its focus on data traceability, transparency, and verifiability, digital accountability goes beyond compliance to embed responsibility and stakeholder trust into organisational systems (Nadkarni & Prügl, 2020; Yaqub & Alsabban, 2023). The COVID-19 pandemic further reinforced the need for accountable digital decision-making, highlighting the importance of auditable and resilient information infrastructures (Maione et al., 2024).

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In sustainability contexts, digital accountability frameworks play a vital role in enabling real-time monitoring of environmental and social performance (Hsu & Schletz, 2023; Petrakaki, 2018). They also influence citizen behaviour by increasing perceived benefits and social expectations related to service quality and environmental responsibility (Syed, 2024). Emerging technologies such as blockchain and IoT offer de centralised, tamper-proof trust mechanisms that enhance both institutional transparency and public confidence (Angiulli et al., 2018; Urquhart et al., 2018; Argento et al., 2020). These tools have reshaped sustainability reporting, shifting it from static, periodic disclosures to dynamic, data-driven practices that support strategic decision-making and stakeholder engagement (Seele & Lock, 2017; Martínez-Peláez et al., 2023; Gulluscio et al., 2020; Gomez-Trujillo & Gonzalez-Perez, 2021).

Accountability today must be understood as multidimensional—encompassing environmental, social, and financial components. Social accountability focuses on service equity and citizen involvement, while environmental accountability targets waste reduction, emissions control, and alignment with global sustainability goals. At the same time, financial accountability is evolving to integrate non-financial metrics (e.g., ESG indicators) that reflect the values and expectations of increasingly sustainability-conscious stakeholders (Schneider & Kokshagina, 2021). For management, digital accountability frameworks offer tools for real-time decision-making, KPI monitoring, and ROI analysis—enabling data-driven governance and performance benchmarking.

However, implementation challenges remain. Blockchain and IoT systems raise critical concerns about data privacy and security (Angiulli et al., 2018), while the absence of standardized ESG metrics and unbalanced power relations among stakeholders can limit the effectiveness of digital transparency (Hsu & Schletz, 2023). Despite these barriers, a supportive policy environment, digital infrastructure maturity, and collaborative ecosystems can significantly improve adoption and impact (Urquhart et al., 2018). Alia Servizi Ambientali S.p.A. embodies these dynamics through its integration of AI analytics, IoT sensors, and real-time platforms to overcome traditional inefficiencies in urban waste governance and service delivery.

2.2 Accountability and digitalisation in waste management

The waste management sector has become a key testing ground for smart and circular economy innovations, particularly through the adoption of IoT-enabled sensors, GIS mapping, and real-time data analytics. These technologies allow for continuous monitoring of waste levels, dynamic route optimisation, and spatially informed decision-making (Sosunova & Porras, 2022; Gulyamov, 2024; Putu et al., 2024). In sectors such as medical waste, IoT systems have enhanced safety by monitoring transport and storage conditions. The recent convergence of IoT, blockchain, and AI has also improved waste supply chain transparency, increasing recycling rates and reducing landfill dependence—core outcomes of circular economy strategies (Hegde et al., 2024).

Yet, despite growing attention to operational efficiency and cost-effectiveness, the accountability dimension of waste management digitalisation remains relatively underexplored. Research has largely focused on infrastructure investment, technological feasibility, and cost-benefit evaluations (Mia, 2024; Mdukaza et al., 2018), with limited emphasis on how these systems contribute to regulatory compliance, ESG performance, or stakeholder trust (Perez-Duran, 2023; Hall et al., 2017).

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The role of citizen engagement—often reduced to user behaviour or service satisfaction—has not been fully integrated into accountability frameworks, despite its growing importance for transparent and participatory governance.

Beyond technological and operational aspects, several studies emphasize that the effectiveness of digital waste systems depends on citizen participation and behavioural adoption models. Frameworks such as the *Technology Acceptance Model* (TAM) and the *Unified Theory of Acceptance and Use of Technology* (UTAUT) have been applied to explain how perceived usefulness, ease of use, and social influence shape citizens' willingness to engage with smart recycling tools and digital feedback systems (Venkatesh et al., 2003; Chen & Aklikokou, 2020). In the context of waste management, these models highlight that digital engagement is not only a function of technological availability, but also of perceived fairness, environmental concern, and trust in public institutions (Marrucci et al., 2021; Hsu & Lin, 2018). Accordingly, citizen-centred design and transparent communication mechanisms—such as real-time feedback dashboards or incentive-based PAYT schemes—can strengthen accountability by aligning behavioural motivation with sustainability goals.

Blockchain platforms have introduced new possibilities for traceability and verification across the waste management lifecycle. However, their integration into broader frameworks of digital accountability is still emerging. For public service providers like Alia, which operate within complex, multi-stakeholder environments, the convergence of real-time monitoring and verifiable data certification is essential for building trust, managing performance, and meeting environmental and social goals. Accountability frameworks in this sector must therefore connect technological capacity with institutional responsibility and public legitimacy.

Reliable, auditable data is increasingly essential not only for environmental policy design but also for community engagement and public oversight. Blockchain-based systems offer immutable ledgers that reduce the risk of data manipulation and enhance institutional credibility (Faiz et al., 2024; Bułkowska et al., 2023; Cao et al., 2024). These features are particularly relevant as civil society and advocacy groups demand more transparent, verifiable, and participatory governance mechanisms. In this context, Alia's approach illustrates how digital innovation can strengthen accountability along the entire waste management chain—enabling data-driven services that support circular economy transitions and foster stakeholder collaboration.

2.3 The circular economy and the role of digital technologies in waste management

The circular economy (CE) has emerged as a paradigm aimed at reducing environmental impact through resource efficiency, reuse, and the minimisation of non-recoverable waste. Unlike the traditional linear model of production and consumption, CE emphasizes the extension of product lifecycles and the reintegration of materials into new production processes (Kouhizadeh et al., 2019; Upadhyay et al., 2021). From a systems perspective, circularity is achieved not only through recycling, but through design, monitoring, and governance strategies that allow materials to circulate as long as possible within the economy (Haleem et al., 2021; European Commission, 2019). In this context, utility companies—particularly in the waste management sector—play a central role in operationalising CE principles, as they mediate the flow of materials, resources, and data across the urban metabolism (Perey et al., 2018).

Comparative analyses across Europe confirm that digital innovation in waste management has evolved within a broader trend that combines operational efficiency with participatory governance. Studies on Barcelona, Stockholm, and Amsterdam

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highlight how smart bins, IoT sensors, and data platforms enable municipalities to monitor waste flows, optimize logistics, and promote citizen engagement in circular practices practices (Johansson & Corvellec, 2018, Barca et. al 2024, Laureti et. al 2024, Krúpová, 2025). Beyond the academic sphere, companies such as Enevo (Finland) and FCC Environment (Spain) have implemented predictive collection systems that use fill-level sensors and analytics to improve service efficiency and transparency. These initiatives demonstrate that Europe's most advanced waste systems integrate three complementary pillars: digital infrastructure for real-time monitoring, citizen-oriented models for behavioural engagement and accountability, and policy and financial instruments that sustain the transition toward circular economy goals. Positioning the Italian case of Alia within this multi-dimensional framework strengthens its international relevance and provides empirical insights into how digital accountability operates at the intersection of technology, governance, and citizen participation.

Digital technologies are increasingly critical enablers of the CE transition. Artificial intelligence (AI), Geographic Information Systems (GIS), and Internet of Things (IoT) sensors provide the infrastructure needed to monitor waste flows, optimize collection routes, and analyse user behaviour in real time. These systems make it possible to anticipate inefficiencies, reduce emissions, and support proactive maintenance strategies, aligning operational performance with environmental objectives. Moreover, blockchain technology enhances traceability by securing data related to waste origin, disposal behaviour, and regulatory compliance—adding a layer of verifiability that reinforces both institutional accountability and stakeholder trust.

Despite its promise, the integration of CE principles through digital innovation presents organisational and governance challenges. Utility companies must not only adopt new technologies, but also reshape internal workflows, adapt to evolving regulatory frameworks, and engage citizens as active participants in sustainability efforts (Borrello et al., 2017; Marrucci et al., 2021). This multidimensional shift requires a transformation in how waste is conceptualized—not simply as a by-product to be managed, but as a resource to be reintegrated into the economy through digitally supported accountability mechanisms. In this sense, the convergence of AI, IoT, GIS, and blockchain becomes a foundational infrastructure for enabling data-driven circularity in urban services.

A further dimension of accountability concerns the financial sustainability of digital transformation in waste services. While smart systems can yield efficiency gains and cost reductions, their deployment often requires high initial investments in infrastructure, sensors, and data platforms, followed by recurring maintenance and training costs (Romero-Hernández & Romero, 2018; Das et al., 2019). These challenges are particularly pronounced for small and medium-sized municipalities, where limited financial and managerial capacities may hinder large-scale adoption. Research on European PAYT schemes and inter-municipal collaborations suggests that cost-sharing, modular platform design, and incremental implementation can mitigate financial risks while preserving the accountability and transparency benefits of digital waste systems (EEA, 2022). Addressing financial sustainability thus becomes essential to ensure that digital innovation translates into long-term public value rather than short-term pilot success.

2.4 Research questions development

The reviewed literature highlights the transformative potential of digital technologies—including IoT, AI, GIS, and blockchain—in enhancing decision-making, service quality, and operational efficiency in waste management. However, most

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studies address these technologies in isolation or focus narrowly on technical, financial, or policy constraints. The combined, systemic role of these tools in enabling digital accountability—across transparency, regulatory compliance, and stakeholder engagement—remains insufficiently studied.

This research contributes to bridging that gap by adopting an integrated perspective that explores how the convergence of real-time analytics, predictive AI, spatial data, and blockchain notarisation supports a more accountable, resilient, and participatory waste management model. By investigating a case where these technologies are applied holistically, we offer a novel understanding of how digital infrastructures shape not only operational practices but also social impact, institutional trust, and circular governance.

Building on this review and the identified literature gap, our study focuses on the following research questions:

1. *What are the key challenges in implementing digital accountability frameworks within waste management organisations?*
2. *How do AI, GIS, IoT, and blockchain technologies collectively enhance transparency, operational efficiency, and accountability in waste management?*

These questions guide our examination of Alia Servizi Ambientali S.p.A., offering actionable insights for organisations, managers, and policymakers interested in the integration of digital tools for sustainable, transparent, and socially responsive waste governance.

3. Methodology

3.1 Case study identification

Managing and quantifying waste production is a critical responsibility for governments worldwide. In Italy, this priority gained renewed focus with the "Ronchi Decree" (Italian Government, 1997), which introduced a more sustainable framework for waste management by providing explicit guidelines on disposal, recovery, and recycling. By emphasizing the importance of separate waste collection, the Decree laid the foundation for heightened accountability among various stakeholders. Subsequently, the Consolidated Environmental Act (CEA) (Italian Government, 2006) reinforced the principle of producer responsibility, particularly for hazardous and special waste, reflecting an ongoing institutional and legislative impetus to enhance lifecycle management.

Within this legislative context, Alia Servizi Ambientali S.p.A. (Alia) offers a compelling vantage point to examine how advanced digital transformation can promote accountability, transparency, and efficiency in large-scale waste management. Operating in 58 municipalities across the Tuscany region and serving over 1.5 million residents, Alia's extensive reach exemplifies the complexity of current urban environments. This scale provides a unique opportunity to investigate how integrated digital solutions address operational, environmental, and stakeholder needs, as highlighted in the broader waste management literature.

At the core of Alia's system is an AI-supported waste management infrastructure based on proprietary sensor technology and electronic boards. These components convert conventional waste containers into intelligent data hubs, continually measuring

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waste volume, attributing disposal activities to individual users, and relaying real-time indicators to a centralised platform for monitoring and analytics. By offering volumetric assessments, analysing collection patterns, and profiling user behaviour, the system aligns with digital accountability frameworks that emphasize real-time data visibility to enhance transparency, assign responsibility to multiple parties, and inform proactive decision-making.

Beyond purely operational metrics, the model harnesses AI and GIS technologies to create digital twins, enabling predictive modelling for optimal route planning, reduced fuel consumption, and diminished CO2 emissions—key considerations for regulatory compliance and sustainability targets. Real-time alerts further bolster maintenance responsiveness, minimizing costs and improving overall service reliability. These features mirror global policy goals, which advocate employing digital innovations to strengthen waste governance and meet sustainable development milestones.

From a user-focused standpoint, the system traceability features enable Alia to link individual deposits to specific users, facilitating tailored feedback loops. This engagement strategy promotes communal responsibility and leverages behavioural incentives (e.g., reward programs for environmentally conscious practices), thus building trust among citizens, municipal authorities, and Alia's operational framework. This multi-stakeholder emphasis exemplifies the convergence of digital transformation and accountability to address the economic, social, and environmental dimensions discussed in the literature.

Ultimately, the model's seamless integration of data collection, storage, and analysis not only enhances operational efficiencies but also yields critical insights for complying with regulations, informing strategic decisions, and advancing sustainability initiatives. By transitioning waste management into a data-driven enterprise, Alia serves as a benchmark for harnessing digital innovations to elevate environmental stewardship and foster stakeholder engagement, central themes highlighted in both the introduction and the literature review.

3.2 Research design

This study employs participant observation at Alia Servizi Ambientali over two months, integrating direct engagement with corporate processes. Following interventionist research methodology, the study applies digital accountability and stakeholder governance frameworks to address practical waste management challenges (Jansen & Wiegand, 2018), bridging theoretical concepts with operational realities. While the relatively short observation period (two months) limited the possibility of capturing long-term behavioural change, this constraint was mitigated through systematic data triangulation combining field observation, semi-structured interviews, and document analysis.

The researcher was directly involved in the observation and analysis of digital processes while maintaining an analytical and reflective stance. This dual role allowed the integration of emic insights from organisational actors with an etic analytical perspective, consistent with interventionist research principles.

The interventionist approach facilitates collaboration with organisational members and enables targeted recommendations, combining external (etic) and internal (emic) perspectives (Jönsson & Lukka, 2005). This immersion provides deeper insights into the socio-technical aspects of Alia's digital transformation, particularly regarding IoT sensors, AI analytics, and user feedback systems. The methodology aligns with stakeholder theory by incorporating diverse viewpoints and promoting transparent interactions among local authorities, company staff, and community members.

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The study supplements participant observation with semi-structured interviews and organisational document analysis. These sources provide critical insights into Alia's strategic priorities, compliance approaches, and technological implementation. This integrated approach illuminates emerging challenges in real-time data governance and sustainability while examining the broader societal impacts of Alia's innovative waste management practices (Suomala & Lyly-Yrjänäinen, 2011).

The interventionist methodology addresses competing stakeholder interests, from municipal authorities to citizens, emphasizing collaborative governance (Suomala et al., 2014). Through direct field engagement, the study contributes to the theoretical discourse on digital accountability and stakeholder-focused resource management while providing practical operational insights for Alia's ongoing transformation. Triangulating these complementary sources compensated for the limited observation period by validating findings through convergent evidence.

3.3 Interviews data

This research employs data triangulation to enhance findings' reliability (Flick, 2004), combining semi-structured interviews, internal document analysis, and literature review. This comprehensive methodology aligns with established qualitative research practices (Blaikie, 1991) and enables a thorough investigation of complex technological implementations in waste management.

To ensure methodological transparency, a structured interview protocol was developed, organized into five thematic sections—Perception of digital technologies, Organisational impact, Accountability and transparency, Challenges and solutions, and Future perspectives—and is summarized in Appendix A. The full questionnaire is available upon request.

The interviews, conducted over two months, totalled approximately 400 minutes. A strategically selected group of participants, including senior managers, consultants, and technical experts, provided detailed insights on AI integration in waste management, operational strategy development, and technological innovation. As outlined in table 1. These interviews explored specific themes such as:

- Digital transformation challenges and opportunities
- Implementation of AI-driven waste management systems
- Stakeholder engagement strategies
- Sustainability metrics and monitoring
- Operational efficiency improvements

The research followed strict data triangulation principles, comparing information across multiple sources to verify findings (Flick, 2004). Interview data underwent systematic cross-referencing with project documentation, including:

- Internal technical reports
- System architecture documents
- Implementation guidelines
- Performance metrics
- Stakeholder feedback records

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Table I: Interviews data

Respondent ID	Professional Profile	Interview Length
R1	Field operators	2 h
R2	Maintenance and field operation manager	30 m
R3	Head of service and territorial management	1:10 h
R4	Head of service planning and digitalisation	35 m
R5	Innovation Specialist	1 h

Source: Authors' elaboration

This multi-source approach strengthened the analysis's credibility while mitigating potential biases. The triangulation process revealed critical insights into waste management and technological innovation intersections, particularly regarding AI's role in optimizing operational efficiency and advancing sustainability goals. The diverse professional backgrounds of respondents provided comprehensive perspectives on challenges and opportunities in integrating circular economy principles with emerging technologies.

The methodological approach aligns with recent studies in the field (e.g., Secinaro et al., 2021), demonstrating how multiple data sources effectively illuminate complex technological and operational phenomena. Through systematic analysis of varied perspectives, the research developed a nuanced understanding of how Alia leverages advanced technology to enhance transparency, operational efficiency, and sustainability in waste management operations.

Each interview was recorded, transcribed, and coded using qualitative data analysis software, ensuring a systematic and thorough examination of the collected data. An inductive coding approach was adopted, combining open coding with iterative thematic aggregation to identify recurring patterns related to accountability, technological adoption, and stakeholder engagement. The coding process identified key themes and patterns across interviews, enabling a comprehensive analysis of technological implementation challenges, success factors, and strategic considerations in waste management innovation.

4. Results

4.1 Challenges in implementing digital accountability frameworks in Alia Servizi Ambientali

A digital accountability framework refers to the integration of interconnected technologies and digital processes that enable real-time monitoring, systematic data management, and transparent stakeholder reporting. While the potential of these systems is broadly recognized, literature highlights a lack of case-based understanding of how to implement them effectively, particularly in operationally complex public service environments (Agostino et. all. 2021). This study investigates how a digital accountability framework was successfully implemented at Alia Servizi Ambientali S.p.A., highlighting the key challenges, strategic adaptations, and resulting organisational transformation.

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The three-year digitalisation process was initiated by a strategic decision from Alia's management to strengthen territorial asset monitoring, improve traceability of the waste cycle, and increase transparency toward both municipalities and citizens. These goals were tightly linked to the company's broader objective of aligning waste services with sustainability targets and circular economy principles (Lanzalonga et. al. 2024).

The implementation followed a "send-and-return" logic, where active participation from both institutional and citizen stakeholders was crucial. As a semi-public operator, Alia had to navigate regulatory constraints with municipalities while also building credibility and trust with the community. To meet these challenges, the company developed two core initiatives: a centralised GIS-based control room for real-time territorial oversight, and a web-based system for municipal stakeholders to independently monitor operational and performance data. This infrastructure not only improved internal efficiency, but also supported inter-institutional cooperation and transparent, KPI-driven governance.

Alia also introduced digital tools aimed at citizen engagement. These platforms enabled users to access service-related data, report operational issues, and interact with the system in real time. These interventions addressed three main needs: changing internal workflows and service paradigms, enhancing transparency for municipalities, and empowering citizens with access to timely and verifiable information.

Although many companies in the waste management sector have experimented with GIS and IoT integration, these projects often remained disconnected from core business processes. Alia, too, initially relied on static GIS layers and sensor systems lacking real-time feedback, leading to data quality gaps and inefficiencies. The transition to a more fully digitalized infrastructure required the integration of real-time sensors, responsive interfaces, and predictive analytics—an organisational shift that encountered internal resistance, particularly from field staff.

A maintenance and field operation manager noted:

> *"Initially, the procedural changes created resistance because the benefits weren't immediately clear. New methods were seen as obstacles, requiring more time than operators anticipated."*

Similarly, a technician reflected:

> *"Re-entering data multiple times during online procedures increased frustration, slowing the process and amplifying the perception of operational complexity."*

Over time, the system began to show measurable advantages. Real-time IoT-based alerts enabled precise work order generation through GIS dashboards, improving timeliness and planning accuracy. As one operator explained:

> *"Having access to accurate, real-time data allows us to anticipate issues and plan interventions more effectively."*

Before this transformation, spatial and technical knowledge was fragmented across departments and individuals. GIS was used for static planning, and IoT systems collected data that had to be retrieved manually or via vehicle-based antennas. These limitations led to a highly reactive service model.

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To overcome these issues, Alia adopted a set of strategic changes:

1. Digital infrastructure integration:

- Replacement of static GIS and disconnected tools with IoT-enabled devices.
- Integration of real-time sensors with GIS dashboards and a centralised control room.

2. Process automation and data quality:

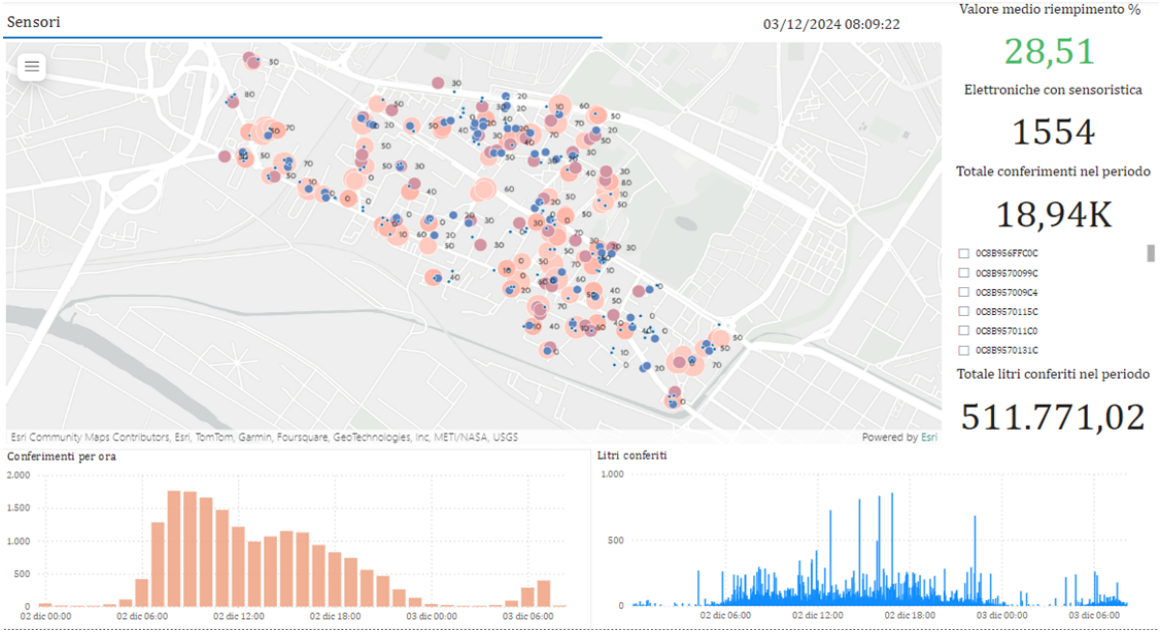
- Automation of work orders and maintenance workflows.
- AI-based data filtering and sensor calibration to ensure reliable insights.

3. Organisational adaptation and skills development:

- Structured training programs for field staff and managers.
- Change management initiatives to support the transition toward proactive service models.

These actions not only improved operational performance but also laid the groundwork for digital governance based on traceability, stakeholder accountability, and social impact.

Figure 1. GIS-based control room displaying real-time container fill levels, usage frequency, and operational alerts supporting territorial monitoring and decision-making.



Source: Authors' elaboration

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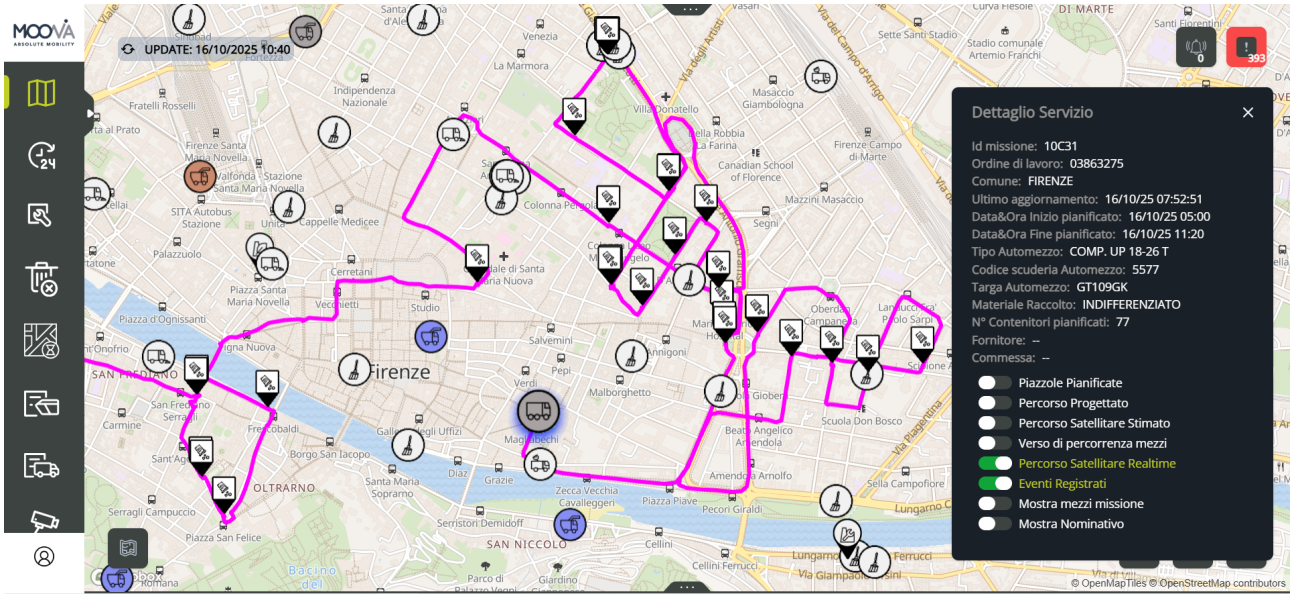
In Italy's multi-actor governance system for environmental services, municipalities act as both regulators and clients, often resulting in tense relationships with service providers. These tensions are exacerbated by issues such as illegal dumping, citizen complaints, and technological reluctance.

Since municipalities determine whether and how smart technologies are deployed in their territories, Alia's digital strategy included new collaboration mechanisms built on data transparency. The introduction of dashboards and web portals enabled municipalities to view territorial performance in real time. The centralised control room allowed them to track operational KPIs, maintenance activities, and criticalities (Figures 1 and 2).

Figure 2. Shared web-based dashboard accessible to municipal authorities, enabling real-time monitoring of service operations, KPIs, and maintenance activities to support transparent and data-driven governance.



Source: Authors' elaboration

As the head of service and territorial management explained:

> "Giving municipalities the ability to query data and perform discovery on Alia's services has strengthened trust with local authorities and reinforced the connection with the territory."

These initiatives redefined institutional roles, enabling evidence-based dialogue and a shared commitment to efficiency and sustainability, reinforcing the governance dimension of the circular economy.

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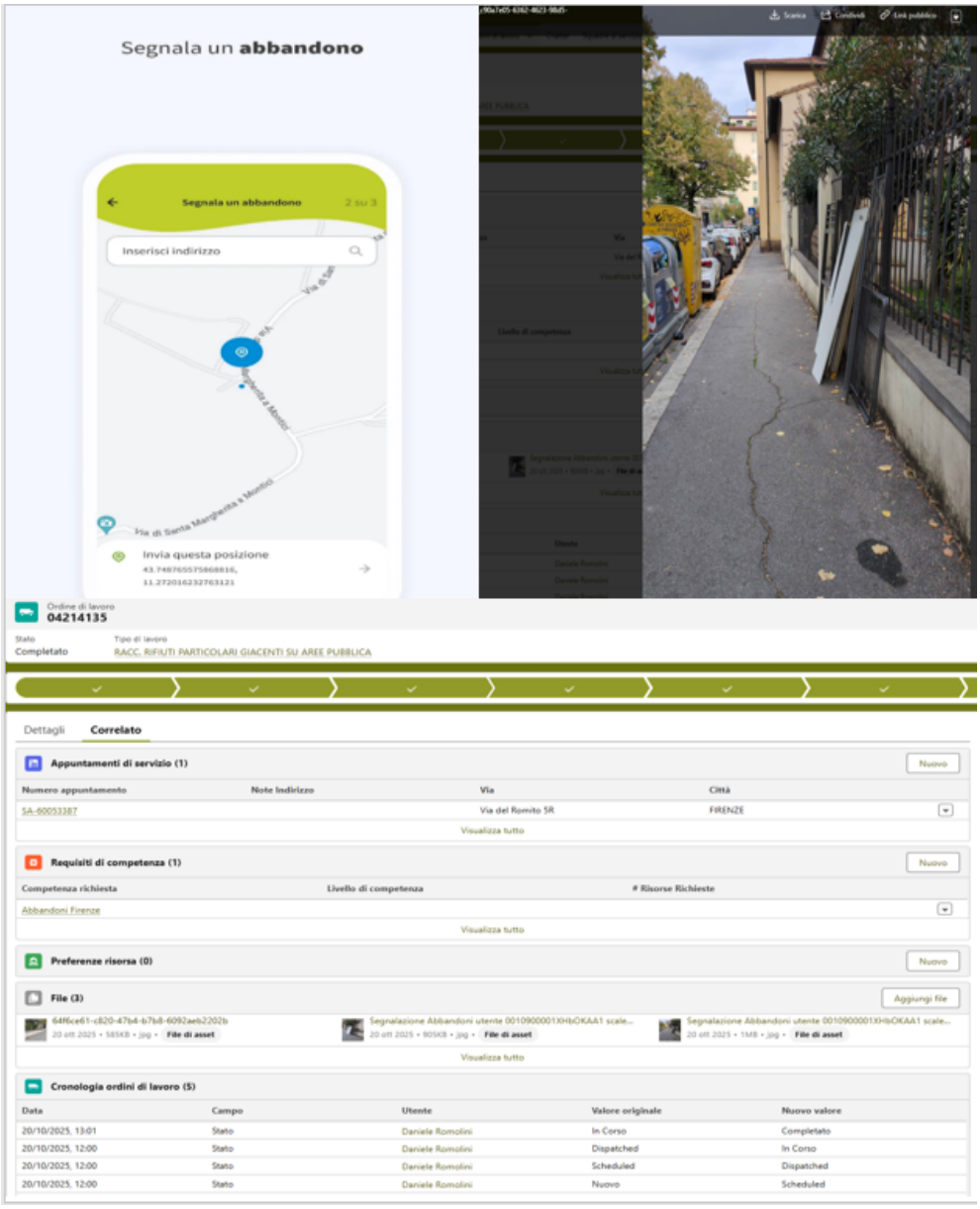
Traditionally considered passive recipients, citizens are now positioned as active stakeholders in Alia's system. Consumption habits, resistance to change, and limited awareness often hindered public participation in sustainability efforts. Alia sought to change this dynamic by making data visible, processes auditable, and user input consequential.

Figure 3. Citizen-facing mobile application and back-office interface enabling geo-referenced reporting of illegal dumping, real-time feedback, and bidirectional communication between citizens and the service provider, reinforcing social accountability and engagement.



Source: Authors' elaboration

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The citizen-facing app offers tariff visibility, waste service tracking, and the ability to submit geo-referenced reports with photographic evidence. This tool created a feedback loop between users and the service provider, building trust and enabling shared accountability.

> *"In the last year, we responded to approximately 2,000 citizen reports. The geo-referenced data from the app, combined with photographic attachments, enabled us to intervene within 24 hours,"* explained the maintenance and field operation manager.

Thanks to this digital channel, 85% of submitted reports were resolved within 48 hours. Citizens can now follow the status of their reports and receive feedback—closing the communication loop and increasing perceived service quality and responsiveness.

The platform also supports strategic planning. Aggregated reports reveal recurring issues, inform predictive maintenance, and facilitate targeted interventions. Public trust has improved through greater visibility of service quality, open communication, and the organisation's demonstrated commitment to transparency and responsiveness. These efforts led to a 45% increase in citizen engagement during the 12-month implementation period.

4.2 Enhancing transparency, operational efficiency, and accountability

Alia's digital accountability model is supported by a robust, multi-layered technical architecture. IoT sensors gather real-time field data; AI filters and calibrates signals; GIS generates spatially optimised workflows; and blockchain technology secures data integrity. These elements work together to ensure high data quality, efficient planning, and strong traceability.

The company's implementation workflow includes:

1. Signal generation: IoT sensors register bin fill levels, access logs, and environmental telemetry in real time.
2. Cloud processing: AI-based algorithms process raw data and convert it into actionable signals.
3. Data calibration: sensor calibration ensures consistent accuracy and reduces false positives.
4. Operational integration: cleaned and verified data feeds into the GIS platform, triggering work orders with spatial optimisation.

This pipeline supports Alia's transition to proactive service delivery—identifying emerging issues before escalation and reducing system downtime. It also supports transparency through verifiable, traceable workflows.

The integration of AI, GIS, IoT, and blockchain has created a data ecosystem capable of supporting performance optimisation, stakeholder engagement, and ESG compliance. Smart bins equipped with advanced telemetry collect and transmit data on fill levels, user interactions, and operational status to a cloud platform. Once notarized on blockchain, the data becomes tamper-proof and ready for reporting or audit purposes.

As the innovation specialist noted:

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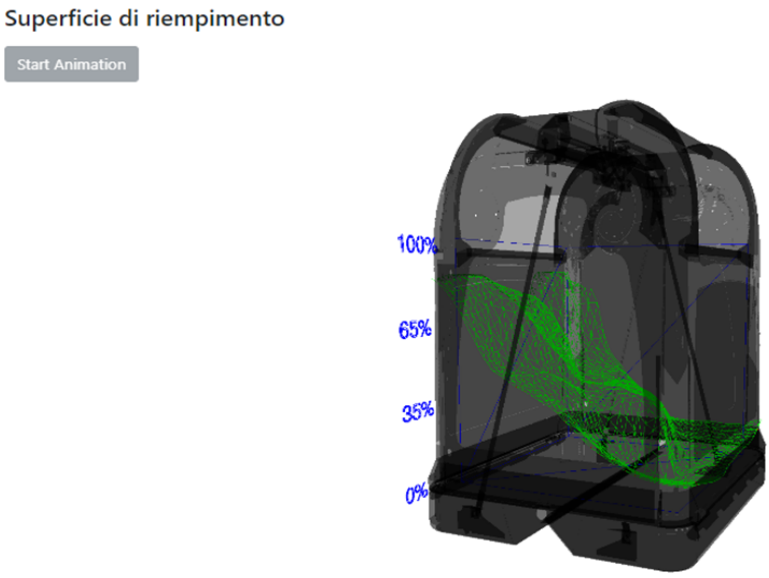
"With the notarisation of data through blockchain, we are able to provide transparency and consistency of data from the field."

This system now forms the foundation of Alia's ESG reporting processes and supports municipal and public audits with reliable, immutable records. It also gives users access to personal waste disposal histories, reinforcing transparency and accountability at every level.

Sensor analytics—supported by 3D LIDAR—are used at the street level, enabling smart waste management closer to citizens. Challenges such as volatile fill-level readings were addressed through refined sensor filtering and better calibration, yielding consistent and usable insights.

Figures 4: Real-time visualization of waste fill levels inside smart containers, generated through IoT sensors and AI-based data processing, and integrated into the GIS platform to support predictive maintenance and optimised collection planning.



Source: Authors' elaboration

Before this system, Alia relied on static GIS maps and staff knowledge for route planning. As the head of service planning and digitalisation explained:

"The design of the routes and their modification over time are based on the experience of individual drivers and field operators."

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Now, route optimisation is dynamically calculated using real-time data. This has led to shorter routes, reduced stress for drivers, fewer heavy vehicles in residential areas, and significant reductions in fuel consumption and emissions—key contributions to circular economy objectives.

Table II: Mapping of key operational and organisational challenges to digital solutions and outcomes within Alia's digital accountability framework.

Challenge	**Solution**	**Outcome**
Organisational Resistance	Training & change management	Higher user acceptance and reduced friction
Limited Real-Time Data	IoT + GIS integration	Faster interventions and better service punctuality
Inefficient Waste Collection	AI-driven route planning	Optimised routes and reduced CO_2 emissions
Data Integrity and Trust Issues	Blockchain-based notarisation	Transparent, auditable ESG and service data
Manual Input & Redundancy	Automated workflows	Decreased errors, improved operational fluidity

Source: Authors' elaboration

From a financial perspective, the digital accountability system introduced measurable cost efficiencies and improved the economic governance of waste services. The integration of predictive analytics reduced service redundancy and optimised fleet usage, yielding both operational and budgetary savings. These effects supported Alia's strategic alignment with performance-based contracts and circular economy funding frameworks, strengthening the link between technological innovation and financial accountability. Furthermore, the traceability of cost drivers through real-time dashboards provided municipalities with tools to assess service value and justify investment decisions, promoting shared financial responsibility across public stakeholders.

Alia's experience demonstrates how integrated digital tools can move beyond operational optimisation to support governance, transparency, and community engagement. The combined use of IoT, GIS, AI, and blockchain not only improved internal efficiency, but also contributed to measurable outcomes in citizen satisfaction, environmental sustainability, and stakeholder trust—key pillars of circular and socially accountable urban infrastructure.

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5. Discussion

Building on the empirical evidence presented in the previous section, this discussion interprets the findings through the lenses of digital accountability, stakeholder governance, and circular economy theory. The case study of Alia Servizi Ambientali suggests that digital accountability frameworks may play an important role The case study of Alia Servizi Ambientali suggests that digital accountability frameworks may play an important role that digital accountability frameworks can play in modern waste management systems. By integrating IoT, GIS, AI, and blockchain technologies, Alia addressed long-standing operational inefficiencies while enhancing service transparency, regulatory compliance, and stakeholder trust. These outcomes contribute to the broader discourse on digital transformation in public services (Hsu & Schletz, 2023; Nadkarni & Prügl, 2020) and offer practical, real-world insights for both scholars and practitioners.

What are the key challenges in implementing digital accountability frameworks within waste management organisations? The study reveals that implementation challenges fell into two main categories: organisational adaptation and technical integration.

On the organisational side, the transition from fragmented legacy systems to a real-time digital infrastructure required significant cultural and procedural change. Initial resistance—particularly from field staff—was linked to perceived workload increases and unfamiliarity with new tools, confirming existing literature on resistance during digital transformation (Vial, 2019). Alia successfully mitigated these challenges through structured training, phased rollouts, and process reengineering. These managerial strategies underscore the importance of change management and digital capability-building in facilitating successful technological adoption.

While citizen participation represents a key dimension of behavioural adoption, similar dynamics can be observed within organisations themselves. Employees and managers also interpret digital transformation through perceptions of usefulness, effort expectancy, and social influence—dimensions identified in behavioural adoption frameworks such as the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003). In Alia's case, initial hesitation among field staff mirrored common barriers described in these models, particularly regarding workload perceptions and technological complexity. Targeted training and communication efforts effectively enhanced perceived ease of use and reinforced positive social norms, facilitating acceptance and sustained engagement with the new digital systems.

On the technical side, achieving reliable and actionable real-time data required advanced filtering algorithms, sensor calibration, and AI-driven signal refinement. Ensuring interoperability between subsystems was essential to generating coherent spatial outputs for operational decisions. These efforts contributed to data quality, accuracy, and traceability—critical prerequisites for both performance optimisation and accountability.

Together, these insights provide a comprehensive view of the practical steps required to implement digital accountability frameworks in complex service organisations. They emphasize that technology integration alone is insufficient without parallel organisational and process transformation—an important takeaway for managers and policymakers alike.

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How do AI, GIS, IoT, and blockchain technologies collectively enhance transparency, operational efficiency, and accountability while promoting social impact and circular economy practices?

The findings highlight the synergistic value of integrating AI, GIS, IoT, and blockchain technologies into a unified digital accountability model. Operational efficiency was significantly enhanced through AI- and GIS-driven route optimisation based on real-time sensor data, enabling predictive interventions, reducing fuel consumption, and streamlining task scheduling—benefits that directly support both environmental and economic sustainability (Seele & Lock, 2017; Xu et al., 2022). Transparency and accountability were reinforced through blockchain, which provided immutable records of service operations, supported ESG reporting, reduced audit-related disputes, and built institutional trust—an area that remains underexplored in waste services.

Alia's implementation of blockchain aligns with emerging demands for more robust digital governance models within environmental management. Moreover, the system's ability to monitor waste flows in real time and dynamically schedule collections enabled key circular economy practices by reducing emissions, increasing recycling efficiency, and improving the use of public infrastructure. The platform's capacity to minimize unnecessary collection trips also promoted more sustainable consumption and resource allocation. Finally, the initiative generated meaningful social impact by redefining the role of citizens as active co-producers of service quality. The citizen-facing app gave users the ability to monitor services, report problems, and access billing information transparently, fostering civic participation and improving public perceptions of fairness, responsiveness, and accountability in urban waste services.

The study contributes to the literature by showing how the combination of real-time data ecosystems and blockchain-enabled traceability may inform accountability arrangements in waste management. While previous research has acknowledged the efficiency gains from digital tools (Gulyamov, 2024; Putu et al., 2024), Alia's approach uniquely integrates technical, managerial, and participatory dimensions to create a socially and environmentally responsive service model.

From a management perspective, this case study highlights how performance-based monitoring, citizen engagement platforms, and inter-municipal dashboards can serve not only as operational tools but also as strategic governance instruments. These technologies enable more informed decision-making, better ROI tracking on digital infrastructure investments, and improved regulatory compliance.

Beyond organisational and operational aspects, financial sustainability emerged as a crucial dimension in the digital transformation process. The deployment of IoT infrastructures, AI-driven analytics, and blockchain notarisation required significant upfront investment in hardware, connectivity, and data management systems. However, these costs were balanced by measurable efficiency gains, including reduced fuel consumption, optimised workforce allocation, and improved service planning. This finding supports prior research indicating that the long-term economic viability of digital innovation depends on a careful alignment between technological investment and value creation in public services (Romero-Hernández & Romero, 2018; Das et al., 2019). Alia's experience suggests that strategic financial planning and cross-sectoral partnerships can mitigate initial investment barriers, making digital accountability frameworks more accessible for smaller municipalities.

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For policy development, the case underscores the need for flexible regulatory frameworks that support the integration of emerging technologies while safeguarding data integrity, public interest, and accessibility. The success of Alia's system illustrates how data traceability and real-time reporting mechanisms can reinforce trust between public institutions and communities.

While the study provides a robust empirical foundation, it is subject to several limitations. First, it focuses on a single case within a specific regional and organisational context, which may limit the generalizability of findings to other public service settings. Second, the observation period covers only the initial phase of implementation, offering a snapshot rather than a longitudinal assessment of long-term outcomes. Future research should therefore investigate cross-case comparisons and extended timeframes to better capture the evolving dynamics of digital accountability systems. Additionally, it would be valuable to investigate the long-term impact of citizen engagement tools on user behaviour, perceptions of service quality, and environmental outcomes. Further work is also needed to develop standardized and cost-effective protocols for integrating AI, GIS, IoT, and blockchain technologies in waste management systems, particularly in under-resourced or developing regions where infrastructural and financial constraints pose additional challenges.

The success of Alia's initiative demonstrates that digital accountability frameworks—when implemented holistically—can drive meaningful improvements in waste service delivery. By combining technological innovation with participatory governance, the organisation created a model that enhances operational performance, promotes circular economy practices, and supports transparent, citizen-oriented management. These findings may offer useful indications for organisations facing similar sustainability-transition challenges. organisation Overall, the Alia case illustrates that successful digital accountability requires not only technical and organisational alignment but also behavioural readiness and financial foresight. Addressing these dimensions holistically can enhance the replicability and sustainability of digital transformation initiatives in the public sector.

6. Conclusion

This study examined how the integration of Geographic Information Systems (GIS), artificial intelligence (AI), Internet of Things (IoT), and blockchain technologies enhanced the operations of Alia Servizi Ambientali S.p.A.—a leading waste management organisation in Tuscany. The study suggests that an integrated digital accountability framework can contribute to operational performance, foster institutional trust, and support circular economy practices.

Through the coordinated use of IoT sensors and real-time analytics, Alia achieved dynamic route optimisation and significantly improved the responsiveness of its waste collection services. Blockchain technology ensures data integrity, traceability, and compliance with regulatory requirements, while the introduction of a mobile application empowered over 10,000 citizens to actively contribute to service monitoring and improvement. Over a 12-month period, these innovations led to a 45% increase in stakeholder engagement and enabled the resolution of 85% of citizen-reported issues within 48 hours—clear indicators of strengthened transparency and meaningful social impact.

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This study directly responds to the research questions by identifying key implementation challenges, including organisational resistance and technical integration, and highlighting the critical role of change management, targeted training, and phased implementation in overcoming them. Furthermore, it demonstrates how the convergence of AI, GIS, IoT, and blockchain technologies enhances transparency, operational efficiency, and stakeholder accountability, while also advancing environmental sustainability and public participation—core pillars of the circular economy.

The research contributes to theoretical development in three significant ways: first, by expanding the concept of organisational transparency through real-time monitoring and traceability tools that reinforce governance structures and ESG accountability; second, by underscoring citizen engagement as a catalyst for social impact and a mechanism for continuous service improvement; and third, by establishing the strategic relevance of blockchain-based data systems in fostering public trust and institutional credibility—critical components of accountability in environmental services. From a practical perspective, the results of Alia's transformation are substantial: sensor-based route optimisation is projected to improve efficiency by 80%, reduce fuel consumption, and lower CO_2 emissions, directly contributing to circular economy goals and climate action. At the same time, the success of the citizen-facing platform reaffirms the importance of transparency and participation in strengthening collaborative relationships between institutions and communities.

This research is not without limitations. As a single-case study conducted in a specific region of Italy, the findings may not be fully generalisable to contexts characterized by different regulatory frameworks, infrastructure maturity, or cultural dynamics. While the findings are not statistically generalisable, the study supports analytical generalization by illustrating mechanisms and governance dynamics that may be transferable to similar public service contexts. Additionally, the fast pace of technological advancement may render some of the tools and systems used in this study outdated in the near future. Cultural factors that facilitated high levels of citizen participation in Alia's case may not easily translate to other contexts, requiring localized adaptation. Building on these limitations, future research should prioritize cross-regional comparative studies of digital accountability frameworks to examine how variations in governance models and policy environments influence outcomes. Further investigation is also needed into the behavioural dimensions of user adoption, using established technology acceptance models to refine public engagement strategies and improve long-term participation.

From a policy standpoint, the findings highlight the importance of aligning digital innovation strategies with supportive governance and funding mechanisms. Public decision-makers can play a decisive role by promoting interoperable standards, incentivizing open data ecosystems, and allocating dedicated resources to digital infrastructure in the environmental sector. Such initiatives not only enhance transparency and accountability but also strengthen coordination between utilities, municipalities, and regional authorities, accelerating the transition toward data-driven and circular models of urban management.

Finally, regarding scalability and replicability, future research and practice should focus on how integrated IoT and blockchain solutions can be adapted to smaller or under-resourced municipalities. While large utilities can sustain the initial investment and maintenance costs associated with digital transformation, small and medium-sized municipalities often face financial and

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managerial barriers. Developing modular, low-cost, and interoperable architectures could facilitate adoption in these contexts, ensuring that the benefits of innovation are equitably distributed.

Overall, the integration of advanced digital technologies into waste management systems marks a significant advancement not only in operational performance but also in transparency, stakeholder accountability, and public value creation. Alia's experience offers a replicable model for organisations seeking to align digital innovation with environmental responsibility and community engagement. To maximize the transformative potential of such initiatives, organisations should assess their digital readiness, invest in capacity-building for both staff and stakeholders, and adopt staged implementation strategies that prioritize measurable sustainability outcomes. In doing so, they contribute not only to more efficient service delivery but also to the broader shift toward socially responsible, transparent, and circular models of urban governance.

Appendix – Interview Protocol (Key Themes)

Table III: Resume of the semi-structured protocol designed to explore participants' perceptions, experiences, and expectations regarding the digital transformation of waste-management systems.

Section	Focus	Example guiding questions
1. Perception of digital technologies	Experience with IoT-enabled sensors, GIS, and digital platforms	"How would you describe your experience with the current digital tools implemented by the organisation?"
2. Organisational impact	Internal collaboration, relations with municipal authorities, and citizen engagement	"How has the introduction of digital tools affected collaboration within the organisation?"
3. Accountability and transparency	Effectiveness of blockchain systems and data integrity mechanisms	"What features of the system are most beneficial for improving transparency with stakeholders?"
4. Challenges and solutions	Resistance to digitalisation, problem-solving, and system limitations	"What resistance did you observe among staff or management during the transition?"
5. Future perspectives	Desired technological improvements and personal role evolution	"What additional technologies could further enhance the system?"

Source: Authors' elaboration

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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Acknowledgments

This study was conducted under the oversight of Alia Servizi Ambientali S.p.a., which ensured adherence to ethical guidelines and principles in research. Although the company does not have a formal ethics committee, all necessary measures were taken to safeguard the rights, privacy, and well-being of participants. Informed consent was obtained from all participants prior to their involvement in the study.

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